PUBLISHER
Association Marocaine pour les Sciences et Techniques de l'Environnement et la Santé (AMSTES)
Email: amstesmaroc@amstes.org

DIRECTOR OF PUBLICATION
Prof. Bouchaib BAHLAOUAN
Tel.: +212 661 38 93 85
Email: b.bahlaouan@nbseh.org

EDITOR-IN-CHIEF
Dr Michael BRETT-CROWTHER
Email: drmichaelbrettcrowther@gmail.com

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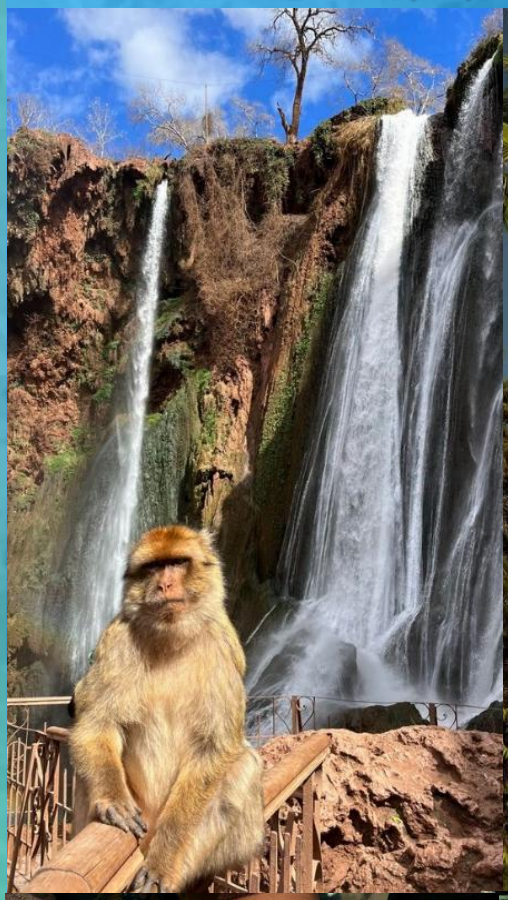

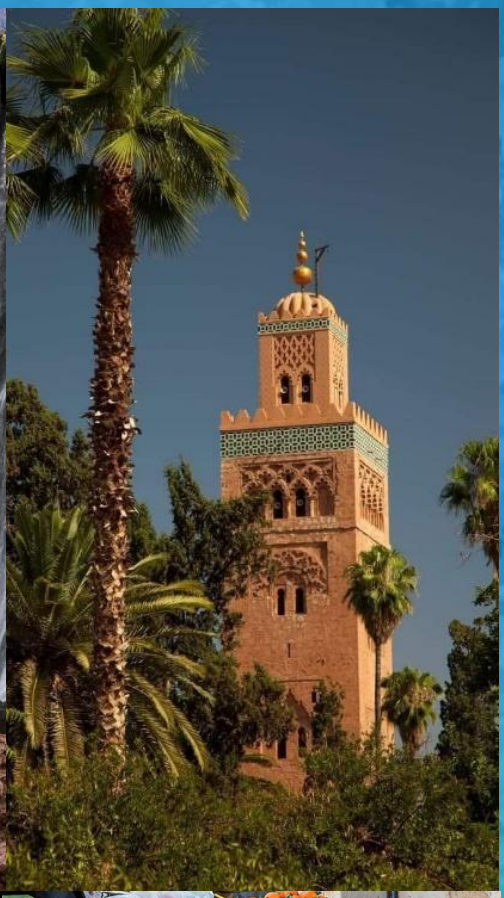

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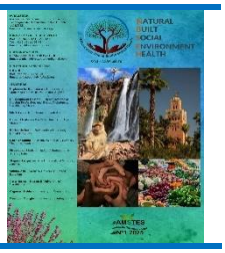

IN MEMORIAM

Dr Geoff O'Brien (1952-2023)

Dr Geoff O'Brien, Senior Lecturer in Environmental Management in Northumbria University, was a Geordie - born in Newcastle upon Tyne [1]. This was a centre of the flourishing heavy industry of the British Empire at its height, with firms such as Vickers and Parsons, and inventors such as Armstrong and Stephenson whose work transformed the world. The city itself has traces of the Roman Wall, mediaeval buildings and a magnificent 18th Century heritage of buildings as well as improvements to the ancient city plan.

O'Brien was educated at Washington Grammar School, and subsequently qualified with a degree from what was then Newcastle Polytechnic in 1974 (since 1992 the University of Northumbria at Newcastle upon Tyne) as an electrical engineer, and worked in the global (USA and Norwegian) oil and gas exploration worlds, both offshore and onshore, between 1975-1986 for Chevron and Statoil. He became more and more interested in and committed to environmental management, local (e.g., Surfers against Sewage in North Tyneside), national and international. Dr O'Brien worked as a UK national civil servant for a while in London (at the then Department of the Environment), writing drafts of ministerial speeches etc. in the environmental and local government domains in the late 1980s.

He became, upon return to Tyneside, a consultant in environmental management, put together as editor and author a number of case studies for learning, and was recruited in 1991 by Northumbria University to teach on its then undergraduate degree in Environmental Management. A short while later Dr O'Brien's expertise was called upon as lecturer, module leader and supervisor on Northumbria University's MSc in Disaster Management and Sustainable Development, which still continues after 25 years, to provide a UK sustainable development and emergency management strand, with the associated policy and practice sector. Dr O'Brien was working in the 2000s especially in relation to the much-needed transformations to the UK emergency management sector. In 2008, he successfully defended at Northumbria University his PhD thesis 'by published work'. This meant that his published peer-reviewed articles, held together by a framing thematic analysis and an overall

methodology and epistemology, had to be evaluated by two external examiners, including a viva voce defence [2]. This was entitled 'Disaster Management, Climate Change and Variability and Social Resilience'.

He was instrumental in taking this type of learning to various parts of the world, including East Asia (Taiwan, South Korea, China), South East Asia (Malaysia, Philippines), and the Gulf (Oman and Kuwait) as part of the expansion of the new paradigm of bottom-up emergency planning. Dr O'Brien also taught by invitation in Taiwan, South Korea and the Gulf states, as well as the Caribbean (Saint Vincent and the Grenadines), where he had a number of PhD students from their public sector.

Dr O'Brien was eager and effective in assisting student education in building sustainable problem-solving approaches, drawing on his experience in academia. engineering and the public sector. He made notable scholarly contributions to UK emergency preparedness and response, local government, energy and climate adaptation, and preservation and development of cultural and social assets. The general theme of his scholarly contributions was the global, international, national, and local, interfaces between social, institutional and governance learning for climate change, disaster risk reduction and energy transition transformations.

He was also a compassionate and effective local councillor (rising to alderman) from 1991 to 2018 (ward councillor in Moorside and then, after the 2004 boundary review, a new ward called Westgate taking in the whole of the city centre), being Sheriff in 2011 and Lord Mayor in 2012. As Lord Mayor, he chose Muslim Aid for his charity for his period of office. He visited Birzeit University, Palestine, November 16-17th 2011, where he made an encouraging contribution to people who needed to be recognized and better supported by the rest of the world [3]. This political and civic activity included trusteeship of the key community asset The Beacon in the West End of Newcastle upon Tyne (owned by North East of England charities Centre West and Groundwork South Tyneside and Newcastle), the historic Tyne Theatre and Opera House, and also the Byker Community Trust. He died peacefully in St Cuthberts Hospice, Durham, on 22nd November 2023. A man of the people, and a man with vision [4].

References

[1] Newcastle University Library, 2023 (May 11), Defining Geordie – Geordie guide. Newcastle University. https://libguides.ncl.ac.uk/c.php?g=130223&p=851119

[2] Shams, R. (2024, March 27). Publication-based doctorate: Is it for me? THE Campus. https://www.timeshighereducation.com/campus/publicationbased-doctorate-it-me

[3] O'Brien, G., 2012, Keynote address at Conference on Environmental Education, Birzeit University, Ramallah, Palestine, 16 November 2011. *International Journal of Environmental Studies* **69**(1), 3–6. https://doi.org/10.1080/00207233.2012.648472

[4] Holland, D. (2023, November 30). Tributes paid to 'generous' and 'hugely charismatic' former lord mayor of Newcastle. Chronicle Live. https://www.chroniclelive.co.uk/news/north-east-news/geoff-obrien-newcastle-tributes-mayor-28197401

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richard.kotter@northumbria.ac.uk

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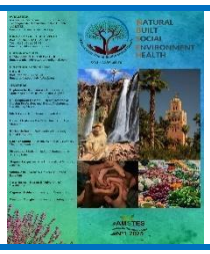

Cities – Good for the Environment?

Geoff O'Brien (© 2025 estate of the late Dr Geoff O'Brien) and Richard Kotter *

School of Geography and Natural Sciences, Faculty of Science and Environment, Northumbria University (https://ror.org/049e6bc10), Ellison Place, Newcastle upon Tyne, NE1 8ST, UK

* ***Corresponding author:*** Richard Kotter; ***Email***: richard.kotter@northumbria.ac.uk

Graphical Abstract

This graphical abstract illustrates the evolution of the relationship between cities and the environment. It begins with the demand for agriculture, the first transformation that supported urban growth. The Industrial Revolution is shown as a turning point that intensified environmental impacts. Consumerism is represented as a driver of ecological degradation. The final stage highlights eco-cities as a pathway towards sustainability and human well-being. The central question, *"Cities – Good for the Environment?"*, emphasises that cities are both a source of environmental problems and a potential solution to climate change.

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Abstract: Cities have played a huge role in human development over millennia, shaping the environment and the earth's climate system for many years. Over the last 200 years, the rate of impact has accelerated. The Industrial Revolution changed the way we use resources, and resource use has continued to grow. We are still in the fourth phase, which is marked by emerging technology breakthroughs in a number of fields. The present economic system is based on consumerism and economic growth. The global population has continued to grow. Urbanization has increased, with now more than half of the global human population living in cities. This is forecast to grow to 70 percent of the global population by 2050. To improve the environmental performance of cities, we will need smart solutions for energy, transport and resource use. Cities must have a low environmental footprint. This will require smart solutions and a change in lifestyles. Future cities must focus on human well-being, and our environmentally (and socially) destructive consumerist lifestyle. Current generations have no right to trash the planet and deny opportunities for other species.

Keywords: *Cities, Climate Change, Resources, Technology, Consumerism.*

Introduction

According to Glaeser [1], cities are humanity's 'greatest invention'. Taylor *et al.* [2] argue that cities are demanding. Using Jacobs' 'city first' theory (which argues that cities effectively started organized agriculture as they required it to feed them – and that cities were driven by craft production and economic processes such as the 'export multiplier' and 'import replacement' effects [4]), Taylor *et al.* also claim that the city demanded the invention of agriculture. As cities grew it was realized that pastoralism could not provision the city, and another source of food was needed – thus agriculture was invented by city demand. Drawing on the work of Ruddiman [3], Taylor *et al.* [2] conclude that climate change is an unintended consequence of the demand of cities. In his 'early Anthropocene' hypothesis, Ruddiman [3] sees nature in control of the climate until some 8000 years ago human beings took control. Increasing deforestation along with a growing population led to an increase in carbon emissions and some 5000 years ago methane, a greenhouse gas, was being generated by rice production. Over many millennia, there is a story of a uniquely dangerous species whose material reproduction is becoming enormous, simply too big for the Earth.

Cities emerged at various times and places across the world as special settlements orchestrating local/non-local relations. According to Jacobs [4], 'in modern and historical times, no creative local economy – which is to say, no city economy – seems to have grown in isolation from other cities. A city does not grow by trading only with a rural hinterland. A city seems always to have implied a group of cities, in trade with one another.' Living in a city as part of a network of cities means a whole new world of enhanced communication, in terms of both quantity and quality. Compared to hunter-gatherer bands of some 150 people that may be in contact with other bands, city networks would show far greater numbers. It has been estimated that in Catalhoyuk (one of the earliest cities) in Anatolia, in about 7000BC residents had a human communication enhancement greater than pre-urban people by a factor of nearly 2,700, and for Uruk (in Mesopotamia, perhaps the first great city) about 4000 years later the enhancement factor was over 550,000 [5]. In other words, living in cities totally transformed the density and diversity of communications of people providing direct access to so much more information and knowledge than could ever be experienced in previous non-urban worlds.

Does this make a difference? According to Glaeser [1], all this additional communication enables city residents to become 'smarter' than their less connected country cousins; they have more and diverse people to learn from who are also smarter from being in cities. In particular, Glaeser argues that 'cities speed innovation by connecting their smart inhabitants to each other' to become very creative places. This is the reason cities have such a strong historical track record for creative change: 'cities' are

literally synonymous with 'civilizations [6]. But being 'smarter' is not just about transformative innovations; living in cities can instigate collective changes in ways of living in numerous economic, social and ethical ways. Overall, urban populations did grow and continue to do so, and today another of the unintended consequences of urbanization is an increasingly elderly population in cities [7].

Social development had increasing impacts on the climate system and the physical environment. In terms of climate change there is speculation that interactions between civilizations led to the Little Ice Age. Nevle *et al.* [8] and Powell [9] claim that the early explorers of the Americas brought diseases to which the native populations had no resistance. Up to 80 million people are thought to have died. This catastrophic population drop led to the rapid regrowth of deforested areas in the Americas. This lowered the carbon concentration, and some maintain that was the cause of the Little Ice Age in the northern hemisphere. Clement *et al.* [10] argue that there is clear evidence that the Amazonian basin had a large area cleared for agriculture. Remote sensing has found remains of cities, roads and other infrastructure. This supports reports by early explorers such as conquistador Francisco de Orellana, who claimed that in 1542 he saw many large towns along the banks of the Amazon [11].

Human beings have interacted with the environment for many millennia. But, over the last 200 years we have seen a marked change in the relationship between humanity and the planet on which we depend.

The Industrial Revolution, beginning in the eighteenth century in the northern hemisphere, was a major turning point in Earth's ecology and humanity's relationship with the environment – compounding what the Agricultural Revolution had started with intensification. The Industrial Revolution dramatically changed every aspect of human life and lifestyles, and continues to do so with its environmental, economic, social and cultural legacy via the intensified mass-scale use of machines and fossil fuels etc. [12].

Weber's 1904-5 work on *The Protestant Work Ethic and the Spirit of Capitalism* [13] argued that in particular Calvinist Protestantism with an emphasis on 'hard work', asceticism (of various degrees and depth for the industrial patrons), and reinvestment expanded capitalism in both Europe and North America. The sociologist Collins [14] considers Weber's thesis on the 'psychological impetus for rationalize, entrepreneurial capitalism' as 'only a fragment of Weber's full theory', and essentially an 'idealist' one.

Tawney [15] argued in 1926 in *Religion and the Rise of Capitalism*, that the mediaeval European Protestant Reformation, and in particular the Calvinist doctrine, made a critical contribution by

separating religious ethical or moral codes of behaviour from economic actions, in the sense of emphasizing afresh material wealth, its accumulation and self-interest connected to that.

Novak [16] writes against this view to some extent, drawing on Collins' [17] work, to argue that capitalism was bound up with the mediaeval Church, which was a major landowner in Europe, with a continent-wide legal system across multiple other jurisdictions. The Church provided administrative bureaucracies at various levels and with requisite special skills to facilitate trade and investment, a highly motivated labour force. For example, the Cistercians were noted entrepreneurs separating themselves from mainstream feudalism and local settled restrictions.

There are four currently recognized phases to the Industrial Revolution. The first phase took place from the 18th to 19th centuries in Europe and (mostly Northern) America. It was a period when mostly agrarian, rural societies became industrial and urban. The iron and textile industries, along with the development of the steam engine, played central roles in the Industrial Revolution. Cities grew and urbanization increased. Today, more than half of the global population lives in cities. It is forecast to grow to close to 70 percent by 2050, with nearly 7 billion of 9 billion people projected overall in 2018 by the United Nations in their World Urbanization Prospects report [18].

During this first phase, the financial system began to change with a shift in banking practice that has now culminated in the capitalist system. The second phase, termed the Technological Revolution, took place between 1870 and 1914. This was a period of growth for pre-existing industries and expansion of new ones, such as steel, oil and electricity, and used electric power in order to create mass production. Major technological advances during this period included the telephone, the light bulb and the internal combustion engine. The third phase, known as the Digital Revolution, refers to the advances in technology from analogue electronic and mechanical devices to the digital technology available today. The era started during the 1980s and continues [19]. Advances during this phase include the personal computer, the internet and information and communications technology (ICT). The Fourth Industrial Revolution builds on the Digital Revolution, representing new ways in which technology becomes embedded within societies and even the human body. The fourth phase is marked by emerging technology breakthroughs in a number of fields, such as robotics, artificial intelligence, nanotechnology, quantum computing, biotechnology, the Internet of Things, 3D printing and autonomous vehicles [20].

Global Environmentalism

There is not a great deal of evidence that the environment was a major concern for our developing societies. Even after the Industrial Revolution there is little evidence that the environment and our impact on it was a concern. Some scientists such as Arrhenius had hypothesized that carbon dioxide could impact the climate by making it warmer [21]. But in general concerns about the environment did not really take shape until after World War II.

Three women are eminent in promoting environmentalism.

Rachel Carson, in her book *Silent Spring*, set out the dangers of chemicals on the natural environment [22]. Some commentators credit this work as being instrumental in shaping the Environmental Protection Agency (EPA) in the United States. Much of the agency's early work, such as enforcing the 1972 Federal Insecticide, Fungicide, and Rodenticide Act, was directly related to Carson's work [23].

The writings of Barbara Ward crossed so many disciplines and interest groups that different people remember her for different things. Environmentalists know her for the 'unofficial report' commissioned by the Secretary-General of the United Nations Conference on the Human Environment, 'prepared with the assistance of a 152-member committee of corresponding consultants in 58 countries', she wrote with René Dubos called *Only One Earth: The Care and Maintenance of a Small Planet* (published in 1972, republished as a book in 1983) [24]. Barbara Ward also made fundamental contributions to the UN Conference on the Human Environment in Stockholm (also in 1972), as well as to the concept of sustainable development and how it might be applied [25].

Gro Harlem Brundtland, who served as the Prime Minister of Norway, was invited in 1983 by the then United Nations' Secretary-General Javier Perez de Cuellar to establish and chair the World Commission on Environment and Development (WCED), the Brundtland Commission. This commission published its report, Our Common Future, in 1987 [26]. This provided the momentum for the 1992 Earth Summit / United Nations Conference of Environment and Development (UNCED), headed by Maurice Strong, who had been a prominent member of the Brundtland Commission. The Brundtland Commission also provided momentum for Agenda 21, the principal outcome of UNCED), often also known as the Rio de Janeiro conference. The United Nations describes Agenda 21 as 'a comprehensive plan of action to be [under]taken globally, nationally and locally by organizations of the United Nations System, Governments, and Major Groups in every area in which humans impact on the environment' [27].

The Brundtland Commission gave a definition for the term sustainable development: 'Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs' [26]. In the last 30 years most countries and many organizations and movements have adopted the Brundtland definition of sustainable development and many state that they are using this to guide policy development. Hopwood *et al.* [28] point out that many developed world nations and bodies such as the World Bank and the European Union tend to favour the status quo (see Figure 1). There is evidence of some change, but it is very incremental. It also varies between countries and other organizations.

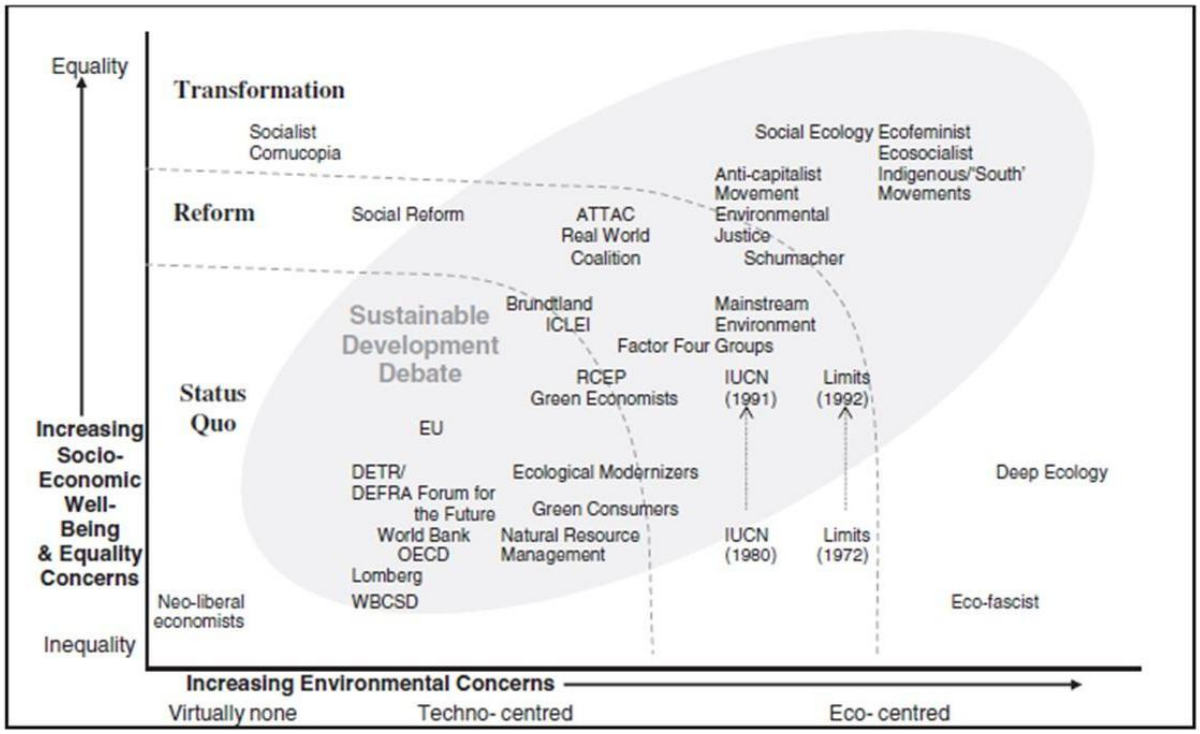

Figure 1. Mapping Sustainable Development (Source: [28])

O'Brien and O'Keefe [29] use the Kyoto Protocol as a means of showing the difference between countries. When the United Nations Framework Convention for Climate Change (UNFCCC) was formed in 1992 [ratified in 1994 by 50 signatory states], most countries became signatories. It was quickly realized that a more formal and flexible agreement was needed. This was realized in the Kyoto Protocol, adopted in 1997 and coming into force in 2005. Although its targets were modest, there were different responses. The USA left the Protocol under the first Presidency of Trump,

claiming that its terms would damage its economy. The European Union took a (net reduction) flexible approach with some Member States, such as Germany and the UK, having relatively higher targets to meet, and others, such as Portugal, being allowed to increase greenhouse gas emissions. The Kyoto Protocol was successful, but as stated earlier its target was very modest. The international community has continued to look for ways to develop an international agreement to limit greenhouse gas emissions. The latest agreement, the Paris Agreement, adopted in 2015, came into force in 2016. The United States became a signatory in 2016, and U.S. President Obama signed an Executive Order to ratify it, committing US$3 billion to the Green Climate Fund. In 2017, U.S. President Trump announced that the United States would cease all participation (although it later stated that the U.S. would abide by the 4-year exit process). Trump's view was that the Paris Agreement would "undermine" the U.S. economy and put the U.S. "at a permanent disadvantage". In 2019, the first Trump Administration gave formal notice of the intention to withdraw, which it did formally in November 2020. The U.S. rejoined in 2021 under President Biden, through an Executive Order, and withdrew again in January 2025 shortly after President Trump's second inauguration (again by an Executive Order).

Sustainable Cities

Cities themselves can promote good environmental performance. Meyer [30] points out that, using New York as an example, cities appear to be very resource-extravagant. An analysis of the city as a whole shows that city-centre areas, where resident density is high, vehicle ownership is below the norm and public transport is well planned, have a lower resource consumption per capita than corresponding suburban areas [30].

UNEP and Habitat maintain that cities have historically constituted efficient settlement patterns because of the correlation between higher density and lower per-capita rates of resource use and emissions [31]. They manage to accommodate more than 50% of the earth's people on just 3% of its surface area and generate some 80 percent of its wealth. In theory, the concentration of resources and talent should also make cities more resilient since city structures allow decision-makers to plan resource use and the consolidated wealth in cities should be able to buffer socio-economic shocks. UNEP and Habitat have stated that cities and urban areas now consume 75 percent of the earth's natural resources and produce 60 percent of its greenhouse gas emissions and 50 percent of its waste. Because of urban sprawl and bad or no planning, cities are losing the efficiency advantages they have historically possessed.

Clearly, the problems of sustainability will have to be addressed at the city-level. There have been a number of initiatives to reduce the environmental impacts of cities.

One of them, 'The Garden City' concept, was initiated in 1898 by Ebenezer Howard. Garden cities were intended to be planned, self-contained communities surrounded by greenbelts, containing proportionate areas of residences, industry, and agriculture. The ideal garden city would house 32,000 people on a site of 6,000 acres (2,400 ha), planned on a concentric pattern with open spaces, public parks and six radial boulevards, 120 feet (37 metres) wide, extending from the centre. The garden city would be self-sufficient and when it reached full population, another garden city would be developed nearby. Howard envisaged a cluster of several garden cities as satellites of a central city of 58,000 people, linked by road and rail. Research suggests that the Garden City concept can have many benefits such as improved health and social cohesion [32]. These ideas were promoted by British town planners, but the British 'New Towns' were mainly built to accommodate the larger (and often homeless) populations of postwar Britain, and to end slums. Coping with bomb damage with a huge national debt did not produce the most imaginative examples of Howard's hopes. There are examples where only certain aspects of the concept have been selected, which mitigates the positive effects. Further, there is evidence that it is the wealthier areas of the city that gain the most [32].

Urbanization and Future Cities

Ritchie *et al.* [18] show with data that 'more than half of the world's population now [after 2007] live in urban areas — increasingly in highly dense cities.' This is uneven between high-income and low-income countries: 'Across most high-income countries – across Western Europe, the Americas, Australia, Japan, and the Middle East – more than 80% of the population lives in urban areas. Across most upper-middle-income countries – in Eastern Europe, East Asia, North and Southern Africa, and South America – between 50% to 80% of people do. In many low to lower-middle-income countries, the majority still live in rural areas. But this is changing quickly.' The UN World Urbanization Prospects projected estimates of "urban" shares of population world-wide through to 2050 in 2018. With projected population growth being based on the UN's medium fertility scenario, the global human population is estimated to be about 9.8 billion in 2050, with close to 7 billion – that is more than 2/3 – to be forecast to live in urban areas then. That does not mean they will live well, as quality of living standards should be considered in the urban context also. According to Ritchie *et al.* [18], 'one metric of living standards is the share of the urban population living in slum households. A slum household is defined as a group of individuals living under the same roof lacking one or more of the following conditions: access to improved water, access to improved sanitation, sufficient living area,

and durability of housing. The most recent global estimates [available since 2000] suggest just under 1-in-4 people in urban areas live in slum households … [where] most countries across Asia and Latin America had between 10 to 50% of urban populations living in slum households. Slum households are most prevalent across Sub-Saharan Africa; in most countries, more than half of the urban populations live in slum households, and in some (such as Chad) around 8 in 10 people live in slum households.'

According to the Worldwatch Institute [33], there are now more than 1.7 billion members of "the consumer class" - nearly half of them in the developing world. A lifestyle and culture that became common in Europe, North America, Japan, and a few other pockets of the world in the twentieth century is going global in the twenty-first. The Institute gives a frightening array of statistics. Worldwide, private consumption expenditures- the amount spent on goods and services at the household level - topped $40 trillion in 2015. As incomes rise, people are gaining access to a multitude of consumer items associated with greater prosperity; for example, 1.4 billion of the 1.9 households have a television set and some 3.2 billion people have internet access. The Institute concludes that we must find ways of curbing excessive consumption.

This explains why a number of cities have opted to become 'ecocities'. There are other terms such as 'sustainable cities' and 'green cities'. For our purposes, we will use the eco-city term that was coined by Richard Register in 1987 [34]. An eco-city is a city designed with consideration of environmental impact, inhabited by people dedicated towards minimization of required inputs of energy, water and food, and waste outputs such air pollution and greenhouse gases.

According to Joss [35], there is no complete agreement about what a sustainable city should be or what its components should be. But, a sustainable city should meet the needs of the present without sacrificing the ability of future generations to meet their own needs. There is likely to be a great deal of variation in terms of how cities carry out their attempts to become sustainable. Ideally, a sustainable city creates an enduring way of life across the four domains of ecology, economics, politics and culture. A sustainable city should at least firstly be able to feed itself with a sustainable reliance on the surrounding countryside. Secondly, it should be able to power itself with renewable sources of energy. The aim is to create the smallest possible ecological footprint, and to produce the lowest quantity of pollution possible, to use land efficiently; compost used materials, recycle or convert waste to energy, and so the city's overall contribution to climate change will be minimal.

But as Taylor *et al*. [36] point out, the increase in the number of large cities that we see through the Industrial Revolution coincides with very rapid increases in greenhouse gases. They make clear that the key environmental trigger is immensely heightened urban demand. Traditional bourgeois thrift

has been transformed into bourgeois conspicuous consumption, making modern cities ultra-demanding. It is this toxic urban process which we have inherited today. A technocratic approach to 'smart cities' may well imply that city development has a technological focus as opposed to a people focus - and this is still the case today, even within the eco-city movement [37]. Other authors, such as Shao and Min [38], consider the 'smart sustainable cities' concept to be 'human-centered, involving the multidimensional integration of people and digitization'.

Amongst environmentalists, the role of respective technologies – including sources of energy – has been discussed, e.g. by O'Brien [39] and O'Keefe *et al.* [40], and will continue to be discussed [41] - including with controversial advocacy by Lovelock [42] and Brand [43] (e.g., on the role of civilian nuclear energy [44], forms of hydrogen generation, carbon capture, and genetically modified intensive agriculture for global food provision). There has been a change of tone and emphasis from the popular thinkers more aligned to an anti-urban outlook – because of 'ecological carrying capacity concerns' – e.g., views of Giradet [45].

One other direction, connected to the Garden City movement, is the ''co-cities' urban governance framework, or locally adaptable design principles, proposition by Foster and Iaione [46], which – like the UK Transition Town movement [47-48] - argues that 'cities also often harbour the solutions to the inequalities they create'. '... [The] majority of the world's inhabitants live in cities, but even with the vast wealth and resources these cities generate, their most vulnerable populations live without adequate or affordable housing, safe water, healthy food, and other essentials.' 'Practices, laws, and policies (for the production, delivery and management of urban assets or local resources) that are … fostering innovation in the provision of urban services, spurring collaborative economies as a driver of local sustainable development, and promoting inclusive and equitable regeneration of blighted urban areas.'

This paper will argue that the eco-city should be about human well-being. It will also reflect on the impacts of continued consumerism.

Can we develop cities that provide human well-being? First of all, we need to understand what we mean by well-being. According to Dodge *et al.* [49], well-being is difficult to define. The authors evaluate the debates on well-being from Aristotle onwards. They propose a new definition of well-being as the balance point between an individual's resource pool and the challenges faced as shown in Figure 2.

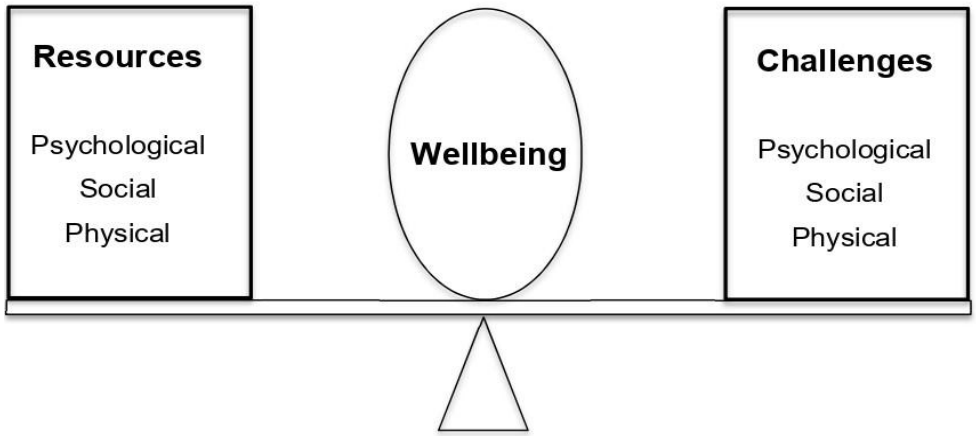

Figure 2. Balance Point (Source: [49])

In order to address well-being we need to address human needs. Two scholars, Maslow [50] and Max-Neef [51], offer solutions. Both argue that in order to address human well-being we must look at both our physiological and psychological needs. McLeod [52] discusses Maslow's approach by looking at his hierarchy of needs that is usually illustrated as a pyramid, as shown in Figure 3.

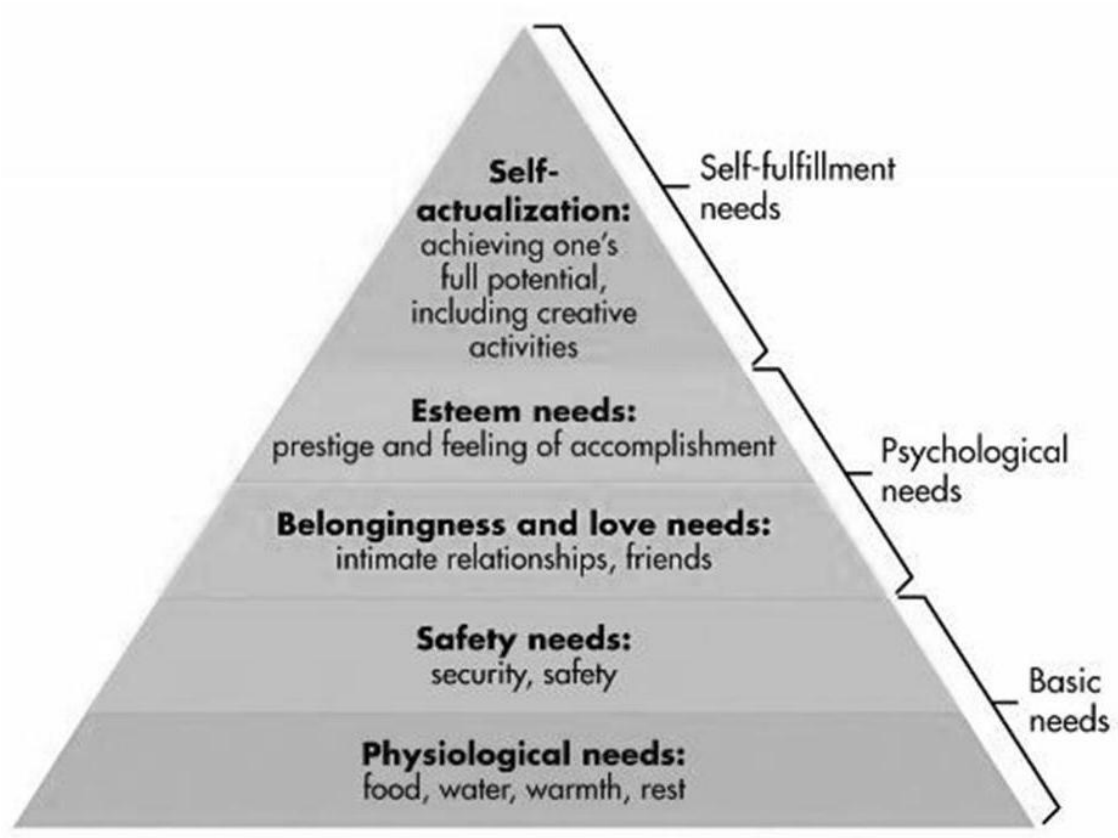

Figure 3. Maslow's Hierarchy of Needs (Source: [52])

McLeod [52] argues that negative events in meeting physiological needs such as losing a job or a divorce can impact the journey to meeting people's psychological needs.

Human needs are seen by Max-Neef *et al.* [53] as being ontological (stemming from the condition of being human), are few, finite and classifiable (as distinct from the conventional notion of conventional economic "wants" that are infinite and insatiable). They are also constant through all human cultures and across historical time periods. What changes over time and between cultures are the strategies by which these needs (and created desires) are satisfied. Human needs can be understood as a system - i.e., they are interrelated and interactive. In this system, there is no hierarchy of needs (apart from the basic need for subsistence or survival) as postulated by Western psychologists such as Maslow. Rather, simultaneity, complementarity and trade-offs are features of the process of needs satisfaction.

Doyal and Gough's [54] theory of human need is also worth noting here. This is to do with social participation as a process and outcome, and grounded in two fundamental or basic needs: the autonomy of an individual and physical health. Further to this, their theory speaks of a number of intermediate needs, namely food, clean water, economic security, protective housing, non-hazardous work environment, healthcare, physical security, pre-natal security and childhood security. These in turn are said to be linked to 'universal satisfier characteristics' applying across cultural contexts. These universal satisfier characteristics, e.g. goods, activities, services, and relationships, are argued to enhance the prospect of meeting intermediate needs. They differ from so-called 'need satisfiers' specific to time, place, and culture.

In essence then, the eco-city has to meet two needs. The first is physiological needs:-

A sustainable city must have clean water and air and access to secure high quality food supplies. Good quality and affordable accommodation is also required. It is important that citizens feel that their physical needs are met where there are physical places for leisure and interaction. This will contribute to a sense of security. There is a need also for connectivity through transport and multi-media communications systems along with a variety of sustainable livelihood options.

In short, a sustainable city has to meet our physical needs.

The second is psychological needs:-

Meeting human needs starts at birth where the relationship with parents is so important. Throughout life relationships will be important and the sustainable city will need to devise ways of ensuring we have a range of relationships that build a sense of belonging and togetherness. Underpinning this will

be education and life-long learning as well as leisure time that will help people to express themselves in different ways.

The challenge for the eco-city movement is to retrofit or redevelop cities that promote human well-being. But as Monbiot [55] suggests, since the collapse of the Soviet Union the predominant economic system is neoliberal market economics that has led to conspicuous consumption. The current dominant economic paradigm requires that we produce more and more products (e.g., mobile phones) and that we purchase new upgraded models in a relatively short time so that producers can keep making phones. The reality is that we do not consume – we use, and then discard.

The Forthcoming Reality

Many governments appear to be committed to a low-carbon (emissions) future, in part by existing domestic legislation or international agreements. Many governments are apparently committed to addressing climate change and other environmental problems, including reducing poverty. But, there is no real fundamental change. The rhetoric is focused on growth – neoliberalism is the driving force. Neoliberalism sees competition as the defining characteristic of human relations. It redefines citizens as consumers, whose democratic choices are best exercised by buying and selling, a process that rewards merit and punishes inefficiency. It maintains that "the market" delivers benefits that could never be achieved by planning [56].

There appears to be a contradiction about what many say at the national level (e.g., in the UK) about sustainability and prevailing economic policy. So, what are the implications? Will a low-carbon approach really boost sustainability? The following thematic case studies try to address this.

Energy

Energy is clearly important to society. There is extensive literature about the adverse impacts of fossil fuel usage to produce energy. There is considerable interest in shifting to more renewable sources such as photovoltaics, wind, nuclear and hydropower. One of the problems is the amount of subsidy that is being given to the fossil industry as compared to the renewable sector. Kavanagh [57], reporting on data from the International Energy Agency (IEA), states that the global subsidy bill for fossil fuels stood at about $490bn in 2014. Subsidies to aid the deployment of renewable energy technologies were $112bn in 2014, with another $23bn spent on supporting biofuels. So, while many developed countries are increasing financial backing for the expansion of green energy supplies, total

subsidy support for "dirty" fuels across the world still exceeded that for renewables by a considerable margin in 2015/6. Coady *et al.* [58] calculated that subsidies for fossil fuels were US$ 4.9 trillion worldwide in 2013, and US$5.3 trillion in 2015 (6.5% of global GDP in both years). They claim this is because of the undercharging, e.g., of the costs of climate change. They calculated that eliminating subsidies would have reduced global carbon emissions in 2013 by 21% and fossil fuel air pollution deaths by 55%, while raising revenue by 4 percent and social welfare by 2.2 percent of global GDP.

The figures have been changing, but with fluctuations owing to economic and political election cycles very notably in the USA (but not just there) – and also pressures of state/government public budgets and some hedging from the private sector too (including major global energy companies). According to Gunay *et al.* [59], a 2022 International Energy Agency report stated that up to 2030, more than US$ 50 billion of public funds could be levied for pilot-projects of large-scale low-carbon energy technologies in order to drive the green transition, but noted that it is not very clear how the public energy R&D spending would evolve following the pressure on government budgets after the Covid-19 pandemic. The report also argued that the private/corporate sector has a leading role in supporting public policies concerning both clean energy and energy efficiency.

The International Energy Agency's Global Energy Review 2025 [60], including the years 2022, 2023 and 2024 with world-aggregated data for total energy supply, electricity generation, technology deployment and CO2 emissions, provides a rounded depiction of recent trends in the energy sector with data on fuels, technologies, world regions and key countries, as well as associated CO_2 emissions. In 2024, world-wide energy demand rose faster than before, across all energy sources such as oil, natural gas, coal, renewables and nuclear power. This was principally down to the power (electricity) sector, because of higher demand for cooling, rising consumption by industry, electrification of transport as well as the growth of data centres and artificial intelligence. Almost all of this extra demand was satisfied by low-carbon energy production, led by solar photovoltaic production as well as other renewables and nuclear power. But gas demand rose also substantially, in contrast to oil and coal. Overall for 2024, this meant an increase in energy-associated CO_2 emissions – of which about half was caused by higher temperatures - but still less so than in 2023. The good news according to the IEA [60] is that 'the continued rapid adoption of clean energy technologies is limiting emissions growth, according to new analysis – avoiding 2.6 billion tonnes of additional CO_2 emissions per year.'

According to Cubitt [61], the amount of energy being used by the information and communication technologies, which were seen as one of the drivers of a low-carbon economy [62], is rising rapidly. There seems to be a contradiction between the need for low-carbon technology and the developments

needed to achieve it, e.g., data centres. As a sector, these talk about 'sustainable or responsible procurement', including from civilian nuclear power plants, which the European Commission in 2022 classified as 'sustainable and 'clean' and thus as 'eligible green investment' in its Sustainable Finance Taxonomy for investment purposes alongside gas if certain conditions such as being fitted with carbon capture, use and storage technology are met [63]. Yet data centres are likely to be the fastest growing contributors to greenhouse emissions as their demand for electricity will increase leading to further greenhouse gas emissions, as pointed out in a recent study published by the lobby-group Beyond Fossil Fuels [64].

Organizations such as Google tend to site facilities close to hydroelectric dams (which does not address concerns of water needed for cooling of major data centres) and more recently wind farms and Apple builds biomass generators at their new sites. And most global 'big data' and internet search companies have invested greatly in nuclear energy expansion in recent years. Worthy though this is, Carr [65] argues that the main driver is energy costs – and also electricity availability arguably - as opposed to sustainability in its own right. Private sector white papers are now emerging for 'driving data centres from environmental liability to sustainable powerhouse', e.g. by Partington and Mark at IQ-EQ [66], which emphasizes advanced energy procurement strategies, closed-loop cooling systems, waste heat recovery, sustainable construction methods, etc. There is also a focus on management, and the need for monitoring with comprehensive reporting.

Zie [67] argues that 'the time has come to start focusing on reducing the energy consumption of digital and the technological infrastructures, which underpin nearly all of our daily activities.' Zie thinks it can be done, if matters are taken seriously and there is necessary investment. Ertugrul [68] makes the case for the low-carbon transformation of the power grid through the scaled-up integration of renewable energy, storage, and grid modernization.

This moral and practical engagement, collective action and ('just' / 'fair') transformation action programme across sectors can also be stimulated at regional level, including in the historic heartlands of the Industrial Revolution [69].

Semiconductors

Semiconductors are the basis of the electronics industry. Semiconductors are used to manufacture the electronic components that are used in all sorts of devices such as personal computers and mobile phones. Although the industry produces waste, many of its products become waste. There has been a history of outsourcing and offshoring in the industry, often in very harsh conditions for the workforce.

Despite efforts in the last 5 to 10 years to clean up atmospheric emissions, waste dumping and water pollution there are historic emissions of perfluorinated chemicals that will persist in the atmosphere for many thousands of years and have twenty thousand times more impact than carbon on the greenhouse effect [70].

The latest and fourth (2024) UN's fourth Global E-waste Monitor (a report by the International Telecommunication Union and the United Nations Institute for Training and Research [71]) revealed that the world's e-waste is in fact rising five-fold in comparison to documented recycling thereof. In 2022, less than a quarter of e-waste was reported to be properly collected and recycled – with 'US$ 62 billion worth of recoverable natural resources unaccounted for and increasing pollution risks to communities worldwide'. Recycling of rare earth elements is stated to satisfy only 1% of the demand for them. The trend is alarming: 'A record 62 million tonnes (Mt) of e-waste was produced in 2022, up 82% from 2010, and on track to rise another 32%, to 82 million tonnes, in 2030. Worldwide, the annual generation of e-waste is rising by 2.6 million tonnes annually, on track to reach 82 million tonnes by 2030, a further 33% increase from the 2022 figure.'

Cubitt [61] argues that many wastes of these semiconductor-producing plants are composed of carcinogenic materials and others of unknown effects will persist in the vicinity of these plants for many years. There is clear evidence that employees in these plants are contaminated. It is very likely that female employees that have families will contaminate their children. Some 2,200 gallons of water is needed to make the average integrated circuit. Some 1500 gallons of that has to be Ultrapure Water (UPW). It takes 1,400 gallons of water to make 1000 gallons of UPW, and the US regards the removed minerals as toxic waste. Much of the digital waste is disposed of illegally and much of it has yet to enter the waste cycle. We have no idea what are the long impacts of many of these technologies.

On the other hand, there is little doubt that electronics have had a significant effect on industrial development. The introduction of new electronic products has had a significant impact on society. Many workers can now work from home, relying on advanced means of communication to speak with and see people without the energy costs and financial costs of long-distance travel. There have been improvements to manufacturing processes, and this is welcome. But, the massive growth of demand for electronic products is likely to outstrip any gains made in improved environmental performance of individual processes.

Electric Vehicles (EVs)

EVs are increasingly popular, and commentators such as Seba have stated that the internal combustion engine (ICE) is likely to be obsolete by 2025 [72]. This has not happened yet, although in many

countries pure ICE-powered road light-duty vehicles (cars and vans at least) are scheduled for prohibition in terms of new registrations from either 2035 or 2040 or at least 2050. Various (often financial) levels of incentives for (especially pure) EVs are in place and are now being modified and extended in many jurisdictions. And the state-of-the-art in electric vehicles [73] is changing continuously also – with the next level of developments likely to concern common standards for charging, Vehicle-to-X (including Vehicle-to-Grid bidirectional charging) expansion across more models and perhaps new EV battery technologies. But the major question is what can electrical vehicles and electric batteries do for us in a more holistic sense?, e.g., EVs for energy services, including with temporary stationary storage for energy services and also vehicle-to-building bidirectional charging [74]. This needs multi-stakeholder business and societal models, with acceptance and supporting regulation from both the public but crucially also from the private sector (investment, insurance etc.) [75].

Hawkins *et al.* [76], assessing the environmental life cycles of both electric and conventional vehicles over a decade ago, found out that EVs powered by the present European electricity mix offer a 10 percent to 24 percent decrease in global warming potential (GWP) relative to conventional diesel or petrol vehicles assuming lifetimes of 150,000 km. But, they noted that EVs exhibit the potential for significant increases in human toxicity, freshwater eco-toxicity, freshwater eutrophication, and metal depletion impacts, largely emanating from the vehicle supply chain if the demand for EVS increases rapidly. Hawkins *et al.* [76] pointed out that in regions where fossil fuels are the main sources of power, electric cars/vehicles offer no benefits and may even cause more harm.

Magill [77] reported on a study undertaken, again over a decade ago, by the University of Minnesota that the environmental and human health costs of operating an electric vehicle using electricity generated from coal may be as much as 80 percent greater than driving a gasoline-powered vehicle. But, the study showed that the environmental health cost of driving an electric vehicle using electricity from solar or wind generators could be as much as 50 percent less than the environmental and health toll of using gasoline. It is clear that EVs offer real environmental benefits, but it should be noted that any innovations in transport may also have some adverse impacts.

The Union of Concerned Scientists has made this point for some time - but crucially noting also that grid transformations regionally produce clear both net use and life-cycle environmental benefits for EVs in regions turning away from coal and gas, and by adding solar and wind power, as an energy source [78].

Batteries

EVs rely on batteries for energy storage. Lithium is currently used in the manufacture of batteries used in EVs. According to Wanger [79] about 75 percent of the global reserves of lithium are found in the salt lakes of Uyuni in Bolivia, Atacama in Chile and Hombre Muerto in Argentina: the "lithium triangle." This desert expanse in the high Andes provides the raw material that moves the world of information technology and communications. The salt lakes do not have much flora or fauna, but they do provide a home for flamingos. Wanger points out that the flamingos feed on cyanobacteria - food for the birds but lethal to human beings, animals and plants [80]. The impact of mining lithium is devastating, particularly on water supplies. Although lakes exist despite low rainfall there is concern that more mining will disrupt water supplies for people and agriculture. In addition, crops can be affected by runoff saline solution from which the lithium salts are gathered. Traditionally, gathering salt has been part of local livelihoods. This becomes impossible as the salt ponds are contaminated by lithium mining [80-81].

Investing in alternative battery technologies is essential to achieving sustainability. Improving lithium recycling is crucial for advancing sustainable practices. Developing more environment-friendly mining methods is necessary to achieve sustainability goals. We must balance the benefits of lithium-based technologies with their environmental costs [82].

There is also concern that regulation designed to minimize the adverse environmental impacts of lithium mining will not be effectively enforced. None of the governments of the lithium triangle have a good history of environmental regulation and there is evidence that poorly paid officials often take bribes [81,83]. There are fears that in the long run lithium mining will make the area unfit for its indigenous inhabitants. The demand for lithium is increasingly driven by the push for EVs. These should solve the urban air quality issue (especially if fully battery electric), but their batteries are causing environmental degradation in both their production and disposal. This will continue with more 'rare earth' metal extraction – although this can be made more sustainable [84] - and also more second-life use and recycling of end-of-life batteries should certainly occur [85-86].

There are 2 types of batteries used for electric and hybrid vehicles. Hybrid vehicles initially used nickel-metal hydride batteries. EVs use lithium-ion batteries. EV batteries often contain other useful metals such as high-grade copper and aluminium - in addition to depending on the active material, metals such as cobalt and nickel as well as 'rare' earths. To prevent a future shortage of cobalt, nickel, and lithium and to enable a sustainable life cycle of these technologies, recycling of lithium batteries must be improved [87,88].

In line with the objectives of the European Green Deal, the European Union (EU) has adopted increasingly strict measures to ensure that the entire life cycle of batteries – from production to recycling – is sustainable, efficient and compliant with the most advanced environmental standards. To ensure a uniform and binding application of the new rules, the previous EU Directive 2006/66/EC was replaced with European Regulation 2023/1542 [89-91]. Recycling electric car batteries includes separating out the valuable materials, e.g. cobalt, lithium salts, stainless steel, copper, aluminium and plastic. All these can be recycled. Cobalt, as a 'conflict-associated' metal in the Democratic Republic of Congo, is also an ethical supply chain issue – though regulatory intervention is far from straight-forward globally and also in-country [92-95].

When EVs started to become more popular, the price of elements such as lithium was still low and supplies were plentiful. Re-use as storage capacity as a solution for dealing with batteries from EVs is of course one option [96]. But stationary batteries may also be newly-produced.

According to Kühnbach *et al.*'s Fraunhofer ISE & Fraunhofer ISI study [97], the wider introduction of vehicle-to-grid (bidirectional) charging in both AC and DC connection modes, where EV batteries are accessed for power to offset peaks on the power grid, may bring very substantial benefits e.g. for Europe's more integrated energy system in the decades to come. The AC-mode is less hard-ware intensive and suitable for residential and slow charging, but the DC-mode is more expensive with more hardware requirements and used mainly for fast charging, although it is currently leading in both hardware and communication ISO protocols. Most new EV models focus on vehicle-to-load, thus enabling vehicles to charge electric appliances and vehicle-to-home applications rather than vehicle-to-grid (V2G). Furthermore, the availability of supporting infrastructure such as bidirectional wallboxes for EV charging is still limited. However, Kühnbach *et al.* [97] conclude, 'despite technical, regulatory and acceptance barriers, vehicle-to-X offers socio-technical-economic benefits such as CO_2 emission reductions, integration of renewable energy and grid relief. Compared to smart charging alone, bidirectional charging offers additional advantages, such as decreasing the need for backup capacity from gas and hydrogen power plants and lowering the use of power generation from these sources. The opportunity to integrate PV capacity more effectively is seen as the biggest value of the charging flexibility provided by electric cars, especially when they are connected during the day.'

In the longer term a technological development may offer an even better solution. Nickel metal hydride batteries are not currently used in EVs. But, research by BASF suggests that the capacity of these batteries could be considerably higher than that of lithium-ion batteries. Nickel metal hydride batteries are considerably lighter than lithium-ion batteries which means that there will be a price

advantage [98]. Sodium-ion batteries, currently with lower energy density than lithium-ion, are the other promising alternative [99].

Concluding Thoughts

Cities have played a significant role in human development, with a significant impact on the environment. Early cities demanded the invention of agriculture in order to feed growing populations. The next major transformation was the Industrial Revolution. Cities demanded labour to operate the increasingly complex industrial processes. Simultaneously cities demanded that we become consumers. Today, we have become conspicuous consumers. Neoliberalism, the predominant economic system, demands that we consume more and more products. In reality, we do not consume products but discard them in order to get the latest version. This has distanced us from the sustaining environment: our one home.

The Industrial Revolution has enclosed the commons of everyday skills. Databases and most databanks have enclosed knowledge. In short, we have become divorced from the commons that we all shared. The social change driven by the Industrial Revolution, and the rise of capitalism, has moved into an era of passive consumption. The problem is that we live on a finite planet, and that there are insufficient resources to meet the growing needs of our global population, if we retain the same neoliberal approach. Capitalism is untroubled by seeing poverty in other parts of the world. We have become separate from the environment we need – we should always remember that the environment does not need us. The problem lies in the neoliberal economic system. It assumes that trading is 'perfectly informed' and 'rational', and that there is an infinite amount of resources and carbon / emissions / pollution sinks. Economics assumes markets can find solutions. But this is not always the case. Now and in the future, adapting to the consequences of accelerated climate change and increasing variability with more extreme weather events/periods will be a considerable, and for poorer countries and regions a huge, challenge. Human societal climate adaptation urgently requires rebuilding the resilience of communities in order to ensure that they can cope with climatic disturbances. We can no longer separate risk and development. We need holistic and continuing approaches to adapting to climate change [100].

The majority of the global human population now live in cities, and will do so in the future. The solutions to the problems we face will have to be found in cities. History suggests that cities innovate. The neoliberal market-based system is at the root of the problem. Political leaders must make a huge effort to innovate in their adaptations to our reality. Perhaps a moral revolution is in order! We have

had an Industrial Revolution. Perhaps it is time for an Economic Revolution (for human-wellbeing, social and environmental reasons) as we may well be at the turn where we need protection from the environment, rather than the environment from us. The demands we are making on nature by living in cities have reached a crisis point and unless we make significant changes the prognosis is terminal consumption. We need a radically new integrated global understanding of nature and cities. The challenge of urban stewardship to tackle the climate emergency crisis needs to be at the very centre of our thinking [101]. Climate Change is now key for Disaster Management [102]. Poverty and community disaster risk reduction, both urban and rural, can be said to be in a 'double bind' [103]. Community participation in disaster risk reduction is critical [104]. And we should develop strategies for building resilience for cultural heritage, too [105]. Locally, as much as nationally, we need to produce equitable energy systems [106].

References

[1] Glaeser E, 2011, Triumph of the City (London: Macmillan), p. 6.

[2] Taylor, P. J., O'Brien, G., & O'Keefe, P., 2016, Eleven Antitheses on Cities and States: Challenging the Mindscape of Chronology and Chorography in Anthropogenic Climate Change. *ACME: An International Journal for Critical Geographies* **15**(2), 393–417. https://doi.org/10.14288/acme.v15i2.1287

[3] Ruddiman, W.F., 2003, The Anthropogenic Greenhouse Era Began Thousands of Years Ago. *Climatic Change* **61**, 261–293. https://doi.org/10.1023/B:CLIM.0000004577.17928.fa

[4] Jacobs, J., 1969, The Economy of Cities (New York: Vintage), p. 35.

[5] Taylor P.J., 2013, Extraordinary Cities: Millennia of Moral Syndromes, World-Systems and City/State Relations (Cheltenham: Edward Elgar), p. 99.

[6] Glaeser E, 2011, Triumph of the City (London: Macmillan), p. 7.

[7] Van Hoof J., Kazak J.K., Perek-Białas J.M., Peek S.T.M., 2018, The Challenges of Urban Ageing: Making Cities Age-Friendly in Europe. *International Journal of Environmental Research and Public Health* **15**(11), 2473. https://doi.org/10.3390/ijerph15112473

[8] Nevle R.J., Bird D.K., Ruddiman W.F., Stinchcomb G.E., 2011, Ecological-hydrological effects of reduced biomass burning in the neotropics after A.D. 1500. *Geological Society of America Meeting* **43**, 399.

[9] Powell D., 2011, Columbus' arrival linked to carbon dioxide drop: Depopulation of Americas may have cooled climate. *Science News* **180**(10), 12. https://doi.org/10.1002/scin.5591801012

[10] Clement CR, Denevan WM, Heckenberger MJ, Junqueira AB, Neves EG, Teixeira WG, Woods WI., 2015, The domestication of Amazonia before European conquest. *Proceedings of the Royal Society B* **282**: 20150813. https://doi.org/10.1098/rspb.2015.0813

[11] Pearce, F., 2015, Myth of pristine Amazon rainforest busted as old cities reappear. *New Scientist, Proceedings of the Royal Society B.* https://www.newscientist.com/article/dn27945-myth-of-pristine-amazon-rainforest-busted-as-old-cities-reappear/

[12] Rafferty J.P., n.d.,The Rise of the Machines: Pros and Cons of the Industrial Revolution. Britannica. Online at: https://www.britannica.com/story/the-rise-of-the-machines-pros-and-cons-of-the-industrial-revolution

[13] Weber M., 1905/2001, The Protestant Ethic and the Spirit of Capitalism [transl. by Talcott Parsons] (London: Routledge Classics).

[14] Collins, R., 1980, Weber's Last Theory of Capitalism: A Systematization. *American Sociological Review 45*(6), 925–942. https://doi.org/10.2307/2094910

[15] Ormrod, D. (1984). RH Tawney and the Origins of Capitalism. *History Workshop*, *18*, 138–159. http://www.jstor.org/stable/4288593

[16] Novak M., 2010, How Christianity Created Capitalism. *Religion & Liberty* **10**(3). Online at: https://www.acton.org/pub/religion-liberty/volume-10-number-3/how-christianity-created-capitalism

[17] Collins R., 1986, Weberian Sociological Theory (Cambridge: Cambridge University Press), 356 p.

[18] Ritchie H., Samborska V. & Roser M. 2018/2025, Urbanization: The world population is moving to cities. Why is urbanization happening and what are the consequences? Our World In Data. https://ourworldindata.org/urbanization

[19] Rifkin J., 2011, The Third Industrial Revolution (London: Macmillan).

[20] Schwab K., 2016, The Fourth Industrial Revolution (Geneva: World Economic Forum).

[21] Arrhenius, S. 1896, On the Influence of Carbonic Acid in the Air upon the Temperature of the Earth. *Publications of the Astronomical Society of the Pacific* **41,** 237-276. https://doi.org/10.1080/14786449608620846

[22] Rachel, R., 1962, Silent Spring (Boston MA: Houghton Mifflin).

[23] Hynes P., 1989, Silent Spring: A feminist perspective. *Environmental Impact Assessment Review* **9**(1), 3-7. https://doi.org/10.1016/0195-9255(89)90015-2

[24] Wood B. and Dubos R, 1972 / 1983, *Only One Earth: The Care and Maintenance of a Small Planet. An unofficial report to the United Nations Conference of the Human Environment, Stockholm* (Paris / New York: UNESCO / W.W. Norton and Company).

[25] Satterthwaite D., 2006, Barbara Ward and the origins of sustainable development, International Institute for Environment and Development (UK). Online at: http://pubs.iied.org/pdfs/11500IIED.pdf

[26] World Commission on Environment and Development, 1987, Our Common Future (Oxford: Oxford University Press), p. 27.

[27] United Nations, 1992, Agenda 21 (Rio de Janeiro: The United Nations Conference on Environment and Development. UNCED). Online at: https://sustainabledevelopment.un.org/outcomedocuments/agenda21

[28] Hopwood W., Mellor M., O'Brien G., 2005, Sustainable Development: Mapping Different Approaches. *Sustainable Development* **13**(1), 38-52. https://doi.org/10.1002/sd.244

[29] O'Brien G. and O'Keefe P., 2014, Managing Adaptation to Climate Risk: Beyond Fragmented Responses (London: Routledge).

[30] Meyer W.B., 2013, The Environmental Advantages of Cities (Cambridge MA: The MIT Press).

[31] UNEP and UN Habitat, undated, Greener Cities Partnership. Online at: http://wuf7.unhabitat.org/Media/Default/PDF/Greener%20Cities_final%20(flyer).pdf

[32] Parham S., 2013, Shaping sustainable urbanism: are garden cities the answer? Conference paper for "Shaping Canberra: the lived experience of place, home and capital". Humanities Research Centre Conference Australian National University 17th September 2013. Online at: http://uh-sustainable.co.uk/docs/Shaping_sustainable_urbanism.pdf

[33] Worldwatch Institute, 2017, The State of Consumption Today. Online at: http://www.worldwatch.org/node/810

[34] Register, R., 1987, Ecocity Berkeley: Building Cities for a Healthy Future (*New York:* North Atlantic Books).

[35] Joss S., 2015, Sustainable Cities: Governing for Urban Innovation (London: Palgrave Macmillan).

[36] Taylor P.J., O'Brien G. & O'Keefe P., 2015, Commentary: Human control of climate: introducing cities. *Environment and Planning A* **47**(5), 1023-1028. https://doi.org/10.1177/0308518X15592297

[37] Brooke J., 2014, Climate Change and the Course of Global History (Cambridge: Cambridge University Press).

[38] Shao J. and Min B., 2025, Sustainable development strategies for Smart Cities: Review and development framework. *Cities*, **158**, 105663 https://doi.org/10.1016/j.cities.2024.105663

[39] O'Brien G., 2009, Vulnerability and Resilience in the European Energy System. *Energy & Environment* ***20***(3), 399-410. https://doi.org/10.1260/095830509788066457

[40] O'Keefe, P., Pearsall, N., and O'Brien, G., 2010. *The Future of Energy Use.* 2nd revised edition. (London: Routledge).

[41] Wheeler S.M. (Ed.), 2023, The Sustainable Urban Development Reader 4th ed. (London: Taylor & Francis). https://doi.org/10.4324/9781003288718

[42] Lovelock J., 2009, The Vanishing of Gaia: A Final Warning (New York: Basic Books).

[43] Brand S., 2010, Whole Earth Discipline (New York: Atlantic Books).

[44] O'Brien G., 2017, The fall and rise of nuclear power in Britain: a history. *International Journal of Environmental Studies* ***74***(2), 353–355. https://doi.org/10.1080/00207233.2016.1269586

[45] Giradet H., 1993, The Gaia Atlas of Cities: New Directions for Sustainable Urban (Taunton: Gaia Books).

[46] Foster S.R and Iaione C., 2022, Co-Cities: Innovative Transitions toward Just and Self-Sustaining Communities (Cambridge MA: MIT Press).

[47] Hopkins R., 2006, The Transition Handbook: From Oil Dependency to Local Resilience (Bristol: Green Books).

[48] Hopkins B., 2011, The Transition Companion: Making Your Community More Resilient in Uncertain Times (Taunton: Transition Books).

[49] Dodge R., Daly A., Huyton J., & Sanders L., 2012, The challenge of defining wellbeing. *International Journal of Wellbeing* **2**(3), 222-235. www.doi.org/10.5502/ijw.v2i3.4

[50] Maslow A.H., 1962/1968/1999, Toward a Psychology of Being (Radford MA: Wilder Publications).

[51] Max-Neef M.A., 1992, From the Outside Looking In: Experiences in Barefoot Economics (Oslo: Dag Hammarskjöld Foundation).

[52] McLeod S., 2016/2025, Maslow's Hierarchy of Needs. *Simply Psychology*. Online at: https://www.simplypsychology.org/maslow.html

[53] Max-Neef M.A., Elizalde A., Hopenhayn M., with the cooperation of Herrera F., Zemelman H., Jatobá J., Weinstein L., 1989, Human Scale Development: An Option for the Future. *Development Dialogue* **1**, 7-80. https://www.commentcic.org.uk/sites/default/files/library/Max-neef_Human_Scale_development.pdf

[54] Doyal L., Gough I., 1991, A Theory of Human Need (London: Red Globe Press).

[55] Monbiot G., 2016, How Did We Get into This Mess? (London: Verso).

[56] Monbiot G. and Hutchinson P., 2024, The Invisible Doctrine: The Secret History of Neoliberalism (& How It Came to Control Your Life) (London: Allen Lane).

[57] Kavanagh M., 2016, A world map of subsidies for renewable energy and fossil fuels. *Financial Times***,** July 26, 2016. Online at: https://www.ft.com/content/fb264f96-5088-11e6-8172-e39ecd3b86fc?mhq5j=e2

[58] Coady D., Parry I.' Sears L., Shang B., 2017, How Large Are Global Fossil Fuel Subsidies? *World Development*, **91**, pp. 11–27. https://doi.org/10.1016/j.worlddev.2016.10.004

[59] Gunay S., Kurtishi-Kastrati S., Sraieb M.M., Rexhepi G., 2025, Energy sources and global sustainability connectedness: Evidence from green and dirty energy. *Sustainable Futures*, **10**, 101012. https://doi.org/10.1016/j.sftr.2025.101012

[60] International Energy Agency, 2025, *Global Energy Review 2025*. IEA: Paris. Online at: https://www.iea.org/reports/global-energy-review-2025

[61] Cubitt S., 2017, Finite Media: environmental implications of digital technologies (Durham NC: Duke University Press).

[62] Boccaletti G., Loffler M., Oppenheim J.M., 2008, How IT can cut carbon emissions. *McKinsey Quarterly*, October. Online at: http://www.kyotoclub.org/docs/mckinsey_it_otto.pdf

[63] Han J., 2022, Nuclear and gas in the EU taxonomy: what this means for the energy mix of tomorrow. Allianz Global Investors. Online at: https://www.allianzgi.com/en/insights/outlook-and-commentary/nuclear-and-gas-in-the-eu-taxonomy

[64] Beyond Fossil Fuel, 2025, New data centres could undermine Europe's energy transition, eating into its emissions cuts, study finds. BFF: Berlin. Online at: https://beyondfossilfuels.org/2025/02/10/new-data-centres-could-undermine-europes-energy-transition-eating-into-its-emissions-cuts/#:~:text=%5B1%5D%20It%20reveals%20that%20data,other%20sectors%20onto%20fossil%20fuels.

[65] Carr N., 2009, The Big Switch: Rewiring the World, from Edison to Google (New York: W.W. Norton).

[66] Partington J. and Mark T., IQ-EQ, 2025, Driving data centres from environmental liability to sustainable powerhouse – a new whitepaper. Online at: https://iqeq.com/insights/driving-data-centres-from-environmental-liability-to-sustainable-powerhouse-a-new-whitepaper/

[67] Zie E., 2023, Decarbonise Digital: Facts. Methods. Action (Luxembourg: Physical Products / Kindle Direct Publishing).

[68] Ertugrul N., 2025, Reinventing the Power Grid. Renewable Energy, Storage, and Grid Modernization (Boca Raton FL: CRC Press).

[69] Stark P, OBE, 2019/2020, North East England and the Climate Crisis. From Cause to Effect (Newcastle upon Tyne: Vonne). Online at: https://www.vonne.org.uk/sites/default/files/210115FromCausetoEffectFinal.pdf

[70] Baldé C.P., Wang F., Kuehr R., Huisman J., 2015, The global e-waste monitor – 2014 (Bonn: United Nations University, IAS – SCYCLE). Online at: https://i.unu.edu/media/ias.unu.edu-en/news/7916/Global-E-waste-Monitor-2014-small.pdf

[71] Baldé C.P, Kuehr R, Yamamoto T, McDonald R, D'Angelo E., Althaf S., Bel G., Deubzer O., Fernandez-Cubillo E., Forti V., Gray V., Herat S., Honda S., Iattoni G., Khetriwal D.S., di Cortemiglia V.L., Lobuntsova Y., Nnorom I., Pralat N., Wagner M., 2024, Global E-waste Monitor 2024 (Geneva / Bonn: International Telecommunication Union (ITU) and United Nations Institute for Training and Research). Online at: https://ewastemonitor.info/the-global-e-waste-monitor-2024/

[72] Seba, T., 2014. Clean Disruption of Energy and Transportation: How Silicon Valley Will Make Oil, Nuclear, Natural Gas, Coal, Electric Utilities and Conventional Cars Obsolete by 2030. (California: Clean Planet Ventures). Available at: https://books.google.co.ma/books?id=xRdMBAAAQBAJ

[73] Putrus G., Kotter R., Wang Y., Das R., Bentley E., Dai X., O'Brien G., Heller R., Prateek R., Gough R., Herteleer B., 2020, State-of-the-Art Assessment of Smart Charging and Vehicle 2 Grid services (Viborg: EU Interreg North Sea Region Secretariat). Online at: https://researchportal.northumbria.ac.uk/admin/files/31453652/State_of_the_Art_Assessment_of_Smart_Charging_and_V2G_services.pdf

[74] van Bergen E., van der Hoogt J., 2020, Kotter R., Bentley E., Warmerdam J., Rimmer C., Herteleer B., 2020, Vehicle 4 Energy Services (V4ES) Evaluation for Upscaling and Transnational Potential (Viborg: EU Interreg North Sea Region Secretariat). Online at: https://researchportal.northumbria.ac.uk/admin/files/33039838/Final_Report_V4ES_Evaluation_for_Upscaling_and_Transnational_potential.pdf

[75] Kotter R., Herteleer B., Asanova S., van den Hoed R., Dong Y., Putrus G., O'Brien G., Jablonska B., 2020, SEEV4-City Policy Recommendations and Roadmap: Recommendations towards integration of transport, urban planning and energy (Viborg: EU Interreg North Sea Region Secretariat). Online at: https://researchportal.northumbria.ac.uk/admin/files/31971098/SEEV4_City_Policy_Recommendations_and_Roadmap_1.pdf

[76] Hawkins T.R., Gausen O.M. & Strømman A.H., 2012, Environmental impacts of hybrid and electric vehicles - a review. *International Journal of Life Cycle Assessment* **17**: 997-1014. https://doi.org/10.1007/s11367-012-0440-9

[77] Magill, B., 2014, Electric Cars a Mixed Bag for Health, Climate, Climate Central. Online at: http://www.climatecentral.org/news/electric-cars-mixed-bag-for-climate-18447

[78] Reichmuth D., 2025, Electric Vehicles Help Combat Climate Change, Here's Why. (Cambridge MA: Union of Concerned Scientists**)**. Online at: https://blog.ucs.org/dave-reichmuth/electric-vehicles-help-combat-climate-change-heres-why/

[79] Wanger T.C., 2011, The Lithium Future – Resources, Recycling and the Environment. *Conservation Letters* **4**(3), 1-5. https://doi.org/10.1111/j.1755-263X.2011.00166.x

[80] Tahill W., 2007, The Trouble with Lithium: Implications of Future PHEV Production for Lithium Demand (Martainville: Meridian International Research). Online at: www.evworld.com/libraray/lithium_shortage.pdf

[81] Hollender R. and Schultz J., 2010, Bolivia and Its Lithium: Can the "Gold of the 21st Century" Help Lift a Nation out of Poverty? (Cochabamda: Democracy Center).

[82] Ukpanah I., 2024, Is Lithium Mining Bad for the Environment (Greenwatch). Online at: https://www.greenmatch.co.uk/blog/is-lithium-mining-bad-for-the-environment

[83] Ribera M.O., Requena C., 2011. Bolivia's lithium: Opportunities and challenges. In: Transparency International (Ed.), Global Corruption Report: Climate Change. (London: Earthscan), 400p., 207–210. https://doi.org/10.4324/9781315870274

[84] Filho W.L.; Kotter R.; Özuyar P.G.; Abubakar I.R.; Eustachio J.H.P.P.; Matandirotya N.R., 2023, Understanding Rare Earth Elements as Critical Raw Materials. *Sustainability* **15**, 1919. https://doi.org/10.3390/su15031919

[85] Mancha A., 2016, A look at some international lithium-ion battery recycling initiatives. *Journal of Undergraduate Research* **9**, 1-5. https://scholar.archive.org/work/t3f4dkewcjg2rboe7eitazi4zy/access/wayback/http://journals.uic.edu/ojs/index.php/JUR/article/download/7546/6038

[86] Zhu J., Mathews I., Ren D., Li W., Cogswell D., Xing B., Sedlatschek T., Nithin S., Kantareddy R, Yi M, Gao T, Xia Y., Zhou Q., Wierzbicki, Bazant, M.Z., 2021, End-of-life or second-life options for retired electric vehicle batteries. *Cell Reports Physical Science* **2**(8), 100537. https://doi.org/10.1016/j.xcrp.2021.100537

[87] Kumar A., 2011, The Lithium Battery Recycling Challenge. *Waste Management World*. Online at: https://waste-managment-world.com/a/1-the-lithium-battery-recycling-challenge

[88] Taylor P., 2009, When an electric car dies, what will happen to the battery? *Scientific American*. Online at: https://www.scientificamerican.com/article/lithium-ion-batteries-hybrid-electric-vehicle-recycling/

[89] DriveElectric, 2022, What happens when electric car batteries die? Online at: https://www.drive-electric.co.uk/guides/general/what-happens-when-electric-car-batteries-die/

[90] EBRA, no date (Brussels: European Battery Recycling Association). Online at: http://www.ebra-recycling.org/

[91] Flash Battery, 2025, From production to recycling: a comprehensive guide to the new European Battery Regulation 2023/1542. Online at: https://www.flashbattery.tech/en/blog/eu-battery-regulation-obligations-updates/

[92] Prause L., 2020, Conflicts related to resources: The case of cobalt mining in the Democratic Republic of Congo. In: Bleicher A. and Pehlken A. (eds), The Material Basis of Energy Transitions (Amsterdam: Elsevier), pp. 153-167. https://doi.org/10.1016/B978-0-12-819534-5.00010-6

[93] Hönke J. and Skender L, 2022, Cobalt as 'conflict mineral'? On the opportunities and limits of new supply chain laws. INFRAGLOB 20/12/2022. Online at: https://infraglob.eu/2022/12/20/cobalt-as-conflict-mineral-on-the-opportunities-and-limits-of-new-supply-chain-laws/

[94] Calvão F., Mcdonald C.E.A., Bolay B., 2021, Cobalt mining and the corporate outsourcing of responsibility in the Democratic Republic of Congo. *The Extractive Industries and Society* **8**(4), 100884. https://doi.org/10.1016/j.exis.2021.02.004

[95] Umpula E, Dummett M., 2024, The Blood Cobalt Narrative: Addressing Human Rights Concerns or Scaremongering? *Business and Human Rights Journal* **9**(2), 308-314. https://doi.org/10.1017/bhj.2024.4

[96] Chauhan R., Santran R., Obrecht M., Rhythm Singh R., 2024, Energy storage potential of used electric vehicle batteries for supporting renewable energy generation in India. *Energy for Sustainable Development* **81**, 101513. https://doi.org/10.1016/j.esd.2024.101513

[97] Kühnbach M., Klobasa M.; Stephan A, Lux B., Frank F., Surmann A., Kähler J., Biener W., Kamaci Z., John R., 2024, Potential of a full EV-power-system-integration in Europe and how to realise it. Study on behalf of Transport & Environment (T&E) Europe (Freiburg / Karlsruhe: Fraunhofer Institute for Solar Energy Systems, ISE / Fraunhofer Institute for Systems and Innovation Research, ISI), p. 6. Online at:

https://www.transportenvironment.org/uploads/files/2024_10_Study_V2G_EU-Potential_Final.pdf

[98] Bullis K., 2015, Old Battery Type gets an Energy Boost. *MIT Technology Review*. Online at: https://www.technologyreview.com/s/535251/old-battery-type-gets-an-energy-boost/

[99] Koloch, J. Schneider J., Seidenfus M., Lienkamp M., 2025, Beyond lithium: A comprehensive use-case-analysis of sodium-ion-battery technology in battery electric vehicles. *e-Prime – Advances in Electrical Engineering. Electronics and Energy* **12**, 100995. https://doi.org/10.1016/j.prime.2025.100995

[100] O'Brien, G., Devissher T., O'Keefe P., 2011, The Adaptation Continuum: Groundwork for the Future (Saarbrücken: Lambert Academic).

[101] Taylor P.J., O'Brien G., O'Keefe P., 2020, Cities Demanding the Earth: A New Understanding of the Climate Emergency (Bristol: Bristol University Press).

[102] O'Brien G., O'Keefe P. Rose J., Wisner B., 2006, Climate Change and Disaster Management. *Disasters* **30**(1), 64-80. https://doi.org/10.1111/j.1467-9523.2006.00307.x

[103] Ferdinand I., O'Brien G., O'Keefe P., Jayawickrama J., 2012, The double bind of poverty and community disaster risk reduction: A case study from the Caribbean. *International Journal of Disaster Risk Reduction* **2**, 84-94. https://doi.org/10.1016/j.ijdrr.2012.09.003

[104] Ruhizal Roosli Nordin J and O'Brien G., 2018, The Evaluation of Community Participation in Post-Disaster Housing Reconstruction Projects in Malaysia. *Procedia Engineering* **212**, 667–674. https://doi.org/10.1016/j.proeng.2018.01.086

[105] O'Brien G. O'Keefe P. Jayawickrama J. Jigyasu R., 2015, Developing a Model for Building Resilience to Climate Risks for Cultural Heritage. *Journal of Cultural Heritage Management and Sustainable Development* **5**(2), 99-114. https://doi.org/10.1108/JCHMSD-06-2013-0021

[106] O'Brien G. and Hope A., 2010, Localism and energy: Negotiating approaches to embedding resilience in energy systems. *Energy Policy* **38**(12), 7550- 7558. https://doi.org/10.1016/j.enpol.2010.03.033

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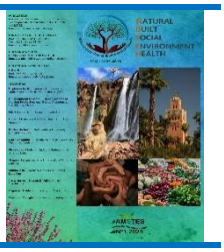

Grassfires Threaten to Devastate Forests in the Kurdistan Region of Iraq

Salam Abdulqadir Abdulrahman

College of Law and Politics, University of Human Development (https://ror.org/02jz38b76), Sulaymaniyah 46001, Iraq

Corresponding author: Salam Abdulqadir Abdulrahman, ***ORCID****: 0000-0002-3102-7244*;

☑ **Email address:** *salam.abdulrahman@uhd.edu.iq*; *salam.abdulrahman@gmail.com*, **Phone:** +964-750-307-3111

Graphical Abstract

This paper highlights the escalating problem of grassfires in the Kurdistan Region of Iraq. The graphical abstract depicts the rapid destruction of reforestation efforts, the struggle of firefighters with inadequate tools, and the preventive role of firebreaks. It calls attention to the urgent need for stronger measures to protect forests and biodiversity.

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Abstract: Grassfires constitute a formidable environmental threat in the Kurdistan Region of Iraq (KRI). Wild seasonal grasses dry out soon after the region enters its long dry period, usually from the middle of spring. Hundreds of grassfires occur every year in the KRI and cause significant damage to the environment, especially the burning of forests. The forest trees largely exist in isolation from each other; hence, they do not burn in large numbers except when ignited through the grassfires. This paper examines the problem of grassfires in the KRI. It explains that, besides climatic factors, anthropogenic factors are the leading causes of grassfires in the KRI. The paper also highlights the human cost of grassfires and urges the government to take urgent and appropriate action.

Keywords: *Grassfires, Damage, Native trees, Planted trees, KRI.*

Introduction

Native self-sown trees, as well as those in plantations, are part of the visible features of the Kurdistan Region of Iraq's landscape. The trees are the region's pride, for they create beautiful scenery**,** provide habitat for birds and plants, hold the soil, offer shade for picnickers and mountain hikers, serve as shelter for a variety of local species, shed leaves for animal consumption, store carbon dioxide, and reduce the ambient dust. Additionally, the trees are an important source of income for rural communities. This precious resource is increasingly being destroyed by grassfires.

During late autumn and throughout winter until early spring, wild seasonal grass, both short and tall, grows and covers nearly everywhere, including the mountains, hills, plains, and valleys. The grass dries out soon after the region enters its long dry period, usually beginning in May and lasting until early November. This period is accompanied by a sharp rise in temperature, especially in July and August. The grass becomes fine fuel for fires; hence, many places are at risk of burning.

Grassfires are a common occurrence in the KRI during the hot and dry months. They cause a significant amount of damage to wildlife, agriculture, and the region's biodiversity in general, in addition to the terrifying scenes they create for viewers. The causes of the fires remain unresolved, and firefighting teams equipped with modern tools and technology are non-existent. The KRI's environment is suffering enormous and lasting damage. The damage grassfires cause to the forests is the most devastating and irreversible.

It takes years, and even decades, for a tree to grow, especially in arid and semi-arid regions like the KRI. The Goizha mountain ranges, for example, which surround the eastern part of Sulaymaniyah City, are an example of losing human-planted trees to fire. The mountains have, or rather had, many pine trees that were planted over 60 to 70 years ago as part of a green project by the Iraqi government. The trees create beautiful scenery and have many environmental benefits. Little precaution has been taken to protect them from fire.

The threat to human life from grassfires should not be underestimated either. Volunteers from rural areas sometimes try desperately to battle the fires. Owing to a lack of protective clothing, and having ineffective tools, and training, many of these firefighters suffer injuries; they may choke, burn, or die as a result. Other people, such as foragers and animal herders, as well as animals, wild animals, and birds, may also be hurt and die from grassfires.

This paper attempts to highlight the problem of grassfires in the KRI, which have so far received little academic attention. Media reports about fire incidents are useful tools in this case, along with a few scientific papers. The paper seeks to answer a key question: 'How damaging are grassfires to the forests in the Kurdistan Region of Iraq?' It also aims to address the following sub-questions:

'What is a grassfire? What causes grassfires in the KRI, and can anything be done to reduce incidents of grassfires or their impacts on the KRI's environment?'

Grassfires and their Causes in the KRI

A grassfire is a type of wildfire that burns wild, dry grasses. The term grassfire is similar to the term forest fire or bushfire, which burns through plantation or native growth forests; e.g., in Greece, Turkey or Portugal or the Australian bushland. Dry grasses have very low moisture content; they are combustible; hence, they provide ample fuel for fire, especially when they are over 10 cm tall. Grassfires can ignite very easily from any sort of spark, spread rapidly—up to 25–30 km/h—especially in windy conditions, and generate intense radiant heat. The radiant heat is highly dangerous; it poses a risk to anyone or anything nearby, including trees [1].

The KRI terrain consists of mountains, valleys, hills, and plains. It has different climatic patterns in different areas: from treeless plains with low precipitation (less than 300 mm of annual rain), mainly in its southern and southwestern areas, and high temperatures, to highlands with higher precipitation (more than 600 mm of annual rain), moderate temperatures, and bushes, shrubs, and trees in its northern and northeastern areas. Wild seasonal grass covers most of the terrain throughout the rainy period. The farther northeast and eastward one goes, the taller the grass becomes. The grass dries out at the beginning of the dry months, usually starting in May and ending in November. This means that all the grassy land in the KRI is at great risk of fire during that period [2,3].

The mountains, usually the side that faces east and northeast, are mainly covered with isolated and occasionally dense trees, bushes, and shrubs. Large amounts of them have been lost to illegal logging, drought, negligence, and arson in the past, and the remaining forested areas are at risk of disappearing because of grassfires.

Grassfires are more common in the mountains than in other places. This is because the mountains have taller grasses, and fire can move uphill very fast. Generally, wildfires occur throughout Iraq; the central and southern regions of Iraq record the lowest number of fires, whereas the northern and northeastern regions, mainly the KRI, record the highest. This is largely attributable to the grass on the mountains and the fact that the northern and northeastern areas receive a higher percentage of annual rain, which supports the growth of wild vegetation [4,5].

Grassfires break out in many places and at many times in the KRI during the dry months, from mid-spring to mid-autumn. Large areas of land in the KRI burn every year, destroying native and planted trees, bushes, shrubs, fruit orchards, vineyards, fruit and vegetable farms, and crops, as well as all the animals living in the area. The figures for grassfire occurrences, the scope of the damage,

and the areas affected vary in official statements, media investigation reports, and other studies. It has been observed that grassfires in the mountains are a continual environmental problem in the KRI, and the damage is immense [4]. It has been found that 'Wildfires [globally] result in the reduction or destruction of the economic value of rangeland species and forest trees, loss of seedlings, plant litter and wildlife habitats, soil degradation, degradation of natural landscapes, reduced soil acidity, reduced nitrogen reserves and the spread of inferior plant species' [6].

The wild, seasonal grass in the KRI, whether it is green or dry, is a source of food for livestock, as well as a source of food for wild animals and a nutrient for the soil. Domestic livestock and cattle roam around the mountains and other places where they graze and consume wild vegetation. Grassfires deprive domestic and wild animals of this rich and free source of food, which imposes a huge economic burden on the owners of livestock and cattle [7].

Information about the KRI's annual grassfire occurrences can best be obtained from local media, as other sources are rarely available to show the problem. Examples of grassfires in Sulaymaniyah Province in 2025 include: in May, hundreds of hectares of land and thousands of native trees, mainly oak trees, were burned as a result of grassfires in various locations across the province; in June, a grassfire incident in the Qaradagh Mountains occurred, in which 25 hectares of trees and bushes were burned; in the same month, a grassfire from Klkasmaq village burned 8 hectares of woodland; and another fire in the Sharbazher region destroyed about 10,000 native trees; in August, grassfires broke out in Halalawa village in Penjwen District and continued for two days, burning about 300 hectares of grassland and forests—Penjwen is the most naturally vegetated area in Sulaymaniyah Province; and in September, approximately 60 hectares of grassland, including native trees, were burned in the Sitak highlands [8–13]. Sulaymaniyah is the largest province of the KRI in terms of territorial size and the second most populated. It has many mountains and numerous native and planted trees.

In August 2025, a massive grassfire broke out in the mountains of the Halabja Province and continued for three days. According to local officials' estimates, the fire burned more than 500 hectares of land, including thousands of native trees and animal species, and harmed six villages. Local volunteers, as well as individuals from the forest police force, tried very hard to battle the blaze using conventional tools, but without tangible results. Two of the volunteers died in the fire. The Halabja Governor later stated that they did not have the necessary tools or equipment to extinguish the fire [14]. Halabja is the smallest province of the KRI in terms of size and the least populated. It is surrounded by mountains and is known for having many pomegranate orchards, along with other fruits and vegetables.

A massive grassfire was reported in August 2023 in Balakyati District in Choman, a naturally vegetated region in the northeast of Erbil Province. Erbil is the second largest province of the KRI in terms of size and the most populated. The fire burned an estimated 6,000 native trees across 450 hectares of land, which included pastures, bushes, shrubs, and green, lush areas. The destruction of the trees was considered a significant loss since many of them were over 50 years old. They included oak, grape vines, and oak apple. The district and the nearby areas saw at least ten fires within one month [15]. In July 2024, the same district reported grassfires in one of its villages, burning about 40 hectares of land, including the destruction of 150 beehives owned by local people [16].

In July 2025, a massive grassfire erupted in the Zaweta District of Duhok Province and marched through a large mountainous area, burning 100 hectares of grass and pasture land, including countless native trees, some of which were over 100 years old. Duhok is the third largest province in the KRI in terms of size and the third most populated. It has over 170,000 hectares of forests and natural vegetation lands, but it is also a zone of military confrontation between the Turkish army and the Kurdish armed groups of the Kurdistan Workers' Party (PKK). This warfare is a leading cause of wildfires in the area. In 2021, about 2,600 hectares of grass and pasture land, including countless trees, were destroyed by fire [17–20].

An example of grassfires burning plantations is Goizha mountain in Sulaymaniyah City. Within four years (2020–2024)**,** large fires fuelled by dry grass and fanned by strong winds burned more than 20 hectares of land, including about 15,000 trees. The damage is beyond any repair, said the spokesman for the Ministry of Agriculture and Water Resources of the Kurdistan Regional Government (KRG). He stated that little care is currently given to the mountain by the government and pointed out that the number of personnel in charge of observing and protecting the area is extremely small. There are no fire alarm systems and no fire extinguishing mechanisms in place to respond to fire incidents [21–23].

Grassfires are a common problem in all the KRI provinces: Sulaymaniyah, Erbil, Duhok, and Halabja. A large number of native and planted trees in all of the provinces are destroyed by fire every year. According to data gathered by local media, in 2025 up until 31 August, 2,860 fires occurred in the KRI, the majority of which were grassfires in the mountains, but also in other terrains: 783 fires occurred in Sulaymaniyah Province, and the most devastating was the one that occurred in Qaradagh; 193 fires occurred in the forests and natural vegetation lands in Erbil Province; 870 fires occurred in Duhok Province, and the most destructive was the Zaweta fire; and 176 fires occurred in Halabja Province [24]. According to one study, grassfires burned over 120,000 hectares of land throughout the KRI in 2024 [25].

The KRI mountains are home to natural trees and various other plant and animal species, some of which are endemic to the region. The region contains over 90 percent of the natural forests in Iraq. Grassfires continue to destroy these resources. According to estimates, the KRI's green areas have decreased from 23.46% to 12.44% over two decades (1999–2018) [26]. A study shows that about 50 percent of the KRI's forests have been lost in the past 70 years [27]. Another study indicates that the KRI's forest areas have shrunk from 1.4 million hectares in 1920 to 300,000 in 2003 [25]. According to information gathered by an environmental civil society group working in Iraq, the KRI had 500,000 hectares of land covered with forests, isolated trees, and natural vegetation in the middle of the twentieth century, but that area had shrunk to half by the end of the century. The information also indicates that since the beginning of the new century up until 2024, half of the remaining forests and vegetation have been destroyed through fire-setting [28].

Besides the environmental cost, grassfires have a human cost too. When a fire breaks out, volunteers, often villagers, herders, and passersby, as well as sometimes government-appointed firefighters, try to put it out, often using simple and traditional tools. This sometimes results in death and injury from a lack of safety equipment and training [29,30]. Fires also cause mines to explode, which leads to more burning and damage and hinders the work of the firefighting teams [31]. During the Iran–Iraq War (1980–1988), the Iraqi government planted millions of mines in the mountains of the KRI in an effort to stop the advance of the Iranian army and also restrict the movements of Kurdish peshmerga forces.

Causes of Grassfires in the KRI

The KRI's hot and dry months are key to understanding why grassfires erupt so quickly. Fires do not naturally occur from the heat of the sun or the dry weather. Grassfires in the KRI happen mainly through human negligence and carelessness, such as throwing still-burning cigarette butts, littering with empty drink bottles and other glass and plastic containers, which can sometimes act as magnifiers for the sunlight gathering heat, sparks from barbecues or hookahs by picnickers, stubble burning of harvested lands, heat from cars and farming machinery, and intentional arson [25].

Grassfires in the mountains can become more aggressive if landmines explode. The KRI still has vast areas uncleared of landmines. The mines can explode under the heat of grassfires, causing further burning and damage to the surrounding areas, killing or maiming any people nearby. They can also hinder firefighting efforts since safety is a critical issue for well-motivated but ill-equipped and ill-trained firefighting personnel [32,34].

Another cause of grassfires is the continuing fight between Türkiye and the PKK, and between Iran and the Kurdish armed groups stationed in the border mountains of the KRI. Shelling from artillery and aircraft, shooting, and explosions of different types often spark fires that spread over a wide area. They burn trees, crops, animals, and agricultural farms, causing great havoc to the environment and everything in it. According to one study that refers to recent conflicts between the Turkish state and the PKK, there is a correlation between the increase in conflicts and the rise in wildfires in the mountainous areas of the KRI. Another study shows that in the first six months of 2024, over 800 attacks and shelling incidents occurred in the KRI and Nineveh Province [35,36]. The KRG has a forest police unit in charge of protecting the forests from logging, sabotage, arson, and other threats. The force is also tasked with monitoring human activities that may lead to wildfires. The KRG also has Civil Defence units with various tasks, including fighting wildfires. The main issue is that these units lack sufficient personnel, are not equipped with the necessary tools, and do not possess the required skills to respond rapidly to fire incidents; they are incapable of fighting or containing fires. Additionally, the size of the areas where grassfires might occur and the nature of the terrain both pose significant challenges to firefighting efforts.

Possible Solution

Seasonal grasses cover most of the KRI during winter and early spring. They dry out soon after the dry months begin and turn into fine fuel, making it difficult to protect the trees and vegetation from fire. Fire accidents can be reduced, and many trees can be saved. There are measures to take in that regard. Among them are training rural people and equipping them with fire extinguishers, hand tools, and protective clothing. Rural people can act very quickly; they can swiftly reach the site of the fire, and their actions can be very effective if they start early before the fire spreads.

Fires usually start in places where human activities occur, such as farms, industrial areas, and entertainment sites. This means that if precautions are taken in those places and their surroundings are isolated from fire, the fire will not spread when it occurs. This makes it easier for the authorities to protect nature from fire; they do not have to protect entire forest areas, which they cannot. The focus can be on places busy with human activities, and the grass around those places can be eliminated by spraying herbicide on it, creating fuel breaks by removing the grass, or mowing [37].

Another possible solution is spreading awareness about what sparks wildfires and providing guidance on taking precautions when engaging in fire-related activities in areas with grass and dry vegetation. Many wildfires in the KRI are blamed on negligent picnickers, mountain hikers, hookah smokers, and people who spend time outdoors who throw litter such as glass bottles and plastic containers. The litter may act like magnifiers, collecting sunlight and igniting fires [3]. The large

fire incident on Goizha mountain in Sulaymaniyah in 2020 was said to have been caused by sparks from a recreational activity involving three men. The Minister of Agriculture and Water Resources of the KRG commented on this particular fire incident, stating that years of effort were all wasted in a few minutes through a few people's negligence and lack of responsibility [38]. The second major fire incident on Goizha occurred in 2024.

Punishing arsonists is also key to reducing fire incidents. Not all the grassfires in the KRI result from negligence. Some are the result of deliberate acts of arson. There are laws in place for the perpetrators of arson attacks, and when punishment is properly administered, it will serve as a deterrent for future attacks. It is always a challenge to find suspects, but it is not impossible, considering the intelligence resources available to law enforcement agencies in the KRI. There have been arrests and prosecutions on charges of deliberately burning grass and trees [39], but that is not enough; more efforts must be made, more resources should be provided for that matter, and people must be encouraged to report suspicious activities. These are measures to be taken at the national level.

At the international level, diplomatic efforts need to be made to stop the continuing fighting between the neighbouring states and the Kurdish armed groups stationed in the mountainous areas near the borders of Türkiye and Iran. Decades-long military conflict between the PKK and the Turkish state, and between the Iranian Kurdish armed groups and the Iranian state, has caused destruction to large areas of forests and thousands of hectares of agricultural land and fruit orchards. Many villagers have left their homes as a consequence of the fighting. It is almost certain that bombardments and exchanges of fire between the militants and the armies of the neighbouring states are leading causes of wildfires in those areas. A study has found that incidents of fighting and incidents of wildfires in the mountains of the KRI are interlinked [40]. Deliberate acts of arson for military tactics and other purposes are also not impossible [41].

Conclusion

Grassfires are an unresolved problem in the KRI. They occur in large numbers every year, especially in the mountains, burning thousands of hectares of land, including native woodland and plantations, bushes, shrubs, seedlings, hedges, hay, straw, and sometimes large fields of crops and fruit orchards. They cause great damage to the villagers' livestock by destroying the pastures and grazing lands. The greatest and most irreparable damage is to the trees, which take many years or decades to grow. The region already suffers from a shortage of rain and increasing temperatures from climate change, which means that it is becoming tougher for the trees to survive. The trees

must be conserved and be able to grow naturally or be planted in greater numbers. Trees are crucial for the well-being of the environment and people.

The KRG has laws to protect the natural habitat and, above all, the natural and planted trees. The KRI has forest police and civil defence units in charge of protecting the wildlands; in addition, they safeguard the trees and wild animals such as deer and mouflons. Yet both the forest police and civil defence units prove incapable of quick and effective response during wildfire events, and they can succumb to injuries and deaths, even when supplemented by the efforts of local people. The lack of training and their inadequate equipment defeat their efforts to quell the fires.

The KRI has over 90 percent of Iraq's natural forests. This resource has been dwindling since the early years of the twentieth century. Climate change, as seen in a shortage of rain, illegal logging, war and conflict, and urbanization**,** is causing the shrinking forest areas of the KRI. Furthermore, grassfires continue to be a key factor in destroying and eliminating this precious resource. The disappearance of one tree means the loss of the environmental, recreational, and economic benefits that the tree offers. These benefits must be more appreciated in Iraq, where the land is largely desert and the entire country suffers from a significant deficit of water. The KRG has launched and sponsored many campaigns to green the KRI by tree planting campaigns on the mountain slopes and in and around the cities, among other locations. These efforts are often not fruitful, as the trees quickly and easily become victims of grassfires. Urgent methods must be taken by the KRG to tackle the grassfires.

References

[1] Sullivan, A. L., 2010, Grassland fire management in future climate. In D. L. Sparks (Ed.), *Advances in agronomy* (Vol. 106). (London: Academic Press), pp. 173–208. https://doi.org/10.1016/S0065-2113(10)06005-0

[2] Forti, L., Perego, A., Brandolini, F., Mariani, G. S., Zebari, M., Nicoll, K., Regattieri, E., Conati Barbaro, C., Morandi Bonacossi, D., Qasim, H. A., Cremaschi, M., & Zerboni, A., 2021, Geomorphology of the northwestern Kurdistan Region of Iraq: Landscapes of the Zagros Mountains drained by the Tigris and Great Zab Rivers. *Journal of Maps* **17**(2), 225–236. https://doi.org/10.1080/17445647.2021.1906339

[3] Rahimi, I., Azeez, S. N., Ahmed, I. H., 2020, Mapping Forest-Fire Potentiality Using Remote Sensing and GIS, Case Study: Kurdistan Region-Iraq. In: Al-Quraishi, A., Negm, A. (eds) Environmental Remote Sensing and GIS in Iraq. Springer Water. (Cham: Springer). https://doi.org/10.1007/978-3-030-21344-2_20

[4] Rasul, A., Ibrahim, G. R. F., Hameed, H. M., Dewana, A. M., Kak, S. F., Ahmed, S. A., Shil, S. K., & Salih, A. A., 2021, A trend of increasing burned areas in Iraq from 2001 to 2019. *Environment, Development and Sustainability* **23**(4), 5739–5755. https://doi.org/10.1007/s10668-020-00842-7

[5] Salar, S. G., Othman, A. A., Rasooli, S., Ali, S. S., Al-Attar, Z. T., & Liesenberg, V., 2022, GIS-Based Modeling for Vegetated Land Fire Prediction in Qaradagh Area, Kurdistan Region, Iraq. *Sustainability* **14**(10), 6194. https://doi.org/10.3390/su14106194

[6] Velayati, A., Boloorani, A., Kiavarz M., Samani N., & Alavipanah S., 2024, Spatiotemporal analysis of wildfire in the Tigris and Euphrates basin: A remote sensing based wildfire potential mapping, *Remote Sensing Applications: Society and Environment* **34**, 101150. https://doi.org/10.1016/j.rsase.2024.101150

[7] Rudaw, Devastating blaze engulfs Sulaimani's mountain, June 11, 1015. Available at: https://www.rudaw.net/english/kurdistan/110620251 (accessed 7 September 2025).

[8] 964media, Massive forest fire in Qaradagh brought under control after 20 hours, June 11, 2025. Available at: https://en.964media.com/36878/ (accessed 10 August 2025).

[9] Esta, پۆلیسی دارستان و ژینگەی سلێمانی: بەهۆی ئاگرکەوتنەوەوە نزیکەی 80 دۆنم پوش و پاوان سووتان [Sulaymaniyah Forest and Environmental Police: around 8 hectares of grass and shrubs were burned], June 6, 2025. Available at: https://esta.krd/354173/ (accessed 18 August 2025).

[10] Xelk, لە ٢٤ کاتژمێردا سەدان دۆنم لە سنووری سلێمانی سووتان [Hundreds of dunams were burned in Sulaymaniyah within the last 24 hours], May 28, 2025. Available at: https://xelk.org/2025/05/28/11467/ (accessed 18 August 2025).

[11] Xendan, 600 دۆنم پوش و پاوان و دارستانی سروشتی لە سیتەك سوتا [600 dunams of vegetation and forest in Sitak were burned], September 7, 2025. Available at: https://www.xendan.org/detailnews/200649 (accessed 7 September 2025).

[12] The New Region, Thousands of dunams burnt by Penjwen wildfire, August 30, 2025. Available at: https://thenewregion.com/posts/2954/thousands-of-dunams-burnt-by-penjwen-wildfire (accessed 7 September 2025).

[13] Rudaw, بەڕێوەبەری دارستان و پاوانەکانی دهۆک: داوای بورجی دژەبرووسکەمان کردووە بۆ ڕێگەگرتن لە ئاگر [Director of Duhok Forests and Grasslands: we have requested anti-lightning towers to prevent fire], June 11, 2024. Available at: https://www.rudaw.net/sorani/kurdistan/110620249 (accessed 9 September 2025).

[14] Kurdistan24, ئاگرەکەی هەڵەبجە زیانی بە شەش گوند گەیاند و پێنج هەزار دۆنم زەویش سووتا [The Halabja fire harmed six villages and burned 5,000 dunams of land], August 21, 2025. Available at: https://www.kurdistan24.net/ckb/story/859091 (accessed 6 September 2025).

[15] Rudaw, Massive fire engulfs northern Erbil, arson suspected, August 16, 2023. Available at: https://www.rudaw.net/english/kurdistan/16082023 (accessed 8 September 2025).

[16] 964, Fire in the mountainous are of Erbil destroys 150 beehives, July 27, 2024. Available at: https://en.964media.com/22543/ (accessed 8 September 2025).

[17] AVA, لە دهۆک دوای 20 کاتژمێر ئاگر نزیکەی 300 دۆنم دارستان سووتا [In Duhok, after 20 hours of fire, about 300 dunams of land were burned], July 5, 2025. Available at: https://www.ava.news/news/30006 (accessed 9 September 2025).

[18] Rudaw, گالەری: سووتانی دارستانەکانی زاویتە [Gallery: the burning of Zaweta Forests], July 25, 2025. Available at: https://www.rudaw.net/sorani/kurdistan/2507202113 (accessed 9 September 2025).

[19] Rudaw, ئاگر زیاتر لە 100 دۆنم پاوان و دارستانی لە زاویتەی سنووری دهۆک سووتاند [Fire burned more than 100 dunams of forests and vegetation in the Zaweta area of Duhok], September 10, 2024. Available at: https://www.rudaw.net/sorani/kurdistan/1009202426 (accessed 9 September 2025).

[20] Rudaw, دارستان و پاوانی دهۆک: 25%ی ئەو ئاگرانەی لە دارستانەکان دەکەونەوە بە ئەنقەستن [Duhok Forest and Vegetation: twenty-five percent of the forest fires are deliberate], June 22, 2023. Available at: https://www.rudaw.net/sorani/kurdistan/220620238 (accessed 9 September 2025).

[21] SNNC, Regional Agricultural Department: Burning Goizha cannot be compensated, September 5, 2020. Available at: https://snnc.co/en/35119 (accessed 16 August 2025).

[22] KNN, Do not look at burning Goizha as a little matter, July 29, 2024. Available at: https://www.knnc.net/Details.aspx?jimare=56890 (accessed 16 August 2025).

[23] Kurdistan24, More than 200 dunams of trees, shrubs burnt down in Goizha mountain, July 29, 2014. Available at: https://www.kurdistan24.net/en/story/396040/More-than-200-dunams-of-trees,-shrubs-burnt-down-in-Goizha-mountain (accessed 9 September 2025).

[24] Channel8, ئەمساڵ 2 هەزار و 860 ئاگر لە هەرێمی کوردستان کەوتوونەتەوە [This year, 2 thousand and 860 fires occurred in Kurdistan Region], August 31, 2025. Available at: https://channel8.com/kurdish/news/142332 (accessed 9 September 2025).

[25] Rasheed, L., & Zwijnenburg, W., 2024, Wildfire analyses in Iraqi Kurdistan, *Pax Analysis*. Available at: https://reliefweb.int/report/iraq/wildfire-analyses-iraqi-kurdistan (accessed 10 August 2025).

[26] Baban, M., 2023, Climate Change in the Kurdistan Region and Iraq; Deforestation, Fires and Burning of Trees, *Rudaw Research Center*. Available at: https://rudawrc.net/en/article/climate-change-in-the-kurdistan-region-and-iraq-deforestation-fires-and-burning-of-trees-2023-08-20 (accessed 11 August 2025).

[27] Gamal-Gabriel, T., Saving the vanishing forests of Iraq's Kurdistan, August 20, 2024, *Al-Monitor*. Available at: https://www.al-monitor.com/originals/2024/08/saving-vanishing-forests-iraqs-kurdistan (accessed 11 August 2025).

[28] VOA, ڕێکخراوێکی ژینگەیی: نیوەی دارستان و پاوەنی کوردستان لە ناوچوون و تۆپبارانەکانی تورکیا و ئێران یەکێکن لەهۆکارەکان [An environmental organization: half of Kurdistan's tree and shrub forests have disappeared, and artillery shelling by Türkiye and Iran is a cause], July 6, 2024. Available at: https://www.dengiamerika.com/a/7687537.html (accessed 9 September 2025).

[29] Xendan, ئاری موختار گریانەیی، شەهیدی ژینگە و ژیان؛ داوا دەکرێت تۆمەتباران دادگایی بکرێن [Ari Mukhtar Gryanaee, martyr of life and environment; there are calls for prosecuting the perpetrators], August 18, 2025. Available at: https://www.xendan.org/detailnews/199662 (accessed 18 August 2025).

[30] ANFNEWS, A Kurdish activist dies, four others injured battling wildfire in Sanandaj, July 26, 2025. Available at: https://english.anf-news.com/kurdistan/kurdish-activist-dies-four-injured-battling-wildfire-in-sanandaj-80480 (accessed 11 August 2025).

[31] Kurdistan24, Fire in Kurdistan burns over 50 acres of mountainous land, detonates mines, August 17, 2019. Available at: https://www.kurdistan24.net/en/story/380446 (accessed 10 August 2025).

[32] The New Region, Penjwen fire burns two, yet to be controlled, August 29, 2025. Available at: https://thenewregion.com/posts/2951/penjwen-fire-burns-two-yet-to-be-controlled (accessed 8 September 2025).

[33] Kurdistan24, Politics: Fire in Kurdistan burns over 50 acres of mountainous land, detonates mines, August 17, 2019. Available at: https://www.kurdistan24.net/en/story/380446 (accessed 8 September 2025).

[34] 964, Fire in Bamo mountains contained after five days with nearly 5000 acres burned. June 29, 2025. Available at: https://en.964media.com/37505/ (accessed 8 September 2025).

[35] Eklund, L., Abdi, A. M., Shahpurwala, A., & Dinc, P., 2021, On the Geopolitics of Fire, Conflict and Land in the Kurdistan Region of Iraq. *Remote Sensing* **13**(8), 1575. https://doi.org/10.3390/rs13081575

[36] Aljazeera, Turkey, PKK clashes spark fire in Duhok province, June 19, 2024. Available at: https://www.rudaw.net/english/kurdistan/19062024 (accessed 18 August 2025).

[37] CFA, Grassfires Rural, August 26, 2025. Available at: https://www.cfa.vic.gov.au/plan-prepare/bushfire-basics/grassfires-rural (accessed 27 August 2025).

[38] Westga news, وەزیری کشتوکاڵ: مخابن گۆیژەی سەوز، رەش پۆشکرا [Minister of Agriculture: unfortunately, the green Goizha has turned black], September 4, 2020. Available at: https://www.westganews.net/dreja.aspx?=hewal&jmara=91416&Jor=1 (accessed 28 August 2025).

[39] VOA, وتەبێژی پۆلیسی بەڕێوەبەرایەتی دارستان و ژینگەی سلێمانی: 47 کەسمان بە تۆمەتی سوتاندنی دارستان و گردەکانی سلێمانی دەستگیرکردووە [Spokesperson for the Sulaymaniyah Forest and Environment Directorate: we have arrested 47 people on the suspicion of burning the forests and hills of Sulaymaniyah], August 18, 2024, Available at: https://www.dengiamerika.com/a/7747307.html (accessed 28 August 2025).

[40] Eklund, L., & P. Dinc, 2024, Fires as collateral or means of war: challenges of environmental peacebuilding in the Kurdistan Region of Iraq. *Ecology and Society* **29**(3), 25. https://doi.org/10.5751/ES-15316-290325

[41] Jongerden, J., de Vos, H., & van Etten, J., 2007, Forest Burning as Counterinsurgency in Turkish-Kurdistan: An analysis from space, *The International Journal of Kurdish Studies* **21(**1,2). https://edepot.wur.nl/307864

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Biofertilizers for Sustainable and Environment-friendly Agriculture

Meriem Mahmoudi [1a], Zakaria Asbai [1b], Tarik Foughal [1c], Rolf Gael Mabicka Obame [2d], Maurice Ognalaga [2e], Juline Diken Malounghou Bounangnan [1f], Bouchaib Bahlaouan [3g], Nadia Boutaleb [1h]☑

[1] *Hassan II University of Casablanca (https://ror.org/001q4kn48), Laboratory of Biotechnology, Agri-Food, Materials and Environment, Team: Biotechnologies, Resource Valorisation, Quality, Health and Ecotoxicology, Faculty of Science and Technology Mohammedia, BP 146, Mohammedia 20650, Morocco*

[2] *University of Science and Technology of Masuku (https://ror.org/03f0njg03), National Higher Institute of Agronomy and Biotechnology (INSAB), Department of Phytotechnology, P.O. Box 901, Franceville, Gabon*

[3] *Higher Institutes of Nursing and Health Technical Professions (ISPITS) (https://ror.org/007h8y788), Laboratory of Care, Health and Sustainable Development 2S2D, Higher Institutes of the Nursing Professions and Techniques of Health ISPITS Casablanca 22500, Morocco*

[a] ***ORCID**: 0009-0002-2682-2478;* **Email:** meriem.mahmoudi2-etu@etu.univh2c.ma

[b] ***ORCID**: 0000-0003-2748-3973;* **Email:** zakaria.asbai@etu.fstm.ac.ma

[c] ***ORCID**: 0000-0001-8439-5924;* **Email:** tarik.foughal@etu.fstm.ac.ma

[d] ***ORCID**:0000-0002-8519-1170 ;* **Email:** rolfgaelmabickaobame@gmail.com

[e] ***ORCID**: 0009-0009-4469-6744;* **Email:** ognalagam59@gmail.com

[f] ***ORCID**: 0009-0004-0654-9501*; **Email:** juline.malounghou-etu@etu.univh2c.ma

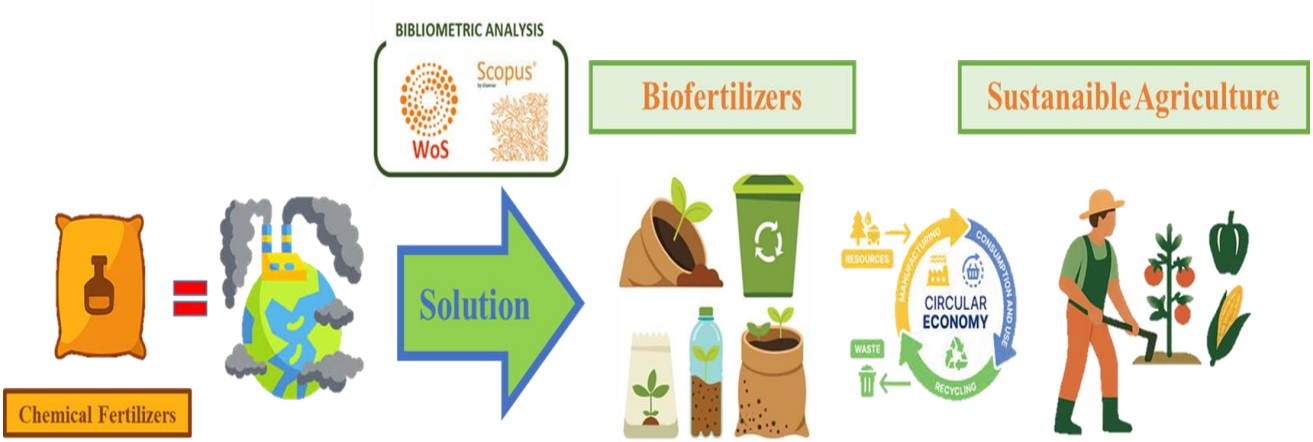
[g] ***ORCID**: 0000-0002-0976-1274;* **Email**: b.bahlaouan@ispitscasa.ac.ma

[h] ***ORCID**: 0000-0003-1628-4311;* **Email:** nadia.boutaleb@fstm.ac.ma

☑ ***Corresponding author:*** Nadia Boutaleb; ***Email***: nadia.boutaleb@fstm.ac.ma

Graphical Abstract

This study provides a concise synthesis of recent progress in biofertilizers, focusing on their main classes, mechanisms of action, their agronomic and environmental benefit, and the challenges they face. Based on a rigorous bibliographic analysis of over 17,000 records from leading databases, it identifies key trends, knowledge gaps, and technical levers to improve fertilizer efficiency. The work supports the development of eco-efficient biofertilizers aligned with the principles of sustainable agriculture and the circular economy.



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Abstract: Biofertilizers are the practical alternative to chemical fertilizers, although it may take long to achieve a transition worldwide. It is clear that biofertilizers have many advantages. These are detailed by reference to major published work on the subject from 2020 to 2025. Biofertilizers increase soil fertility by enhanced nutrient cycling and sustainable cultivation in a circular economy. With emphasis on case histories of success such as on-farm experiments in Morocco demonstrating yield enhancement and soil health enhancement in tomato, pepper and maize, this review considers the diversity of types of biofertilizers and mode of action and their application on cereals and legumes and on horticultural crops. Despite their promise, problems of variable efficacy and short shelf life and the imperative to design region-specific formulations require innovations in technology and system. Innovules through genomics and metagenomics are accelerating the engineering of durable strain microorganisms and the combination of biofertilizers with biopesticides and conditioners of soil present synergetic pathways towards sustainability in agricultural intensification. Actions towards mitigation of soils and enhancement of sustainability in food systems globally are congruent with the promise of using biofertilizers to make significant contributions to climate-resilient, productive and environment-friendly agriculture.

Keywords: *Biofertilizers, Organic farming, Soil fertility, Sustainability.*

Introduction

High-quantity application of chemical fertilizers to support crop production has been the cornerstone to rapid agricultural growth over the past century. Over-application and often indiscriminate application of these inputs have caused harmful health and environmental ills such as soil erosion, eutrophication of lakes and ponds, reduction in biological diversity, and emission of greenhouse gases. Sustainable agriculture is now increasingly popular as an alternative. It aims to reduce the dependency on external sources.

Biofertilizers are formulations consisting of living microorganisms and increase the availability or uptake of key nutrients to sustain plant growth. Biofertilizers are increasingly eco-friendly in relation to traditional fertilizers. Biological input such as biofertilizers act through several mechanisms like fixation of nitrogen, solubilization of phosphate, production of plant growth promoters and stimulation of populations of soil microorganisms. Compared to synthetic fertilizers, these directly deliver nutrients but sometimes ineffectively. This is corrigible, depending on goodwill and good teaching. Biofertilizers act in combination with the system of the plant and soil to achieve sustained soil fertility and environmental sustainability.

New advances in microbial biotechnology and soil microbiome science have continued to expand the application sphere of biofertilizers to improve plant productivity in diverse agro-climatic regimes. Moreover, their application is in the framework of circular economy and organic farming. They are therefore found to be attractive options by industrial as well as by smallholder farmers.

This literature review aims to survey biofertilizers comprehensively, including their classification, mechanisms of action, agronomic and environmental benefits, practical applications, and current limitations. It also highlights recent innovations and future directions in biofertilizer research and usage, as these are central to achieving sustainable and resilient food systems.

Bibliometric Insights into biofertilizers research

Materials and Methods

As part of this research, we adopted a systematic review method, PRISMA (*Preferred Reporting Items for Systematic Reviews and Meta-Analyses*), to ensure more rigorous and less biased systematic reviews, thereby providing reliable data for scientists, stakeholders, and policymakers. We developed a rigorous internal protocol based on four stages:

Search Strategy

A comprehensive search strategy was implemented to identify relevant literature, targeting three major databases: **Scopus**, **Springer** and **Taylor & Francis**. Identical keyword sets (Table 1) were used in both databases to ensure consistency and maximize coverage. The study's eligibility criteria restricted the search to publications between **2020** and **2025.** The review focused on qualitative research related to biotransformation of organic waste, nutrient management in sustainable agriculture, and microbial community interactions. Table 2 shows the full list of inclusion and exclusion criteria.

Table 1. Research Approach for Systematic Review Process

Database	Research Approach
Scopus	Title-Abstract-Keywords "biotransformation" AND "microbial community" AND "biodegradation" OR "composting" AND "anaerobic digestion" AND "biogas" AND "methane" OR "fertilizer" OR "biofertilizer" OR "fertilizers"
Web of Science	Title-Abstract-Keywords "biotransformation" AND "microbial community" AND "biodegradation" OR "composting" AND "anaerobic digestion" AND "biogas" AND "methane" OR "fertilizer" OR "biofertilizer" OR "fertilizers"

Selection Criteria

The selection criteria were based on the PRISMA statement. The search aimed to identify qualitative studies on the organo-mineral fertilizers, biotransformation processes, controlled nutrient release, and nutrient use efficiency, all having been published in reputable journals over the past **5 years**. The definition of inclusion and exclusion criteria was crucial to ensuring that our research question remained focused, unique, and free from selection bias. All articles published before **2020** were excluded. The search was mainly limited to English and French articles, resulting in the exclusion of 70 762 research articles at this stage. A total of **17 564** records were extracted at this stage.

Table 2. Inclusion and Exclusion Criteria for the Systematic Review

Criteria	Inclusion	Exclusion
Publication period	Between 2020 and 2025	Before 2000
Language	English, French	Languages other than English or French
Document Type	Articles, reviews	Reports, book chapters

Quality Assessment

The review focused exclusively on original research articles and review papers to ensure the inclusion of high-quality, peer-reviewed scientific literature. A rigorous screening process was applied to eliminate duplicate records and maintain data integrity. The scope of the analysis was restricted to studies directly relevant to environmental sciences, biochemistry, agricultural and biological sciences, biotransformation of organic waste, nutrient management in sustainable agriculture, and microbial community interactions. Fields that were tangentially related by keywords but fell outside the core scope, such as nursing, veterinary medicine, mathematics psychology, art and humanities, biomedical sciences, and clinical trials were excluded to avoid thematic dilution. After the removal of duplicate entries and a detailed relevance check, a total of **17 564** publications were retained based on the inclusion and exclusion criteria established in Table 2. Figure 1 visually summarizes the selection process following the PRISMA statement.

Data Extraction

Data were extracted from the **17 564** selected articles, including information such as author names, article title, publication year, journal, abstract, citations, affiliations, keywords, references, and language. This information supported analyses of research trends, collaboration networks, keyword co-occurrence, and citation impact.

The data were organized around key themes of the study, including sustainable agriculture, biotransformation of organic waste, nutrient management in sustainable agriculture, and microbial community interactions. providing a structured basis for the systematic review.

Bibliometric Analysis

The bibliometric analysis and mapping aims to give a comprehensive view of the scientific literature on biotransformation of organic waste, nutrient management, microbial community interactions and their roles in sustainable agriculture. We extracted and analysed metadata from peer-reviewed articles published between 2020 and 2025, including citation counts, publication trends, titles, abstracts, and author keywords, obtained from Scopus, Springer and Taylor & Francis databases.

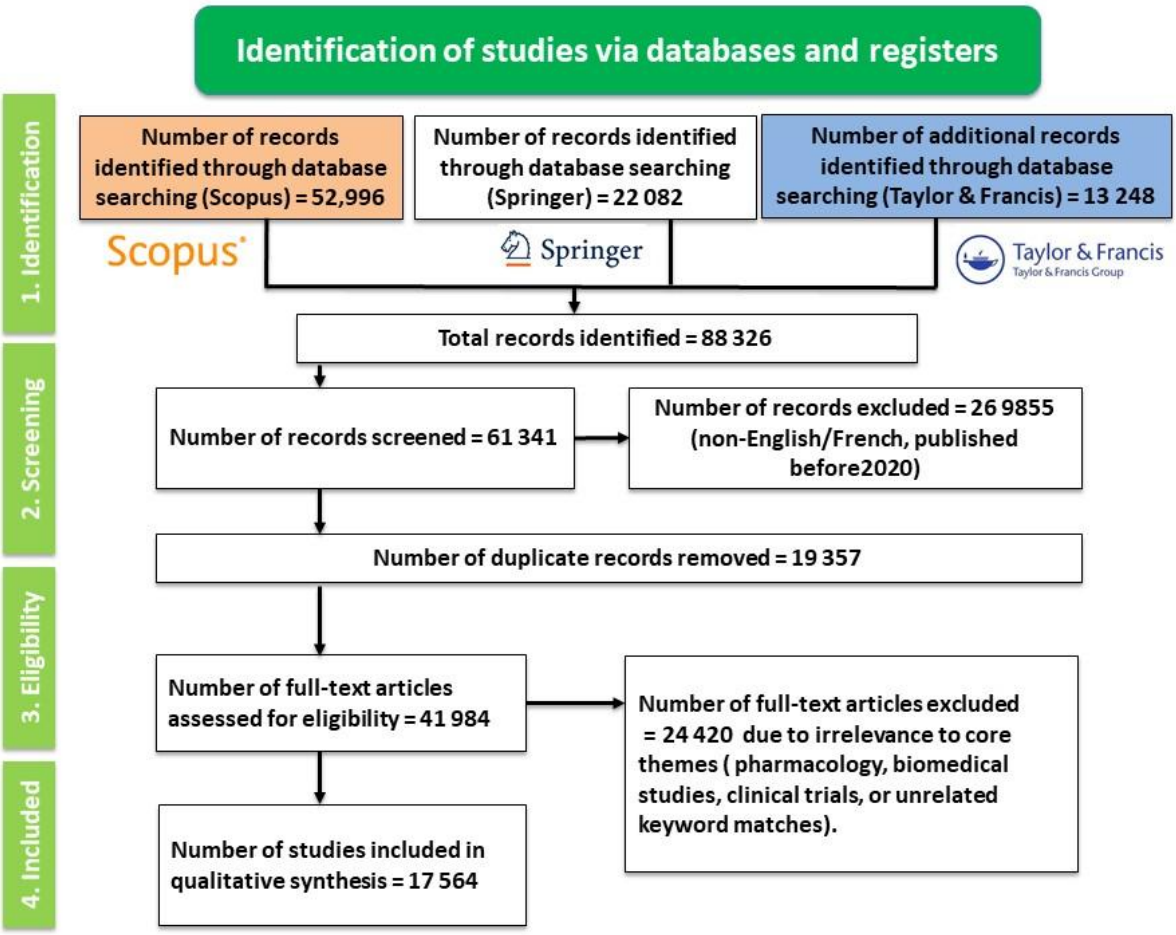

Figure 1. PRISMA 2020: flow diagram for new systematic reviews which included searches of databases and registers

This bibliometric study identifies and visualizes emerging research trends, thematic hotspots, and collaboration patterns in the domain of sustainable agriculture, where both chemical fertilizers and biofertilizers are being applied. VOSviewer (version 1.6.17) was employed to perform various bibliometric analyses, including keyword co-occurrence, co-citation analysis, and bibliographic coupling, enabling the detection of knowledge clusters and conceptual linkages. In parallel, ORIGINLAB 2024b was used to generate descriptive and statistical visualizations, such as publication distributions over time and citation metrics, supporting the interpretation of quantitative data trends.

Results and Discussion

Geographical Distribution of Publications

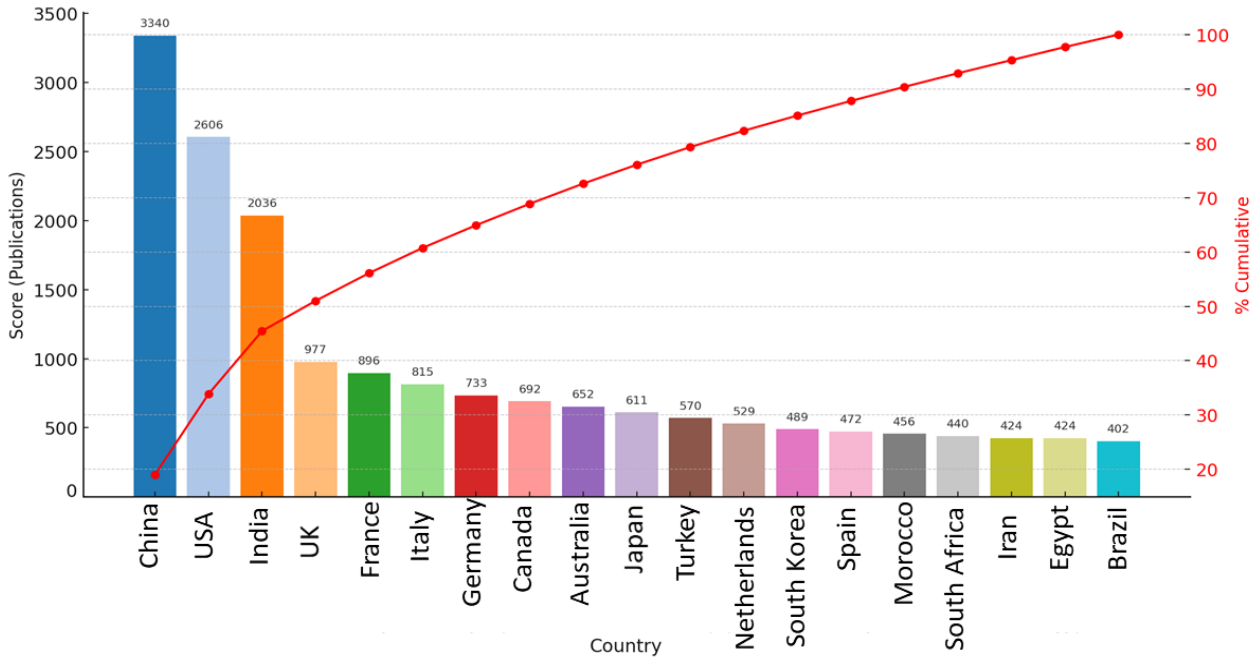

Figure 2. Publication distribution of reviewed papers by country

Figure 2 shows the publishing trend in the global scientific activity in sustainable agriculture and biofertilizers. Since the first three positions are held by China (3,340 publications), the USA (2,606), and India (2,036), it is clear from the data that scientific production is highly concentrated in a limited number of countries. Only three countries account for well over half of all publications and thus command the field of research on the subject of innovations in fertilizers.

European countries such as the UK (977), France (896), Italy (815), and Germany (733) also show a significant contribution, showing how this topic is treated as important within Europe. Further, Morocco (456), Iran (424), and Egypt (424) show the growing interest of developing nations in adopting sustainable substitutes to standard chemical industry products for environmental and soil fertility problems.

The cumulative curve confirms the Pareto distribution: a small group of countries drives most of the global research activity. This imbalance underscores the need for broader international collaboration, particularly to strengthen research capacity in regions with lower publication output. The observed pattern mirrors the global focus on sustainable fertilizer technologies, nutrient use efficiency (NUE), and the integration of circular economy models, where biofertilizers are central to mitigating the limitations of conventional synthetic fertilizers.

Citation Trend Analysis (2020–2025)

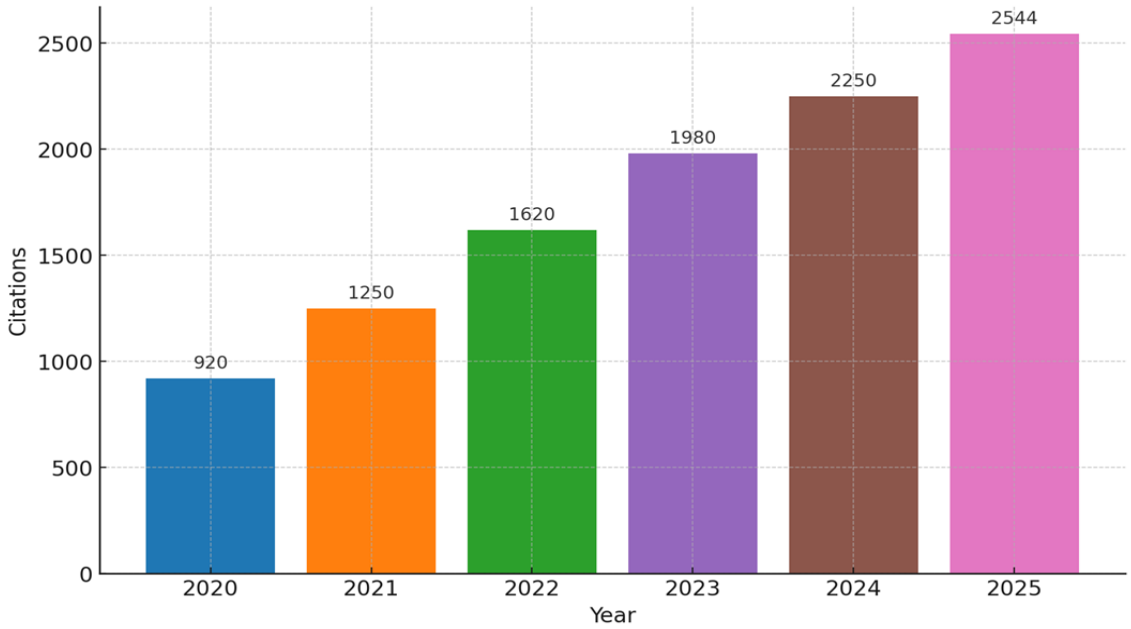

Figure 3. Citation dynamics in biofertilizer research.

Figure 3 shows that there is a remarkable and consistent increase in research from 2020 to 2025. From 920 citations in 2020 to 2,544 in 2025, there has been well over a doubling of citations during these five years. This trend reflects the growth of interest in sustainable fertilization technology and related subjects.

The increase, specifically after 2021, shows that nutrient use efficacy (NUE) is widely understood and so are the problems caused by conventional fertilizers. This trend parallels interest in the adoption of circular economy approaches, specifically valorization of organic byproducts through composting and anaerobic digestion. The methods favour the production of organo-mineral fertilizers enhancing soil fertility while providing environment-friendly alternatives to conventional synthetic products.

Furthermore, the accelerated citation growth reflects the development of controlled-release strategies and advanced coating materials, which optimize nutrient delivery, reduce losses from leaching and volatilization, and synchronize nutrient release with crop demand. The increasing number of citations thus underscores both the relevance of this field and the benefits of sustainable agricultural practices.

Keyword Co-occurrence and Thematic Structure of the Field

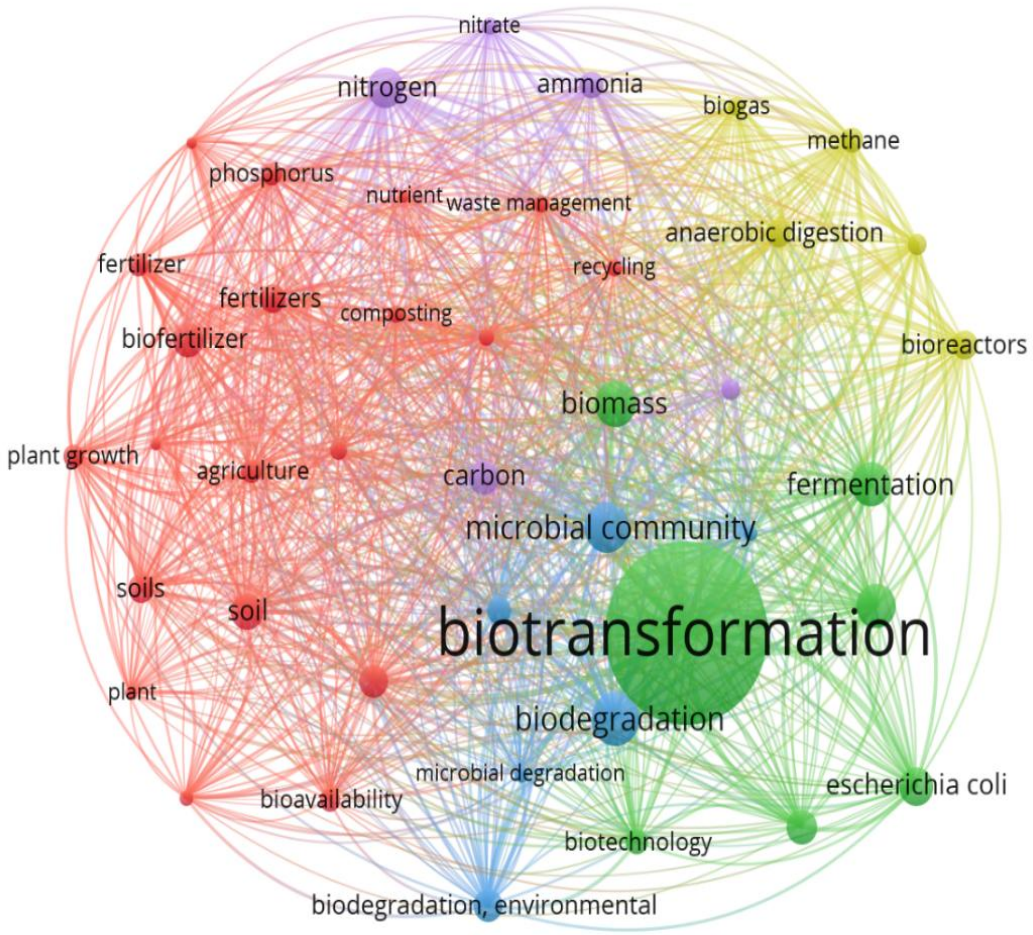

Figure 4. Co-occurrence analysis of author's keyword in VOSviewer.

The co-occurrence map generated through VOSviewer (Figure 4) illustrates the conceptual profile of biofertilizers and biotransformation science with an emphasis on sustainability, microbial processes, and valorization of waste. The dominance by microbial community and biotransformation in the centre highlights the key role of microbial consortia in degrading organics, enhancing soil fertility, and complementing bio-based agricultural input production. Strongly interconnected clusters such as anaerobic digestion, biogas, and methane indicate the relationship of organic waste treatment in the creation of renewable energy and nutrient-intensive digestate to be applied as biofertilizers.

The cluster around *biofertilizer, fertilizers, soil, and plant growth* reflects the agronomic dimension, linking microbial activity and nutrient cycling to improved crop performance and sustainable soil management. The presence of terms such as *nitrogen, phosphorus, and ammonia* further connects the discussion to nutrient use efficiency (NUE) and the optimization of macronutrient cycles, which are critical to reducing losses through leaching and volatilization. Similarly, clusters associated with *biodegradation, biotechnology, and fermentation* point to the biotechnological innovations driving

the field, where microbial engineering and fermentation processes expand the range of usable substrates and enhance the effectiveness of microbial inoculants.

Lastly, related terms concerning recycling, waste management, and environmental biodegradation put biofertilizer science within the broader framework of the circular economy whereby agro-industrial byproducts are upcycled to high-value agricultural products. As a whole, these highly related clusters indicate an integrated research world in which biofertilizers support climate-smart agriculture while reducing application of synthetic fertilizers.

Classification of Biofertilizers

Biofertilizers are inputs which are organic, or which contain living microorganisms, that, on application to seeds or surfaces of plants or in soil, stimulate vegetation growth by raising availability or uptake of macro- and micronutrient elements or enhancing soil health and repletion. Dissimilar to conventional fertilizers, biofertilizers act in perfect consonance with natural processes in the soil and support ecological balance in soil. Biofertilizers are central to sustainable farming because they benefit soil repletion, are efficient in giving nutrition, and reduce a farm's environmental imprint [1].

Biofertilizers are broadly classified into four major categories (Figure 5): microbial, organic, residue-based, and formulated biofertilizers [2].

- Microbial biofertilizers contain beneficial microorganisms that enhance nutrient availability and soil health through biological activity.
- Organic biofertilizers are derived from organic matter such as compost, manure, or plant-based materials, and they enrich the soil with nutrients while improving its structure and microbial activity.
- Residue-based biofertilizers are produced from the valorization of agricultural, agro-industrial, or food residues, offering a circular approach to waste management and soil amendment.
- Formulated biofertilizers are specifically designed products that may combine various biological and organic components, often in stabilized or concentrated forms, to ensure consistent effectiveness and ease of application.

This classification provides a preliminary guideline to select the optimal biofertilizer product according to specific crop needs, types of soils, and environmental goals and aims to stimulate strong and effective farming systems.

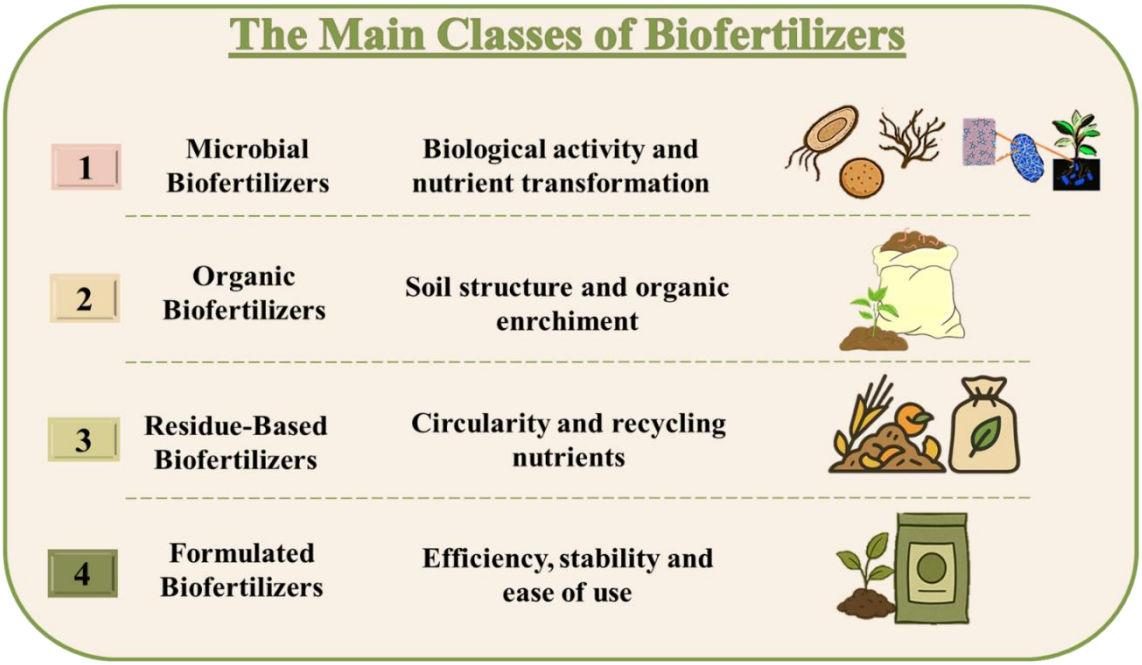

Figure 5. Classification and functions of biofertilizers.

1.Microbial Biofertilizers

Microbial biofertilizers comprise viable, beneficial microorganisms that, when applied to seeds, plant surfaces, or soil, form symbiotic or associative relations with plants. These microorganisms can establish themselves in the rhizosphere, the biologically active zone of soil immediately surrounding the roots of plants, or even in the endophytic sites within plant tissues. After establishing themselves, they enhance uptake by plants to improve their growth and raise soil fertility, especially in degraded or low fertility soils [3].

The use of inoculants in agriculture began in the late 19th century when the first nitrogen-fixing bacterial inoculant, Nitragin, was marketed in 1895 in America. This employed strains of the bacterium genus, Rhizobium, which formed nodules on legume roots and could transform atmospheric nitrogen into substances usable by plants. This opened up the technology of biofertilizers and began several decades of investigation into soil microbiology and plant–microbe interactions [4].

With time, usage of microbial biofertilizers has expanded from mere nitrogen-fixers to include a wide coverage of functional groups of microbes. These include the phosphate-solubilizing fungi and bacteria to release insoluble forms of inorganic phosphorus; potassium-releasing microorganisms to release potassium captured in lattices of minerals; and Plant Growth-Promoting Rhizobacteria (PGPR) to express beneficial effects on plants through diverse processes. New developments have further incorporated beneficial yeasts, cyanobacteria, and microalgae to aid the processes of cycling of nutrients and provide biocontrol and tolerance to stresses [1, 5].

Microbial biofertilizers are effective because they can act through both direct mechanisms, such as nitrogen fixation, nutrient solubilization, and siderophore production and indirect mechanisms, including phytohormone synthesis (e.g., auxins, cytokinins), suppression of phytopathogens through antibiotic production or competitive exclusion, and induction of systemic resistance in plants.

Microbial biofertilizers are especially valuable in sustainable and organic farming systems, where the use of chemical fertilizers is minimized. Their application leads to improved soil structure, enhanced microbial biodiversity, and reduced environmental pollution. Moreover, they play a strategic role in climate-smart agriculture by contributing to carbon sequestration, reduced greenhouse gas emissions, and the circular use of agricultural resources [2].

Nitrogen-fixing Bacteria

Nitrogen-fixers convert atmospheric nitrogen (N_2), an inert form of nitrogen to plants, to ammonia (NH_3), which they can use. This biological nitrogen fixation (BNF) is an eco-friendly replacement of synthetic nitrogenous fertilizers, energy-intensive to make and often pollutant [6].

Scientific knowledge and use of BNF began in the 19th century with the discovery of nitrogen-fixing bacteria such as Azotobacter and the relationship between legumes and the bacterium Rhizobium. Inoculants such as Nitragin made it possible to nourish crops with nitrogen. Since then, nitrogen-fixing microbes have been applied widely and are part of sustainable agriculture [3].

Nitrogen-fixing bacteria can be classified into three main groups based on their mode of action.

- **Symbiotic nitrogen-fixers**: These bacteria form relationships with host plants, typically legumes. The most notable example is the *Rhizobium* genus, which induces root nodules where nitrogen fixation occurs under low-oxygen conditions. Other symbiotic nitrogen-fixers include *Bradyrhizobium*, *Sinorhizobium*, and *Frankia*, the latter associating with non-leguminous plants such as alder and *Casuarina* [7].
- **Free-living nitrogen-fixers**: These microorganisms fix nitrogen independently in the soil or water without a plant host. *Azotobacter* is a well-known aerobic, free-living nitrogen fixer that also produces growth-promoting substances like vitamins and auxins. Other free-living nitrogen-fixers include *Beijerinckia* and anaerobic *Clostridium* species [8].
- **Associative nitrogen-fixers**: These bacteria loosely associate with roots or the rhizosphere of plants, particularly cereals and grasses. *Azospirillum* species are notable for colonizing root surfaces, promoting root growth and nutrient uptake alongside nitrogen fixation, benefiting crops such as maize, rice, and wheat [9].

The efficiency of nitrogen fixation is influenced by environmental factors such as soil pH, moisture, temperature, organic matter, and compatible host presence. Incorporating nitrogen-fixing bacteria into cropping systems reduces reliance on synthetic fertilizers, enhances soil health, fosters microbial diversity, and supports long-term agricultural sustainability [2].

Phosphate- and potassium-solubilizing microorganisms

Phosphate and potassium solubilizing microorganisms stimulate uptake of nutrients by transforming insoluble and otherwise non-available pools of phosphorus and potassium to soluble and plant-usable forms. The microorganisms comprise bacteria and fungi and are exemplified by genera such as *Pseudomonas*, *Bacillus*, *Frateuria*, *Aspergillus*, and *Penicillium* [10]. The microorganisms achieve solubilization of nutrients mainly through the release of organic acids such as gluconic, citric, oxalic, and lactic acids to lower the pH in the rhizosphere and chelate inorganic cations such as calcium, iron, and aluminum. The process de-links the bond holding phosphorus and potassium in insoluble inorganic complexes and release them to the soil solution [11].

Besides the synthesis of organic acids, these microbes release enzymes like phosphatases and potassiumases to catalyze the degradation of organic phosphorus molecules and release potassium held in lattices of minerals, enhancing the availability of nutrients. Certain phosphate-solubilizing microbes even synthesize siderophores to chelate and enhance the uptake of micronutrients and excrete phytohormones to induce root elongation and enlarge the absorptive surface of the plants [12].

From an agronomic standpoint, the use of microorganisms to release phosphate and potassium is a green mechanism aiding in the application of chemicals as fertilizers because these are costly, energy-intensive to produce, and environmentally harmful through eutrophication. By natural improvement in soil nutrient bioavailability, these microorganisms improve fertilizer application efficiency, provide sustainable crop production, and contribute to soil health through the promotion of beneficial microcosms and ameliorative actions on soil structure.

Their integration into biofertilizer formulations and soil amendment strategies is increasingly recognized as a key component of sustainable and precision agriculture, particularly in nutrient-deficient or degraded soils. Continued research aims to optimize their efficacy under varying field conditions and to develop multi-functional microbial consortia that can address multiple nutrient limitations simultaneously.

PGPR (Plant Growth-Promoting Rhizobacteria)

Plant Growth-Promoting Rhizobacteria (PGPR) are a diverse group of beneficial bacteria that colonize plant root surfaces and the surrounding rhizosphere, playing a multifaceted role in enhancing plant growth and health. These microorganisms include well-studied species such as *Bacillus subtilis*, *Pseudomonas fluorescens*, and *Streptomyces* spp., among others [13]. The concept of PGPR emerged

in the late 1970s with pioneering research identifying their ability to suppress soil pathogens and stimulate plant development. PGPR promote plant growth through several direct and indirect mechanisms, with one key function being the production of phytohormones such as auxins (notably indole-3-acetic acid, IAA), cytokinins, and gibberellins. These hormones regulate root architecture by stimulating cell division, elongation, and differentiation, resulting in enhanced root surface area that improves water and nutrient absorption [14].

Additionally, PGPR facilitate nutrient uptake by solubilizing minerals like phosphate and potassium and fixing atmospheric nitrogen [4]. Beyond growth promotion, PGPR contribute to plant defence by suppressing soil-borne pathogens through the secretion of antimicrobial compounds including antibiotics, siderophores which sequester iron and inhibit pathogen growth, hydrogen cyanide, and lytic enzymes that degrade fungal cell walls. This biocontrol activity reduces disease incidence and lessens dependence on chemical pesticides.

Moreover, PGPR improve plant resilience to abiotic stresses such as drought, salinity, and heavy metal toxicity by inducing systemic tolerance responses. They modulate stress-related gene expression and enhance antioxidant enzyme activities, enabling plants to mitigate oxidative damage [15].

PGPR can be applied through various methods including seed inoculation, soil drenching, root dipping, and foliar sprays to ensure effective colonization and activity in the rhizosphere. Scientific studies support their benefits across diverse crops; for instance, *Bacillus subtilis* has enhanced wheat growth and suppressed diseases, *Pseudomonas fluorescens* controlled tomato root rot, and *Streptomyces* species have demonstrated biocontrol potential against fungal pathogens. Field trials with *Azospirillum* showed increased rice yields under nitrogen-limited conditions by promoting root development and nitrogen fixation. The application of PGPR as biofertilizers and biocontrol agents is a sustainable agricultural strategy that boosts crop yield and quality, supports soil health, and enhances environmental safety. Current research focuses on optimizing PGPR formulations, developing microbial consortia, and integrating these microbes into crop management practices to maximize their benefits under diverse agroecosystem conditions [15].

Filamentous fungi and yeasts

Fungal organisms like *Trichoderma, Aspergillus niger, Penicillium spp.*, and *Chaetomium spp.* participate in solubilizing nutrients and in colonization of roots and in pathogen suppression. Yeasts like *Saccharomyces cerevisiae, Candida, and Pichia spp.* are active in the production of growth regulators.

Beneficial fungi and yeasts are established agents to enhance plant shoot and root growth and fertility in soils and are used in agricultural commodity systems for decades in traditional compost and fermentation technology [16].

The *Trichoderma genera* and *Aspergillus niger* are highly studied to solubilize nutrients by degrading macro-organic residues and converting otherwise inert complexes of phosphorus and potassium into plant-uptake forms. The fungi exert effective root colonization to form symbiotic or associative relationships enhancing uptake and inducing growth stimulation in plants. The fungi further provide their services in biocontrol by competitively or antagonistically defeating harmful pathogens using antibiosis, mycoparasitism, and inducing systemic host resistance [17].

Yeasts, including *Saccharomyces cerevisiae*, *Candida*, and *Pichia* spp., contribute to agricultural productivity by synthesizing phytohormones such as auxins and gibberellins, which regulate root development and enhance plant vigour Beyond hormone production, yeasts play a critical role in maintaining soil health by enhancing microbial diversity, participating in organic matter breakdown, and facilitating nutrient cycling. Their fermentative metabolism also contributes to the suppression of soil-borne pathogens by producing bioactive compounds [18].

Applications of these fungi and yeasts as biofertilizers have expanded with advances in biotechnology, leading to commercial formulations used in seed treatments, soil amendments, and foliar sprays. Field studies have demonstrated increased crop yields, improved nutrient use efficiency, and reduced disease incidence following inoculation with *Trichoderma* spp. and yeast-based products [5]. For instance, *Trichoderma* inoculants have been effectively used in crops such as tomatoes, maize, and cereals to enhance growth and resist fungal diseases. Similarly, yeast formulations have improved growth in horticultural and cereal crops under various environmental stresses [19].

The integration of beneficial yeasts and fungi into sustainable crop production systems is continuing, with studies designed to optimize the beneficial impacts on crop production and soil ecosystem sustainability by optimizing consortia of microbes, delivery systems, and synergistic connections with other biofertilizers.

Microalgae and cyanobacteria

Microalgae and cyanobacteria are photosynthetic microorganisms that have long been recognized for their vital contributions to soil fertility and plant growth, with traditional agricultural use dating back centuries in regions where cyanobacteria-rich paddy soils naturally enhanced rice cultivation. Microalgae such as *Chlorella*, *Scenedesmus*, and *Spirulina*, along with cyanobacteria genera like *Anabaena* and *Nostoc*, help maintain sustainable agriculture. They contribute to nitrogen fixation by

converting atmospheric nitrogen into bioavailable forms, which is especially valuable in nitrogen-poor soils. These organisms also produce extracellular polysaccharides that improve soil aggregation and water retention, thereby enhancing soil structure and creating a favorable environment for root development [20].

Microalgae and cyanobacteria also synthesize a wide array of bioactive compounds including vitamins, amino acids, antioxidants, and plant hormones like auxins and cytokinins, which stimulate seed germination, root elongation, and overall plant vigour. Their high growth rates and adaptability to diverse environmental conditions enable cost-effective biomass production, which can be applied as soil amendments, foliar sprays, or incorporated into biofertilizer formulations.

Modes of application include direct inoculation into fields or irrigation systems, coating of seeds, and addition to composts and organic amendments. Experiments in the fields have identified their effectiveness in improving yields of rice, wheat, and maize while reducing the usage of synthetic nitrogenous fertilizers. For example, inoculation with *Anabaena spp.* has been confirmed to improve rice productivity in paddy fields through optimization of nitrogen supply and soil condition [21].

Research continues to optimize cultivation techniques, formulation stability, and synergistic combinations with other beneficial microbes to maximize their agronomic benefits. The use of microalgae and cyanobacteria aligns with global efforts to develop environment-friendly and sustainable agricultural practices by enhancing nutrient cycling, soil quality, and plant resilience.

2. Organic Biofertilizers

Organic biofertilizers are materials of biological origin, rich in **organic matter** and nutrients, which support soil fertility and microbial activity. These include decomposed plant or animal residues and are commonly used in organic agriculture.

- **Compost and vermicompost**: Derived from aerobic decomposition of organic waste, rich in humic substances, beneficial microbes, and nutrients.
- **Animal manure**: Cow, poultry, and goat manure supply macro- and micronutrients and stimulate microbial populations.
- **Green manure**: Leguminous plants (e.g., *Vicia*, *Medicago*, *Symphytum officinale*) grown and incorporated into the soil to add nitrogen and biomass.
- **Bio-slurry**: The solid by-product of anaerobic digestion (before or after composting), useful as an organic fertilizer.

Organic biofertilizers improve soil structure, enhance water-holding capacity, and act as a slow-release nutrient source.

Table 3. Microbial Groups in Biofertilizers and their Agronomic Roles

Microorganism Type	Genus / Species	Primary Function(s)	Target Nutrient(s)/ Effect	References
Nitrogen-fixing Bacteria	*Rhizobium*, *Azotobacter*, *Azospirillum*, *Clostridium*	Biological nitrogen fixation	Nitrogen (N)	[1]
Phosphate-solubilizing Bacteria	*Bacillus*, *Pseudomonas*, *Enterobacter*	Solubilization of inorganic phosphate	Phosphorus (P)	[8]
Phosphate-solubilizing Fungi	*Aspergillus niger*, *Penicillium spp.*, *Chaetomium spp.*	Organic acid production, phosphate release	Phosphorus (P)	[15]
Potassium-mobilizing Bacteria	*Frateuria aurantia*, *Bacillus mucilaginosus*	Mobilization of potassium from silicates	Potassium (K)	[11]
PGPR (Plant Growth-Promoting Rhizobacteria)	*Pseudomonas fluorescens*, *Bacillus subtilis*, *Streptomyces*	Phytohormone production, root stimulation, biocontrol	Growth promotion, stress resistance	[14]
Filamentous Fungi	*Trichoderma spp.*, *Aspergillus spp.*, *Penicillium spp.*	Disease suppression, nutrient cycling, root development	P, organic matter decomposition	[15]
Yeasts	*Saccharomyces cerevisiae*, *Candida spp.*, *Pichia spp.*	Auxin/gibberellin production, microbial balance	Growth regulation, nutrient uptake	[17]
Microalgae	*Chlorella vulgaris*, *Scenedesmus obliquus*, *Spirulina*	Bioactive compounds, stress tolerance	General nutrient enrichment, stress relief	[22]
Cyanobacteria	*Anabaena*, *Nostoc*, *Aulosira*	Nitrogen fixation, soil aggregation	Nitrogen (N), soil structure improvement	[23]
Synthetic Consortia	e.g., *Azospirillum* + *Trichoderma* + *S. cerevisiae*	Multifunctional: N fixation, P solubilization, growth stimulation	Multiple nutrients + stress/disease control	[2]

Organic biofertilizers are natural inputs derived from biological materials rich in organic matter and nutrients, which contribute significantly to soil fertility, microbial activity, and sustainable crop production. These biofertilizers include decomposed plant and animal residues and are widely used in organic and regenerative agriculture. Common types include compost and vermicompost, both

products of aerobic decomposition processes that transform organic waste into humus-rich material teeming with beneficial microbes [24].

Animal manures, such as those from cows, poultry, and goats, are traditional amendments that supply a balanced spectrum of macro- and micronutrients while enhancing microbial diversity in soils [25]. Green manure, often composed of fast-growing leguminous plants like *Vicia* and *Medicago*, is incorporated into the soil to enrich it with nitrogen and organic biomass.

Bio-slurry, a by-product of anaerobic digestion, serves as a nutrient-dense organic fertilizer with added microbial and pathogen control benefits Notably, recent studies by Nadia Boutaleb and colleagues have demonstrated the production of biofertilizers from poultry and fish waste via microbial biotransformation using *Aspergillus niger* and microalgae, offering nutrient-rich formulations effective in crop yield enhancement [26]

In addition to microbial inoculants, non-microbial biostimulants such as protein hydrolysates, humic acids, and seaweed extracts are increasingly recognized for enhancing nutrient uptake efficiency and improving plant resilience under abiotic stress, expanding the toolkit for sustainable agriculture [27].

Beyond nutrient provision, these inputs enhance soil structure, increase porosity and water-holding capacity, and support a thriving soil microbiome. Their gradual decomposition offers a slow-release source of nutrients, minimizing leaching and supporting long-term agroecological health and resilience.

3. Residue-Based Biofertilizers

Residue-based biofertilizers are derived from agro-industrial or municipal waste streams and are part of the circular economy approach to sustainable agriculture. They may contain organic matter, residual nutrients, and active microbial communities.

Residue-based biofertilizers represent a sustainable and innovative approach to nutrient recycling and soil fertility enhancement, emerging from the biological transformation of agricultural, agro-industrial, and organic residues through composting, anaerobic digestion, or fermentation processes [28]. These biofertilizers are typically produced from diverse waste materials such as crop residues (e.g., straw, husks, stalks), fruit and vegetable waste, olive pomace, sugarcane bagasse, beet pulp, molasses, and food or brewery processing by-products, which are rich in organic carbon, essential nutrients, and microbial substrates.

Through microbial activity, these residues are converted into nutrient-rich soil amendments containing stable organic matter, humic substances, and bioavailable macro- and micronutrients. They also host active microbial communities. Digestate, the by-product of anaerobic digestion, is one of the most common forms and is valued for its high ammonium, potassium, and organic carbon

content, contributing to soil fertility and microbial stimulation [29]. Agro-industrial by-products such as molasses serve as fermentable carbon sources that enhance microbial growth. Olive pomace and beet pulp contribute structural organic matter and functional compounds such as polyphenols and fibres that can improve soil texture and stimulate microbial activity.

Enriched composts are specially designed organic amendments inoculated with selectively developed beneficial microorganisms such as fungi in the *Trichoderma* genus, nitrogen-fixing bacteria such as *Azotobacter*, or phosphate-solubilizing bacteria. These beneficial microbes are in synergy within the compost matrix to bring about the degradation of otherwise long-lasting and inert-appearing complexes in an organically available form through enhanced nutrient mineralization. For example, *Trichoderma* spp. are efficient in degrading the lignocellulosic material and are even endowed with biocontrol over soilborne pathogens through their production of antibiotics and enzymes and through ecological niche competition. The incorporation of *Azotobacter* spp. fixes the atmospheric nitrogen so delivering organically available nitrogen enrichment in the compost. Phosphate-solubilizing bacteria release their products in the form of organic acids to convert the insoluble forms of the phosphorus-containing molecules into forms readily accepted by the plants. The combined action of these microorganisms leads to enriched composts to bring about healthier root systems and enhanced uptake efficacy of nutrients and overall enhanced growth and vigour of plants in an array of crops [29].

Similarly, fermented products such as bokashi and compost teas are produced by the controlled fermentation of kitchen residues, rice bran, or herbal drugs by microbial consortia consisting usually of lactic acid bacteria, yeasts, and photosynthetic bacteria. The fermentation processes yield bioactive products rich in enzymes, phytohormones (such as auxins and cytokinins), organic acids, and secondary metabolites stimulating each other to initiate seed germination, root elongation, and shoot elongation. In addition to the delivery of nutrients, these fermented products have been reported to repress soil pathogens by subjecting their growth and propagation to unfavorable conditions and by inducing beneficial populations of microorganisms in the rhizosphere. The application of bokashi and compost teas thus contributes to sustainable management of plant health by combining delivery of nutrients and biological repression of disease using locally available matters of waste [30].

Recent studies have emphasized the role of optimized fungal inoculants and organic formulations in improving microbial enzymatic activity and biomass, particularly in semi-arid and Mediterranean conditions [31], as well as the valorization of olive mill by-products and digestates through composting and co-digestion approaches, improving humification, nutrient bioavailability, and microbial stimulation [26].

Beyond their agronomic value, residue-based biofertilizers play a crucial environmental role by reducing the need for synthetic fertilizers, minimizing nutrient leaching and greenhouse gas emissions, and diverting organic waste from landfills or open-field burning [15]. Their application improves soil structure, water retention, and cation exchange capacity (CEC), particularly in degraded or nutrient-poor soils, while acting as slow-release nutrient sources that align with plant demand and optimize nutrient use efficiency [32]. As integral components of integrated soil fertility management (ISFM) and climate-resilient agriculture, these biofertilizers support the principles of circular bioeconomy by turning waste into high-value resources, contributing to regenerative farming systems, ecological intensification, and long-term soil health restoration.

4. Formulated Biofertilizers

Formulated biofertilizers are advanced commercial products engineered for practical and large-scale agricultural use, focusing on microbial stability, shelf-life, ease of application, and targeted delivery under diverse field conditions. These formulations integrate microbial science and materials engineering to enhance their persistence and efficacy in soil and plant environments. Among the most common are carrier-based biofertilizers, where microbial cultures blend with inert organic or mineral carriers like peat, lignite, charcoal, compost, or vermiculite, typically applied as powders or granules to seeds, soil, or seedlings: an affordable, user-friendly system especially for smallholder farmers [33].

Liquid biofertilizer**s** consist of concentrated microbial cell suspensions in buffered media, often supplemented with glycerol, polymers, or pH stabilizers. Compatible with seed treatments, fertigation, and foliar sprays, they support rapid microbial colonization under favourable conditions [34].

Encapsulated biofertilizers, using matrices such as alginate beads, starch films, or biodegradable polymers, have gained attention for slow-release and protection against desiccation, UV radiation, and adverse soil conditions. For instance, sodium-alginate–gum formulations extended shelf-life and improved maize growth [35]; chitosan-alginate humic-acid capsules releasing NPK and PGPRs showed controlled nutrient delivery over 30 days [36].

Nanotechnology-based biofertilizers and nano-biofertilizers form an emerging next generation, employing nano-carriers, surface-functionalized materials, or nanoparticles to deliver microbial cells, enzymes, or nutrients with precision and controlled release. They exhibit potential in improving root adherence, nutrient use efficiency, stress tolerance, and environmental sustainability and very recent and promising studies developed nanoparticle-coated PGPR for enhanced nutrient uptake and wheat yield [37].

These innovations work well with mechanized systems like drip irrigation and drone applications, uniting lab efficacy and consistent field performance in modern precision agriculture. This provides for predictably good outcomes and thus security for farmers - and thus for consumers.

Mechanisms of Action

Biofertilizers enhance plant growth and soil fertility through a range of biological mechanisms that have direct and indirect interactions between beneficial microorganisms, plant roots, and the surrounding soil environment. Nitrogen-fixing bacteria, such as Rhizobium and Azospirillum, convert atmospheric nitrogen (N_2) into ammonium (NH_4^+), to make this vital nutrient available to plants. Phosphate-solubilizing microorganisms, including Bacillus and Aspergillus niger, release organic acids and enzymes to mobilize insoluble phosphorus compounds in the soil, e.g., on rhizospheric and endophytic bacteria's phosphorus-mobilizing potential [38]. Many microbes produce phytohormones like auxins, gibberellins, and cytokinins. Some strains also modify the rhizosphere by secreting siderophores and volatile organic compounds, improving micronutrient availability and promoting plant resilience. In residue-based biofertilizers, decomposer microorganisms accelerate the breakdown of organic matter, releasing nutrients and enriching soil organic content. These synergistic processes support sustainable nutrient cycling, reduce reliance on chemical fertilizers, and promote environment-friendly agriculture [39].

Biological Nitrogen Fixation

The enzymatic machinery needed to fix atmospheric nitrogen (N_2) in bioavailable forms like ammonium (NH_4^+) is present in some microorganisms, notably *Rhizobium, Azospirillum,* and *Frankia.* This conversion is mediated by the nitrogenase enzyme complex, which operates under anaerobic or microaerophilic conditions to reduce N_2 to NH_3, subsequently assimilated into amino acids and other nitrogenous compounds within plant tissues. This process takes place symbiotically in the specialized root nodules of leguminous plants in the case of *Rhizobium,* where both partners gain from a strictly controlled exchange of nitrogen and carbon [40].

Azospirillum and *Frankia* can establish associative or actinorhizal symbioses, or function as free-living diazotrophs in the rhizosphere, contributing to nitrogen enrichment of non-leguminous crops such as cereals and grasses [41]. Biological nitrogen fixation (BNF) is particularly valuable in low-input or organic farming systems, as it naturally supplements soil nitrogen pools without the environmental drawbacks associated with synthetic fertilizers such as nitrate leaching, greenhouse gas emissions, and soil acidification [42]. By promoting nitrogen self-sufficiency in cropping systems, nitrogen-fixing microbes support sustainable nutrient management, improve soil health over time, and contribute to long-term agricultural productivity.

Phosphate Solubilization and Mobilization

Phosphorus is the second most limiting macronutrient for plant growth after nitrogen, yet a large proportion of soil phosphorus exists in insoluble forms, bound to calcium, iron, or aluminum compounds. Phosphate-solubilizing microorganisms (PSMs), including bacterial genera such as *Bacillus*, *Pseudomonas*, and *Enterobacter*, as well as fungal species like *Aspergillus niger* and *Penicillium*, play a vital role in converting these unavailable forms into soluble orthophosphate ($H_2PO_4^-$, HPO_4^{2-}) that can be readily taken up by plant roots [43]. These microbes secrete a range of low-molecular-weight organic acids including gluconic, citric, lactic, or oxalic acids, which chelate the cations binding the phosphate and lower the pH in the rhizosphere, thereby facilitating mineral dissolution [44]. In addition to acidification, many PSMs also produce phosphatases and phytases, enzymes that hydrolyze organic phosphorus compounds (e.g., phytate) into inorganic phosphate. This dual mechanism of solubilization and mineralization greatly enhances the phosphorus-use efficiency of crops. Moreover, some PSMs improve root growth and root hair development, further increasing the absorptive surface area [45]. Their activity is especially beneficial in phosphorus-deficient or alkaline soils, where chemical fertilizers tend to be rapidly immobilized. By improving phosphorus bioavailability and reducing the need for synthetic phosphate fertilizers whose production is energy-intensive and relies on non-renewable phosphate rock, PSMs contribute to both productivity and sustainability [46].

Production of Phytohormones

In addition to improving nutrient availability, many plant growth-promoting microorganisms (PGPMs) contribute to plant development through the biosynthesis of phytohormones, naturally occurring signaling molecules that regulate key physiological processes [47]. Among the most important microbial-derived phytohormones are auxins (especially indole-3-acetic acid, IAA), gibberellins (GAs), cytokinins, and ethylene modulators [48]. Auxins, produced by genera such as *Azospirillum*, *Pseudomonas*, *Bacillus*, and *Saccharomyces cerevisiae*, play a central role in stimulating root elongation, lateral root formation, and root hair development, thereby enhancing the plant's ability to absorb water and nutrients. Gibberellins, secreted by species like *Azospirillum* and *Rhizobium*, promote stem elongation, seed germination, and flowering, particularly under suboptimal growth conditions [49]. Some microbes also synthesize cytokinins, which delay leaf senescence and promote chlorophyll synthesis and cell division. Certain strains possess 1-aminocyclopropane-1-carboxylate (ACC) deaminase activity, which helps regulate ethylene levels in plants [48]. Ethylene, though essential at low concentrations, can inhibit root growth under stress; thus, microbial

modulation of ethylene through ACC deaminase improves plant tolerance to abiotic stresses such as drought, salinity, or heavy metal exposure. Through the production and regulation of these hormones, biofertilizer microorganisms act as biological stimulants, enhancing root system architecture, improving nutrient uptake efficiency, and supporting plant resilience under variable environmental conditions [47].

Rhizosphere Engineering and Enhanced Nutrient Uptake

The rhizosphere, the narrow zone of soil influenced by root exudates, hosts complex interactions between plant roots and diverse microbial communities that critically affect nutrient availability and plant health. Beneficial microorganisms engineer this environment to enhance nutrient uptake and support plant growth in a sustainable manner [50]. Certain plant growth-promoting rhizobacteria (PGPR) and arbuscular mycorrhizal fungi (AMF) stimulate root system architecture by producing phytohormones such as auxins, cytokinins, and gibberellins. These hormones enhance root elongation, branching, and the development of root hairs, increasing the root surface area and enabling more efficient water and nutrient absorption [51].

Many PGPR produce siderophores, low-molecular-weight compounds with a high affinity for ferric iron (Fe^{3+}), which solubilize and chelate iron from soil minerals, making it available to plants while limiting its accessibility to pathogenic microorganisms. For instance, *Pseudomonas fluorescens* and *Bacillus subtilis* produce siderophores that enhance iron uptake in plants, indirectly suppressing pathogen proliferation in the rhizosphere [52].

Organic acid (e.g., gluconic, oxalic, and citric acid) produced by rhizosphere microorganisms lowers surrounding-root pH to facilitate phosphate and micronutrients such as zinc, manganese, and iron being dissolved from their widespread insoluble forms present in soils [53]. Conversion by biofertilizers of nutrients to a usable form for plants reduces reliance on commercially produced mineral fertilizers. Volatile organic compounds (VOCs) produced by some volatile-assimilating rhizobacteria modify plant hormonal regulation to transform root structure such that nutrient acquisition and water uptake increase with a concomitant systemic disease defence being induced against attacking pathogens through such mechanisms. Preferred microbes effectively recraft the rhizosphere microbiome to support favoured microorganism development over unfavourable pathogens through competitive exclusion, antibiosis, and niche occupation [54]. Beyond stimulating nutrient uptake, such microbiological mediation also works to boost disease suppression and plant resilience to align with goals for sustainable farming.

In summary, rhizosphere engineering by biofertilizers represents a critical mechanism through which plants gain improved access to essential nutrients while maintaining soil health and reducing dependence on chemical fertilizers, building sustainability [51].

Biotransformation and Organic Matter Degradation

In residue-based biofertilizers, the biotransformation of organic materials into simpler, plant-available forms enhances nutrient cycling and soil fertility. This process is mediated by a diverse consortium of microorganisms, including bacteria (*Bacillus*, *Pseudomonas*, *Cellulomonas*), fungi (*Aspergillus*, *Trichoderma*, *Penicillium*), and actinomycetes, which work synergistically to degrade complex organic residues such as lignocellulosic biomass, proteins, and lipids [50].

During biotransformation, these microorganisms secrete a wide range of extracellular enzymes, including cellulases, hemicellulases, ligninases, proteases, and lipases, which facilitate the breakdown of organic polymers into simpler molecules like sugars, amino acids, and fatty acids [55]. These simpler molecules are further mineralized into inorganic forms such as ammonium, nitrate, phosphate, and potassium ions, making them readily available for plant uptake and supporting sustained crop growth.

The degradation of organic matter also contributes to the buildup of soil organic carbon, improving soil structure, aggregation, and water-holding capacity while reducing erosion. Microbial activity during biotransformation also promotes the formation of humic substances, which enhance the cation exchange capacity of soils, further aiding in nutrient retention and reducing the leaching of nutrients [56].

Table 4. Mechanisms of biofertilizer action, key microorganisms, and agronomic benefit

Mechanism	Description	Key Microorganisms	Benefits	References
Biological Nitrogen Fixation	Conversion of atmospheric N_2 to NH_4^+ via nitrogenase under anaerobic/microaerophilic conditions, symbiotic (root nodules) or associative/free-living.	*Rhizobium*, *Azospirillum*, *Frankia*	Provides bioavailable nitrogen, reduces synthetic fertilizer use, improves soil health.	[41]
Phosphate Solubilization & Mobilization	Secretion of organic acids and phosphatases to solubilize insoluble P compounds and mineralize organic P.	*Bacillus*, *Pseudomonas*, *Aspergillus niger*, *Penicillium*	Increases P availability, improves P-use efficiency, reduces chemical P fertilizer reliance.	[44]
Phytohormone Production	Microbial synthesis of auxins (IAA), gibberellins, cytokinins, ACC deaminase activity regulating ethylene.	*Azospirillum*, *Pseudomonas*, *Bacillus*, *Saccharomyces cerevisiae*	Stimulates root growth, enhances nutrient/water uptake, improves stress tolerance.	[48]
Rhizosphere Engineering	Reshaping the rhizosphere via phytohormones, siderophore production, VOCs, organic acid secretion.	*Pseudomonas fluorescens*, *Bacillus subtilis*, AMF	Enhances nutrient uptake (Fe, P, micronutrients), disease suppression, improves plant resilience.	[50]
Biotransformation & Organic Matter Degradation	Microbial enzymatic breakdown of complex residues into simpler nutrients, forming humic substances.	*Bacillus*, *Pseudomonas*, *Cellulomonas*, *Aspergillus*, *Trichoderma*	Enhances nutrient cycling, increases soil organic matter, improves soil structure, aligns with circular bioeconomy.	[57]

Furthermore, certain microorganisms active in biotransformation produce phytohormones (auxins, gibberellins) and siderophores during residue degradation, indirectly stimulating plant growth and improving micronutrient availability (Figure 6). This microbial-driven residue valorization aligns with the principles of circular bioeconomy by transforming agricultural wastes into valuable biofertilizers, reducing pollution and promoting sustainable soil fertility [57].

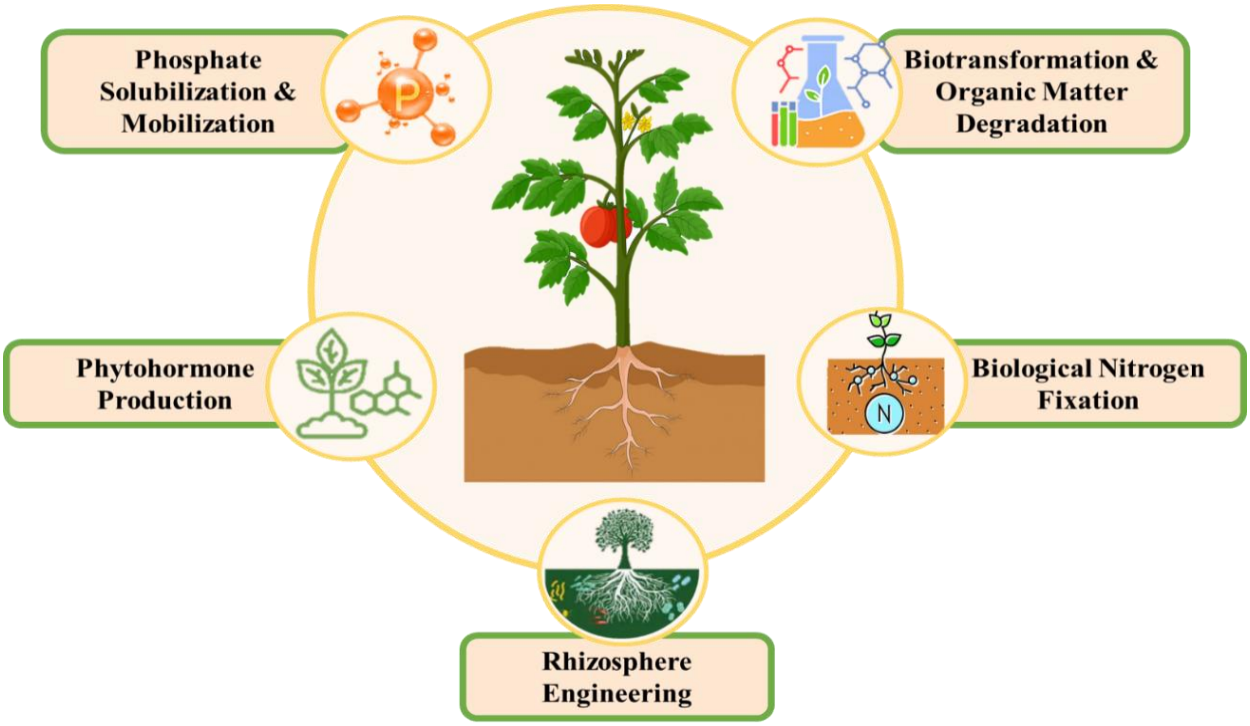

Figure 6. Key mechanisms of plant growth promotion by microbial biofertilizers

Agronomic and Environmental Benefits

Biofertilizers offer multiple advantages over synthetic fertilizers, contributing to agricultural sustainability, environmental protection, and economic resilience. Historically, before the widespread industrialization of agriculture in the mid-20th century, farmers relied heavily on organic manures, compost, and biological interactions in the soil to maintain fertility and productivity. The advent of the Green Revolution in the 1960s brought a surge in the use of chemical fertilizers, significantly increasing crop yields but also leading to soil degradation, water pollution, and greenhouse gas emissions over time [58].

The reintroduction and scientific development of biofertilizers emerged in the late 20th century as a response to these challenges, aiming to reduce the environmental footprint of agriculture while maintaining or improving productivity. Biofertilizers use living microorganisms, such as nitrogen-fixing bacteria (*Rhizobium*, *Azospirillum*), phosphate-solubilizing bacteria (*Bacillus*, *Pseudomonas*), and mycorrhizal fungi, to enhance nutrient availability in the soil through natural processes. This microbial assistance reduces dependency on synthetic nitrogen and phosphorus fertilizers, which are often produced through energy-intensive processes reliant on fossil fuels.

Biofertilizers improve soil fertility by increasing the availability of key nutrients, enriching soil organic matter, and enhancing soil structure and water retention capacity. This leads to healthier root systems and improved plant tolerance to abiotic stresses such as drought and salinity, as well as biotic

stresses like pathogens and pests. By reducing nutrient leaching, biofertilizers help maintain nutrient balance in soils, preventing eutrophication and groundwater contamination [59].

Biofertilizers mitigate the effects of climate change by reducing greenhouse gas emissions associated with the use of synthetic fertilizers. They also support the restoration of degraded soils, promote the biodiversity of soil microbial communities, and enhance the ecological functions of agroecosystems [60]. Economically, the use of biofertilizers can lower production costs for farmers by decreasing the need for expensive chemical fertilizers while improving soil health for sustained long-term productivity. This particularly benefits developing countries. Biofertilizers align with the principles of circular and regenerative agriculture, leveraging local organic resources and microbial inoculants to close nutrient loops within farming systems.

Limitations and Challenges

Despite the vast potential of biofertilizers, their usage is constrained by several limitations to their adoption. Performance-based variability has continued to be a hindrance to their global adoption vis-à-vis synthetic fertilizers. Further, the power of habit (to use the chemical fertilizer which may require serious expenditure in a developing country) may inhibit initiative.

The foremost limitation encompasses the performance of biofertilizers relying on soil physicochemical properties like pH, moisture status, temperature, and nutrient status. For example, nitrogen-fixing bacteria may be less efficient in saline or acidic soils, and phosphate-solubilizing microorganisms may be poor in soils with high phosphate-fixing capacities. Further, suitability with specific crop types and native climatic conditions influences establishment and effectiveness of biofertilizer inoculants [51].

The viability and shelf-life of microbial inoculants is another critical problem. The viability of microorganisms in products used as biofertilizers has been reduced during storage, mainly at non-optimal temperature and humidity regimes. This reduces inoculant performance at application in the farmer’s field and produces inconsistent results. Additionally, inoculants used on soils sometimes fail to establish or compete well in the soil microflora and therefore limit their persistence and their functional contribution to the cycling of nutrients [60].

The lack of standardized formulations and quality control protocols, particularly in developing regions, results in variability in product quality and effectiveness across different batches and manufacturers. This inconsistency can erode farmer confidence, hindering further adoption despite the ecological benefits that biofertilizers offer. Additionally, knowledge gaps and limited extension support pose barriers to effective use. Unlike synthetic fertilizers, the application of biofertilizers

requires an understanding of appropriate timing, methods of inoculation (e.g., seed treatment, soil application, foliar sprays), and the environmental factors influencing microbial activity. The absence of targeted training and support systems for farmers and extension agents often leads to misuse or suboptimal application, further limiting the perceived benefits of biofertilizers [54].

Economic and infrastructural factors also contribute to challenges in scaling biofertilizer use. The production and distribution infrastructure for biofertilizers remain underdeveloped in many regions, affecting availability and accessibility. Moreover, regulatory frameworks governing biofertilizer quality, safety, and efficacy are often lacking or inadequately enforced, allowing low-quality products to enter markets [55].

By tackling these challenges, the potential of biofertilizers as a key component of sustainable agriculture can be fully realized, enabling reduced dependency on synthetic fertilizers while maintaining high agricultural productivity.

Practical Applications and Case Studies

Biofertilizers have been successfully applied in cereals (e.g., rice, wheat, corn), legumes (e.g., soybean, chickpea), and horticultural crops (e.g., tomato, lettuce, pepper) across diverse agroecosystems worldwide. In several field trials, the integrated use of biofertilizers with reduced chemical fertilizer inputs has maintained or even improved yields while reducing environmental impacts and input costs [38].

In cereal systems, biofertilizers such as *Azospirillum* and *Azotobacter* enhance nitrogen uptake and improve plant vigour, supporting sustainable intensification in rice, wheat, and maize systems. For instance, in Morocco's Tadla and Saïss plains, the application of *Azospirillum brasilense* and *Azotobacter chroococcum* in maize (*Zea mays*) has resulted in improved nitrogen uptake, increased root and shoot biomass, and yield increases of 8–12% under semi-arid conditions while supporting soil fertility [56].

In legume systems, rhizobial inoculants have improved biological nitrogen fixation and yield stability, reducing the need for synthetic nitrogen inputs while enhancing soil organic matter and microbial diversity [38].

In horticultural systems, biofertilizers, including arbuscular mycorrhizal fungi and phosphate-solubilizing bacteria, have been applied successfully in crops such as tomatoes (*Solanum lycopersicum*), peppers (*Capsicum annuum*), and lettuce (*Lactuca sativa*). In Morocco's Souss-Massa and Gharb regions, field trials on tomatoes and peppers have demonstrated that the use of arbuscular mycorrhizal fungi in combination with phosphate-solubilizing bacteria (*Bacillus megaterium*) can

enhance phosphorus uptake, improve fruit yield and quality, and increase water use efficiency under semi-arid conditions Notably, a study near Agadir showed that combining biofertilizers with a 25% reduction in chemical phosphate fertilizers led to a 10–15% increase in tomato yields while maintaining soil health and reducing production costs [60].

Promising case studies from India, Brazil, and Morocco demonstrate how localized biofertilizer strategies can enhance food security, reduce production costs, and improve soil health, particularly in regions facing soil degradation and water scarcity challenges [38]. In Morocco, these strategies align with national goals for sustainable agriculture by reducing reliance on imported chemical fertilizers, improving the resilience of agroecosystems, and leveraging local resources within circular bioeconomy frameworks.

Conclusion and the Future

Biofertilizers are a positive tool in achieving sustainable and eco-friendly agriculture through soil fertility accumulation, improvement in nutrient cycling, and decreasing dependency on chemical fertilizers. Their effectiveness in cereals, pulses, and horticultural crops with case examples in Morocco in tomatoes, peppers, and maize highlights their appropriateness to achieve or improve yields while maintaining soil health and reduced production costs, particularly in semi-arid areas.

In spite of these benefits, disadvantages such as performance variability in the field, short shelf life, and the need to generate region-specific formulations still prevent massive adoption. These impediments need multi-level strategies such as creating stress-tolerant and multi-functional microbe strains, sophisticated carrier and encapsulation technologies to enhance viability and delivery, and site-specific training of farmers to achieve effective use.

Future directions include expanding their efficacy and scalability by using microbial consortia where several strains are brought together to exploit their combined effects in a synergistic manner, encapsulation methods to ensure the preservation of microbial viability and to achieve a controlled release, and complementarity with precision agriculture technologies to achieve targeted and efficient application. Genomic, metagenomic, and synthetic biology advances are opening up novel avenues to discover, improve, and design microbial strains with greater plant-growth-promotion characters and stress tolerance to achieve reliable field performance.

The combination of biofertilizers with biopesticides and conditioners could bring multiple answers to problems of nutrient management, pests management, and revival of soil health in the framework of circular and regenerative agriculture. The favourable policies, regulatory climate, and support to

the extension and research are equally important in sustaining product superiority, farmers' satisfaction, and widening the use of biofertilizers.

Biofertilizers can engineer resilient agroecosystems capable of tackling the thorny challenges of agriculture in the present age. This needs strong hands to seize the thorns and go beyond the pain of change.

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References

[1] Santos, F., Melkani, S., Oliveira-Paiva, C., Bini, D., Pavuluri, K., Gatiboni, L., Mahmud, A., Torres, M., McLamore, E., & Bhadha, J.H., 2024, Biofertilizer use in the United States: definition, regulation, and prospects. *Applied Microbiology and Biotechnology* **108**, 511. https://doi.org/10.1007/s00253-024-13347-4

[2] Figiel, S., Rusek, P., Ryszko, U., & Brodowska, M.S., 2025, Microbially Enhanced Biofertilizers: Technologies, Mechanisms of Action, and Agricultural Applications. *Agronomy* **15**, 1191. https://doi.org/10.3390/agronomy15051191

[3] Chaudhary, P., Singh, S., Chaudhary, A., Sharma, A., & Kumar, G., 2022, Overview of biofertilizers in crop production and stress management for sustainable agriculture. *Frontiers in Plant Science* **13**, 930340. https://doi.org/10.3389/fpls.2022.930340

[4] Singh, D., Thapa, S., Geat, N., Mehriya, M.L., & Rajawat, M.V.S., 2021, Chapter 12 - Biofertilizers: Mechanisms and application. In: Rakshit, A., Meena, V.S., Parihar, M., Singh, H.B., Singh, A.K. (Eds.), *Biofertilizers*. (Cambridge: Woodhead Publishing), pp. 151–166. https://doi.org/10.1016/B978-0-12-821667-5.00024-5

[5] Hernández-Fernández, M., Cordero-Bueso, G., Ruiz-Muñoz, M., & Cantoral, J.M., 2021, Culturable Yeasts as Biofertilizers and Biopesticides for a Sustainable Agriculture: A Comprehensive Review. *Plants* **10**, 822. https://doi.org/10.3390/plants10050822

[6] Thomas, L., & Singh, I., 2019, Microbial Biofertilizers: Types and Applications. In: Giri, B., Prasad, R., Wu, Q.-S., Varma, A. (Eds.), Biofertilizers for Sustainable Agriculture and Environment. (Cham: Springer), pp. 1–19. https://doi.org/10.1007/978-3-030-18933-4_1

[7] Abbey, L., Abbey, J., Leke-Aladekoba, A., Iheshiulo, E.M., & Ijenyo, M., 2019, Biopesticides and Biofertilizers: Types, Production, Benefits, and Utilization. In: Simpson, B.K., Aryee, A.N.A., Toldrá, F. (Eds.), *Byproducts from Agriculture and Fisheries*, 1st ed. (Hoboken: Wiley), pp. 479–500. https://doi.org/10.1002/9781119383956.ch20

[8] Chakraborty, T., & Akhtar, N., 2021, Biofertilizers: Characteristic Features and Applications. In: Inamuddin, Ahamed, M.I., Boddula, R., Rezakazemi, M. (Eds.), *Biofertilizers*, 1st ed. (Hoboken: Wiley), pp. 429–489. https://doi.org/10.1002/9781119724995.ch15

[9] du Jardin, P., 2015, Plant biostimulants: Definition, concept, main categories and regulation. *Scientia Horticulturae* **196**, 3–14. https://doi.org/10.1016/j.scienta.2015.09.021

[10] Gupta, R., Singh, H., Sharma, B., & Verma, S., 2018, Isolation and Characterization of Phosphate Solublizing Bacteria from Rhizosphere Soil of Rice in Jammu District, India. *International Journal of Current Microbiology and Applied Sciences* **7**, 2749–2756. https://doi.org/10.20546/ijcmas.2018.706.323

[11] Pandey, K., & Saharan, B.S., 2025, Potassium-solubilizing endophytes: mechanisms and applications in enhancing sustainable agriculture and plant resilience. *Symbiosis* **95**, 291–305. https://doi.org/10.1007/s13199-025-01052-3

[12] Jini, D., Ganga, V.S., Greeshma, M.B., Sivashankar, R., & Thirunavukkarasu, A., 2024, Sustainable agricultural practices using potassium-solubilizing microorganisms (KSMs) in coastal regions: a critical review on the challenges and opportunities. *Environment, Development and Sustainability* **26**, 13641–13664. https://doi.org/10.1007/s10668-023-03199-9

[13] de Andrade, L.A., Santos, C.H.B., Frezarin, E.T., Sales, L.R., & Rigobelo, E.C., 2023, Plant Growth-Promoting Rhizobacteria for Sustainable Agricultural Production. *Microorganisms* **11**, 1088. https://doi.org/10.3390/microorganisms11041088

[14] Ranjan, A., Rajput, V.D., Prazdnova, E.V., Gurnani, M., Sharma, S., Bhardwaj, P., Shende, S.S., Mandzhieva, S.S., Sushkova, S., Minkina, T., Chauhan, A., Jindal, T., Prasad, R., & Wong, M.H., 2024, Augmenting abiotic stress tolerance and root architecture: The function of phytohormone-producing PGPR and their interaction with nanoparticles. *South African Journal of Botany* **167**, 612–629. https://doi.org/10.1016/j.sajb.2024.02.041

[15] Kumar, D., Singh, P.N., Willer, H., Sharma, S.K., Singh, U.B., Lagashetti, A.C., & Husain, R., 2023, Fungal Biofertilizers and Biopesticides and Their Roles in Sustainable Agriculture. In: *Applied Mycology for Agriculture and Foods*. (Palm Bay: Apple Academic Press). https://doi.org/10.1201/9781003369868-9

[16] Devi, R., Kaur, T., Kour, D., Rana, K.L., Yadav, A., & Yadav, A.N., 2020, Beneficial fungal communities from different habitats and their roles in plant growth promotion and soil health. *Microbial Biosystems* **5**, 21–47. https://doi.org/10.21608/mb.2020.32802.1016

[17] Nimsi, K.A., Manjusha, K., Kathiresan, K., & Arya, H., 2023, Plant growth-promoting yeasts (PGPY), the latest entrant for use in sustainable agriculture: a review. *Journal of Applied Microbiology* **134**, lxac088. https://doi.org/10.1093/jambio/lxac088

[18] Ramos-Garza, J., Aguirre-Noyola, J. L., Bustamante-Brito, R., Zelaya-Molina, L. X., Maldonado-Hernández, J., Morales-Estrada, A. I., Resendiz-Venado, Z., Palacios-Olvera, J., Angeles-Gallegos, T., Terreros-Moysen, P., Cortés-Carvajal, M., & Martínez-Romero, E. (2023). *Mycobiota of Mexican Maize Landraces with Auxin-Producing Yeasts That Improve Plant Growth and Root Development*. *Plants*, **12**(6), 1328. https://doi.org/10.3390/plants12061328

[19] Ramakrishnan, B., Maddela, N.R., Venkateswarlu, K., & Megharaj, M., 2023, Potential of microalgae and cyanobacteria to improve soil health and agricultural productivity: a critical view. *Environmental Science: Advances* **2**, 586–611. https://doi.org/10.1039/D2VA00158F

[20] Abinandan, S., Subashchandrabose, S.R., Venkateswarlu, K., & Megharaj, M., 2019, Soil microalgae and cyanobacteria: the biotechnological potential in the maintenance of soil fertility and health. *Critical Reviews in Biotechnology* **39**, 981–998. https://doi.org/10.1080/07388551.2019.1654972

[21] Fernandes, F., 2022, Microalgae Cultivation on Nutrient Rich Digestate: The Importance of Strain and Digestate Tailoring under pH Control. *Applied Sciences* **12**, 5429. https://doi.org/10.3390/app12115429

[22] Paul, T., & Mandi, H., 2024, Management of organic farming through natural assets of nutrients. In S. Brahma, V. Upadhyay, R. K. Nath, R. Sarma, & E. P. Devi (Eds.), Advances in organic farming: Crop production and management (1st ed., pp. 27–xx). (New York: Apple Academic Press). https://doi.org/10.1201/9781003502715

[23] Chaudhari, S., Upadhyay, A., & Kulshreshtha, S., 2021. Influence of Organic Amendments on Soil Properties, Microflora and Plant Growth. In: Lichtfouse, E. (Ed.), Sustainable Agriculture Reviews**.** (Cham: Springer), pp. 147–191. https://doi.org/10.1007/978-3-030-73245-5_5

[24] Foughal, T., Doublali, F.E., Ozi, F.Z., Hadidi, M., Louanjli, F.A., Bahlaouan, B., El Antri, S., & Boutaleb, N., 2024, Biofertilization potential of products from biotransformation of organic waste in Morocco: comparing between aerobic and anaerobic mode. *Biomass Conversion and Biorefinery* **14**, 21729–21739. https://doi.org/10.1007/s13399-023-04467-4

[25] Jmaili, K., Asbai, Z., Waddi, K., Bahlaouan, B., Silkina, A., & Boutaleb, N., 2025, Non-microbial biostimulants for plant growth and abiotic stress mitigation: a review of recent scientific innovations. *International Journal of Environmental Studies* **82**, 401–431. https://doi.org/10.1080/00207233.2025.2457867

[26] Roy, D., Sinha, A.K., Rakesh, S., Rao, K.K., Sahoo, S., Bhattacharya, P.M., Mitra, B., Mukhopadhyay, P., & Padbhushan, R., 2025. Addition of biofertilizers with crop residue in conservation agriculture improves soil carbon sequestration: a long-term field study. *Tropical Ecology* **66**, 119–131. https://doi.org/10.1007/s42965-025-00376-x

[27] Feng, F., Jiang, B., Yan, B., Li, J., & Shaik, F., 2025, Optimization of Biofertilizers Derived from Vinegar Residues to Improve Soil Quality and Alleviate Salinization of the Land under Wheat Cultivation. *Waste and Biomass Valorization* **16**, 1115–1133. https://doi.org/10.1007/s12649-024-02712-z

[28] Asbai, Z., El Amrani, M., Bahlaouan, B., Silkina, A., & Boutaleb, N., 2024, Sustainable approach for nutrient release control in organic fertilisers by using phosphogypsum. *International Journal of Environmental Studies* **81**, 808–825. https://doi.org/10.1080/00207233.2024.2322882

[29] Brindhadevi, K., Chinnathambi, A., & Al Obaid, S., 2024, An investigation on the conversion of infertile soil into fertile soil using crop waste as a remedial (compost) approach and its influence on Vigna mungo biometric and biomolecule profile. *Environmental Research* **258**, 119351. https://doi.org/10.1016/j.envres.2024.119351

[30] Dhull, P., Lohchab, R.K., Kumar, S., Kumari, M., Shaloo, & Bhankhar, A.K., 2024, Anaerobic Digestion: Advance Techniques for Enhanced Biomethane/Biogas Production as a Source of Renewable Energy. *BioEnergy Research* **17**, 1228–1249. https://doi.org/10.1007/s12155-023-10621-7

[31] Patel, C., Singh, J., Karunakaran, A., & Ramakrishna, W., 2023, Evolution of Nano-Biofertilizer as a Green Technology for Agriculture. *Agriculture* **13**, 1865. https://doi.org/10.3390/agriculture13101865

[32] Hamed, R., Jodeh, S., & Alkowni, R., 2024, Nano bio fertilizer capsules for sustainable agriculture. *Scientific Reports* **14**, 13646. https://doi.org/10.1038/s41598-024-62973-5

[33] Arora, P.K., Tripathi, S., Omar, R.A., Chauhan, P., Sinhal, V.K., Singh, A., Srivastava, A., Garg, S.K., & Singh, V.P., 2024, Next-generation fertilizers: The impact of bionanofertilizers on sustainable agriculture. *Microbial Cell Factories* **23**(1), 254. https://doi.org/10.1186/s12934-024-02528-5

[34] Rabani, M.S., Dar, G.H., Bhat, R.A., & Mehmood, M.A., 2023, Introduction of biofertilizers in agriculture with emphasis on nitrogen fixers and phosphate solubilizers. In: Dar, G.H., Bhat, R.A., Mehmood, M.A. (Eds.), Microbiomes for the Management of Agricultural Sustainability. (Cham: Springer Nature Switzerland), pp. 71–93. https://doi.org/10.1007/978-3-031-32967-8_4

[35] Alzate Zuluaga, M.Y., Fattorini, R., Cesco, S., & Pii, Y., 2024, Plant-microbe interactions in the rhizosphere for smarter and more sustainable crop fertilization: the case of PGPR-based biofertilizers. *Frontiers in Microbiology* **15**, 1440978. https://doi.org/10.3389/fmicb.2024.1440978

[36] Jehani, M.D., Singh, S., Archana T.S., Kumar, D., & Kumar, G., 2023. Azospirillum—a free-living nitrogen-fixing bacterium. In: Parray, J.A., Shameem, N., Egamberdieva, D., Sayyed, R.Z. (Eds.), *Rhizobiome, Microbiome Research in Plants and Soil*. (Cambridge, MA: Academic Press), pp. 285–308. https://doi.org/10.1016/B978-0-443-16030-1.00001-8

[37] Alomari, S., Hasan, R., Nazar Al-najim, A., & Saadi, A., 2024, Nitrogen-fixing bacteria and their applications in the environment: a review. *International Journal of Medical Body Health Research* **5**, 178–187. https://doi.org/10.54660/IJMBHR.2024.5.4.178-187

[38] Jehani, M.D., Singh, S., Archana T.S., Kumar, D., & Kumar, G., 2023, Azospirillum—a free-living nitrogen-fixing bacterium. In: Parray, J.A., Shameem, N., Egamberdieva, D., Sayyed, R.Z. (Eds.), *Rhizobiome, Microbiome Research in Plants and Soil*. (Cambridge, MA: Academic Press), pp. 285–308. https://doi.org/10.1016/B978-0-443-16030-1.00001-8

[39] Sarmah, R., & Sarma, A.K., 2023, Phosphate solubilizing microorganisms: a review. *Communications in Soil Science and Plant Analysis* **54**(10), 1306–1315. https://doi.org/10.1080/00103624.2022.2142238

[40] Ahmad, A., Moin, S.F., Liaqat, I., Saleem, S., Muhammad, F., Mujahid, T.Y., & Zafar, U., 2023, Isolation, solubilization of inorganic phosphate, and production of organic acids by

individual and co-inoculated microorganisms. *Geomicrobiology Journal* **40**, 111-121. https://doi.org/10.1080/01490451.2022.2124329

[41] Gurbanov, R., Kalkanci, B., Karadag, H., & Samgane, G., 2021, Phosphorus solubilizing microorganisms. In: Inamuddin, Ahamed, M.I., Boddula, R., Rezakazemi, M. (Eds.), *Biofertilizers*. (Hoboken: Wiley), pp. 151–182. https://doi.org/10.1002/9781119724995.ch5

[42] Aberathna, A. A. A. U., Satharasinghe, D. A., Jayasooriya, A. P., Jinadasa, R. N., Manopriya, S., & Jayaweera., 2022, Increasing the bioavailability of phosphate by using microorganisms. *International Journal of Agronomy*, **2022**. https://doi.org/10.1155/2022/4305501

[43] Oyedele, A.O., Ezaka, E., & Taiwo, L.B., 2024, Microbial biosynthesis of the classical phytohormones by plant growth-promoting microorganisms in plants. In: Chauhan, P.S., Bisht, N., Agarwal, R. (Eds.), *Microbial Biostimulants for Plant Growth and Abiotic Stress Amelioration*, Biostimulants and Protective Biochemical Agents. (Amsterdam: Elsevier), pp. 345–366. https://doi.org/10.1016/B978-0-443-13318-3.00004-5

[44] Kejela, T., 2024, Phytohormone-producing rhizobacteria and their role in plant growth. In: *New Insights into Phytohormones*. (London: IntechOpen). https://doi.org/10.5772/intechopen.1002823

[45] Orozco-Mosqueda, M.C., Santoyo, G., & Glick, B.R., 2023, Recent advances in the bacterial phytohormone modulation of plant growth. *Plants* **12**(3), 606. https://doi.org/10.3390/plants12030606

[46] Valente, I.L., Wancura, J.H.C., Zabot, G.L., Mazutti, M.A., 2025, Endophytic and rhizospheric microorganisms: an alternative for sustainable, organic, and regenerative bioinput formulations for modern agriculture. *Microorganisms* **13**(4), 813. https://doi.org/10.3390/microorganisms13040813

[47] Chaffai, R., Ganesan, M., & Cherif, A., 2024, Plant growth-promoting rhizobacteria (PGPR) and plant growth-promoting fungi (PGPF) for alleviating abiotic stress in plants. In: Chaffai, R., Ganesan, M., Cherif, A. (Eds.), *Plant Adaptation to Abiotic Stress: From Signaling Pathways and Microbiomes to Molecular Mechanisms*. (Singapore: Springer Nature), pp. 457–496. https://doi.org/10.1007/978-981-97-0672-3_17

[48] Chen, Q., Song, Y., An, Y., Lu, Y., & Zhong, G., 2024, Mechanisms and impact of rhizosphere microbial metabolites on crop health, traits, functional components: a comprehensive review. *Molecules* **29**(24), 5922. https://doi.org/10.3390/molecules29245922

[49] Maheshwari, H.S., Agnihotri, R., Bharti, A., Chourasiya, D., Laad, P., Dukare, A., Prabina, B.J., Sharma, M.P., & Sharma, S.K., 2020, Signaling in the rhizosphere for better plant and soil health. In: Sharma, S.K., Singh, U.B., Sahu, P.K., Singh, H.V., Sharma, P.K. (Eds.), Rhizosphere Microbes: Soil and Plant Functions. (Singapore: Springer), pp. 149–173. https://doi.org/10.1007/978-981-15-9154-9_6

[50] Patowary, R., & Kaur, A., 2024, Potential application of microbial metabolites for sustainable agriculture and waste management. In: Verma, P. (Ed.), *Industrial Microbiology and Biotechnology: A New Horizon of the Microbial World*. (Singapore: Springer Nature), pp. 489–508. https://doi.org/10.1007/978-981-97-6270-5_16

[51] Parmar, P., Kumar, R., Neha, Y., & Srivatsan, V., 2023, Microalgae as next generation plant growth additives: functions, applications, challenges and circular bioeconomy based solutions. *Frontiers in Plant Science* **14**, 1073546. https://doi.org/10.3389/fpls.2023.1073546

[52] Renganathan, P., Gaysina, L.A., Holguín-Peña, R.J., Sainz-Hernández, J.C., Ortega-García, J., & Rueda-Puente, E.O., 2024, Phycoremediated microalgae and cyanobacteria biomass as biofertilizer for sustainable agriculture: a holistic biorefinery approach to promote circular bioeconomy. *Biomass* **4**(4), 59. https://doi.org/10.3390/biomass4040059

[53] Mahmoudi, M., Asbai, Z., Jmaili, K., Lahrairi, M., Bahlaouan, B., & Boutaleb, N., 2025, Waste-to-resilience: energy, soil fertility, and sustainability through anaerobic biotransformation. *International Journal of Environmental Studies*, 1–24. https://doi.org/10.1080/00207233.2025.2550922

[54] Wendimu, A., Yoseph, T., & Ayalew, T., 2023, Ditching phosphatic fertilizers for phosphate-solubilizing biofertilizers: a step towards sustainable agriculture and environmental health. *Sustainability* **15**(2), 1713. https://doi.org/10.3390/su15021713

[55] Sreethu, S., Chhabra, V., Kaur, G., & Ali, B., 2024, Biofertilizers as a greener alternative for increasing soil fertility and improving food security under climate change condition. *Communications in Soil Science and Plant Analysis* **55**(2), 261–285. https://doi.org/10.1080/00103624.2023.2265945

[56] Díaz-Rodríguez, A.M., Parra Cota, F.I., Cira Chávez, L.A., García Ortega, L.F., Estrada Alvarado, M.I., Santoyo, G., & de los Santos-Villalobos, S., 2025, Microbial inoculants in sustainable agriculture: advancements, challenges, and future directions. *Plants*, **14** (2), Article 191. https://doi.org/10.3390/plants14020191

[57] Hossain, M.A., Hossain, M.S., & Akter, M., 2023, Challenges faced by plant growth-promoting bacteria in field-level applications and suggestions to overcome the barriers. *Physiological and Molecular Plant Pathology* **126**, 102029. https://doi.org/10.1016/j.pmpp.2023.102029

[58] Ghorui, M., Chowdhury, S., & Burla, S., 2025, Recent advances in the commercial formulation of arbuscular mycorrhizal inoculants. *Frontiers in Industrial Microbiology* **3**, 1553472. https://doi.org/10.3389/finmi.2025.1553472

[59] García de Salamone, I.E., Esquivel-Cote, R., Hernández-Melchor, & D.J., Alarcón, A., 2019, Manufacturing and quality control of inoculants from the paradigm of circular agriculture. In: Singh, D.P., Gupta, V.K., Prabha, R. (Eds.), *Microbial Interventions in Agriculture and Environment: Volume 2: Rhizosphere, Microbiome and Agro-ecology*. (Singapore: Springer Nature), pp. 37–74. https://doi.org/10.1007/978-981-13-8383-0_2

[60] Jmaili, K., Bahlaouan, B., Silkina, A., Lahrairi, M., & Boutaleb, N., 2025, Functional dynamics of plant growth-promoting bacteria (PGPB) in adaptation to abiotic stress and enhancement of crop productivity. *Nature, Built Society and Environmental Health* **1**(3), 125–157. https://doi.org/10.63095/nbseh.25.103623

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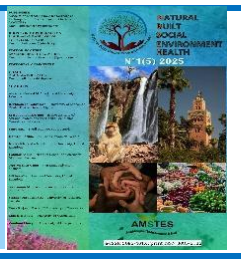


Snail Shells as Circular Biofilm Carriers for the Continuous Treatment of Real Cooperative Dairy Effluent: Performance and Biofilm Age Effect

Amal Aitcheikh [1a], Meriem Mahmoudi [1b], Ikrame Charef [1c], FatimaZahra Boutaleb [1d], Bouchaib Bahlaouan [2e], Mohamed Bennani [3f], Said El Antri [1g], & Nadia Boutaleb [1h] ☑

[1] *Hassan II University of Casablanca (https://ror.org/001q4kn48), Laboratory of Biotechnology, Agri-Food, Materials and Environment, Team: Biotechnologies, Resource Valorization, Quality, Health and Ecotoxicology, Faculty of Science and Technology Mohammedia, BP 146, Mohammedia 20650, Morocco*

[2] *Higher Institutes of the Nursing Professions and Techniques of Health (ISPITS) (https://ror.org/007h8y788), Laboratory of Care, Health and Sustainable Development 2S2D, Casablanca 22500, Morocco*

[3] *Institut Pasteur Casablanca Morocco, Laboratory of Physico-Chemical Analysis of Water, Food and Environment, Casablanca 20250, Morocco*

[a] ***ORCID:*** *0009-0006-4058-9288;* ***Email:*** *aitcheikh.amal@gmail.com*

[b] ***ORCID:*** *0009-0002-2682-2478;* ***Email:*** *meriem.mahmoudi2-etu@etu.univh2c.ma*

[c] ***ORCID:*** *0009-0004-4591-8269;* ***Email****: ikramegp2017@gmail.com*

[d] ***ORCID:*** *0000-0002-1996-8607;* ***Email****: Fatima.boutaleb2-etu@etu.univh2c.ma*

[e] ***ORCID****: 0000-0002-0976-1274;* ***Email****: b.bahlaouan@ispitscasa.ac.ma*

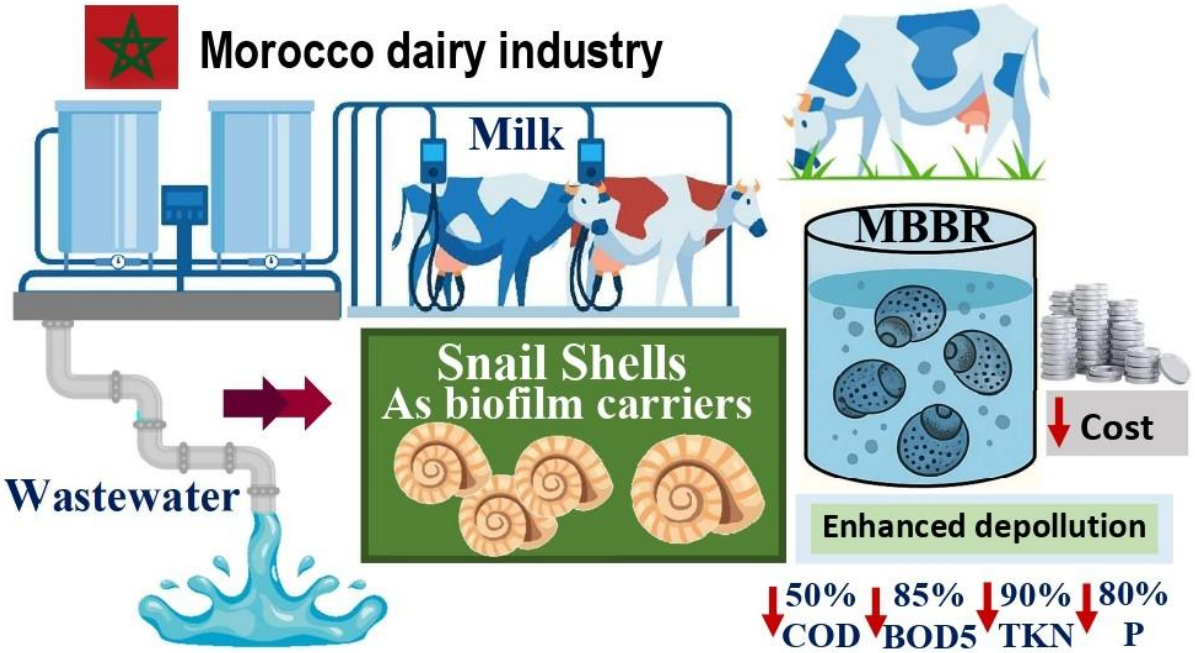
[f] ***ORCID:*** *0000-0002-1749-6095;* ***Email****: bennani2200@gmail.com*

[g] ***ORCID:*** *0000-0003-3534-2476;* ***Email****: said.elantri@fstm.ac.ma*

[h] ***ORCID****: 0000-0003-1628-4311;* ***Email****: nadia.boutaleb@fstm.ac.ma*

☑ ***Corresponding author:*** Nadia Boutaleb; ***Email***: nadia.boutaleb@fstm.ac.ma

This study illustrates a circular and low-cost approach for dairy wastewater treatment in Morocco using snail shells as natural biofilm carriers in an MBBR system. The diagram compares snail shells with industrial Kaldnes K3, both colonized by *Aspergillus niger*. Snail shells achieved superior removal rates for COD (92.9%), BOD_5 (84.75%), TKN (88.7%) and phosphorus (82.9%), with a faster start-up time. The visual highlights the transition from untreated effluent to purified water, emphasizing the environmental and operational advantages of reusing organic waste in decentralized treatment systems.



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Abstract: The rapid growth of Morocco's dairy sector has led to the discharge of high-strength effluents, particularly from cleaning and cooling operations. In the face of water scarcity and limited access to conventional infrastructure, this study proposes a novel, plastic-free treatment strategy using snail shells as circular biofilm carriers in a moving bed biofilm reactor (MBBR). Real effluent was collected directly from a cooperative dairy outlet and treated under continuous flow conditions. The system was inoculated with *Aspergillus niger*, a filamentous fungus known for its biofilm-forming ability. Snail shells achieved higher pollutant removal rates than industrial Kaldnes K3 carriers: 92.9% COD, 84.75% BOD_5, 88.7% TKN and 82.9% total phosphorus within 72 hours of biofilm maturation. Their porous and hydrophilic surface supported faster colonization (16 h start-up) and improved biofilm stability. This is the first study to evaluate the effect of biofilm age and shell surface characteristics in the continuous treatment of real dairy wastewater using natural carriers. In addition to reducing reliance on synthetic polymers, this low-cost approach promotes biodegradability, circular resource use, and enhanced ecological performance. These findings support the replacement of plastic media with nature-based alternatives in decentralized wastewater treatment systems.

Keywords: Biofilm, Carriers, Natural, Dairy, Wastewater, Treatment.

1. Introduction

The development of Morocco's dairy sector, initiated in 1975 with the implementation of the first National Dairy Plan, is a prominent example of agricultural modernization in the country. Through sustained investment across all stages of the supply chain—from on-farm production to industrial processing—Morocco was able to meet approximately 89% of its domestic milk demand by 2010 [1]. Although projections under the Green Morocco Plan aimed to double national milk output and reach five million tonnes by 2020, climatic and structural constraints, such as water stress and fragmented production, have impeded full self-sufficiency [2]. Nevertheless, the sector has contributed significantly to rural employment—supporting over 700,000 smallholder farms—and generated substantial economic value shared between producers, cooperatives, and industrial actors [2].

Yet there has been a significant environmental cost: liquid effluents discharged by dairy processing plants. Each litre of processed milk produces several litres of wastewater, highly loaded with organic matter, nitrogen, phosphorus and pathogenic micro-organisms, with fluctuating flow rates and unstable composition. These discharges originate from product losses, cleaning and cooling operations, salting procedures, and the use of chemical agents for equipment maintenance (notably nitric and phosphoric acids) [3,4]. This complex and variable pollutant mixture presents a serious treatment challenge in a country facing chronic water stress, *where less than 5%* of industrial wastewater undergoes proper treatment [5].

The summary table (Table 1) shows that the main sources of pollution do not stem from the core milk processing steps but rather from auxiliary operations such as cleaning, disinfection, cooling, and steam generation. These processes can account for up to 40% of total water consumption, with volumes sometimes reaching 10 L of water per litre of milk processed [6–10]. Although these practices are essential to maintain hygiene, they produce effluents with high loads of BOD, COD, fats, suspended solids, and chemical agents, often displaying extreme physico-chemical characteristics. Cooling water, though less contaminated, remains abundant. In contrast, core processing stages such as pasteurization, cheese, or butter production contribute to pollution in more moderate proportions. This detailed mapping of water use and effluent generation points to the urgent need for targeted, resource-efficient, and sustainable treatment solutions. These must be adapted to flow variability and aligned with circular valorization principles.

Table 1. Major sources of water consumption and effluent generation in the dairy industry

Source / Process	Water consumption (L per L of milk)	Effluent characteristics	Remarks
Milk, yoghurt, cheese, and butter production	1.3 – 3.2	Low to moderate	Main processing stages
Auxiliary operations (cleaning, disinfection, etc.)	Up to 10	Very high (BOD, COD, organic matter, solids)	Major pollution sources; account for 25–40% of total water use
Butter production	1 – 3	Presence of buttermilk and fats	Moderate pollution depending on specific processes
Cheese production	2 – 4	Brine, starters, organic matter	Saline and fermented effluents
Drinking milk (pasteurization, sterilisation)	2.5 – 9	High organic load	Responsible for episodic pollution peaks
Internal cleaning	0.5 – 1.5	Extreme pH, fats, suspended solids	Highly loaded and unstable effluents
Internal cooling	2 – 4	Variable temperature, conductivity	High-volume effluents with relatively low pollution

Fixed-biomass biological systems represent a strategic alternative. They are less expensive and more environmentally friendly than physico-chemical treatments, and enable the mineralization of biodegradable pollutants without generating secondary pollution [6]. The Moving Bed Biofilm Reactor (MBBR) is among the most effective of these systems. It is robust, adapts well to load fluctuations, and generates limited sludge [11].

The efficiency of this process depends on one key element: the biofilm carrier. The most widely used option, Kaldnes K3, is synthetic, costly, and non-biodegradable. This study explores a circular and sustainable alternative: repurposing a local, abundant, and underused natural residue—snail shells—as biofilm support [12,13].

Snail shells (Theba pisana) offer several intrinsic advantages:

- High specific surface area, supporting bacterial growth [14],
- Porous and hydrophilic structure, promoting biomass adhesion [15],
- Suitable density for fluidization in aqueous media [12],
- Calcareous composition, aiding in pH buffering [16]

This approach follows a "better with less" treatment logic, structured around four core principles:

- **Lower cost**: Snail shells are free or low-cost food waste, unlike industrial carriers.
- **Lower environmental impact**: They eliminate the use of plastics, reduce carbon footprint, and add value to a local by-product.
- **Lower energy and maintenance**: Their natural structure supports rapid colonization, shortening reactor start-up time.
- **Lower sludge production**: High pollutant removal is achieved with reduced accumulation of by-products.

The study follows a rigorous protocol combining real dairy effluent, a continuous-flow MBBR system, and two types of biofilm carriers: industrial-grade Kaldnes K3 and snail shells. The fungal strain *Aspergillus niger* was selected for its strong adhesion, resilience in complex media, and well-documented purification performance [17]. Monitored parameters include COD, BOD_5, TKN, total phosphorus, and TSS, assessed over biomass ages of up to 72 hours.

The expected outcomes will clarify:

- The technical feasibility of using snail shells as biofilm carriers,
- Their comparative efficiency against a standard industrial medium,
- The optimal removal conditions in relation to biomass age,
- The potential for recycling a natural waste product within a circular economy framework.

This work supports water efficiency, industrial ecology, and environmental transition by offering a local, sustainable, and effective solution to accompany the growth of Morocco's dairy sector without jeopardizing natural resources.

2. Materials and Methods

The dairy industry is a major contributor to organic pollution, producing wastewater with high concentrations of biodegradable organic matter, mainly through losses of milk constituents during processing and cleaning operations. The chemical oxygen demand (COD) of such effluents can reach several tonnes annually per production site, reflecting the substantial environmental burden associated with uncontrolled discharge [18]. Among the available treatment strategies, biological processes have been widely adopted for their cost-effectiveness, operational simplicity, and capacity to degrade complex organic compounds. These methods—particularly those based on activated sludge and biofilm systems—remain the most suitable for

treating dairy effluents under both centralized and decentralized conditions [19]. This experimental study evaluates the performance of snail shells as natural biofilm carriers in a moving bed biofilm reactor (MBBR) applied to the semi-continuous treatment of real dairy effluent. The effluent was collected directly from the main outlet valve of a cooperative dairy unit and introduced into the bioreactor without prior storage or dilution, thereby preserving its original composition and potential biocontaminants.

The system was operated at an optimized feeding rate of 5 litres every 6 hours, based on findings from preliminary batch-mode trials conducted by Aitcheikh *et al.* [7]. The objective was to investigate the influence of biofilm age on the removal efficiency of organic matter, while ensuring continual monitoring of treatment performance under realistic, decentralized operating conditions.

2.1. Microorganism Used

The filamentous fungus *Aspergillus niger* (strain 11G323A) was selected as the active biomass because of its strong colonization capacity, high resistance to stress conditions (acidity, alkalis, detergents, phenolic compounds), and efficiency in degrading high organic loads, particularly in dairy effluents [8,10,20]. The fungal inoculum also helps to reduce sludge production and improves biodegradation of compounds that are poorly or not assimilated by the native microbial community [21]. The culture was prepared in the laboratory using liquid LB medium, incubated at 27 °C for three days, harvested by centrifugation (4800 g, 20 min), and introduced into the bioreactor together with the effluent under gentle stirring [8,9].

2.2. Natural Supports Used

Snail shells from the species *Theba pisana* (family: Helicidae) were selected as natural biofilm carriers (Figure 1). This species produces a white globular shell measuring 12–25 mm in diameter. The shells were washed with hot water, rinsed with distilled water, sun-dried, and perforated (1 mm diameter) to ensure internal flow of the effluent. Organic carriers such as snail shells provide a high density of functional groups (carboxyl, hydroxyl, amine), which promote microbial adhesion and biofilm formation [7].

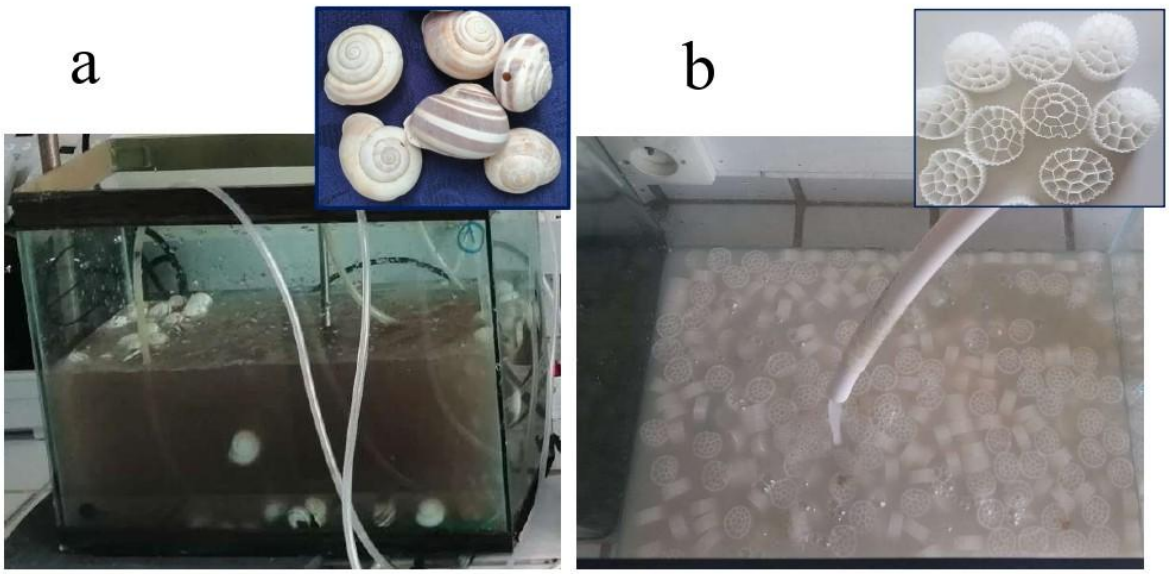


Figure 1. Experimental setup of MBBR units treating dairy effluent using two types of biofilm carriers: (a) natural *Theba pisana* shells used after cleaning and perforation; (b) commercial Kaldnes K3 media made of plastic

2.3. Description of the Experimental Reactor

The reactor is a glass MBBR unit with a total volume of 70 litres. It operates continuously, treating 5 litres of real dairy effluent every 6 hours. Two pumps ensure stable operation: an air pump provides homogeneous aeration, and a hydraulic pump maintains constant agitation. An internal thermometer monitors ambient temperature, which remained close to 21 °C throughout the experiment (Figure 2).

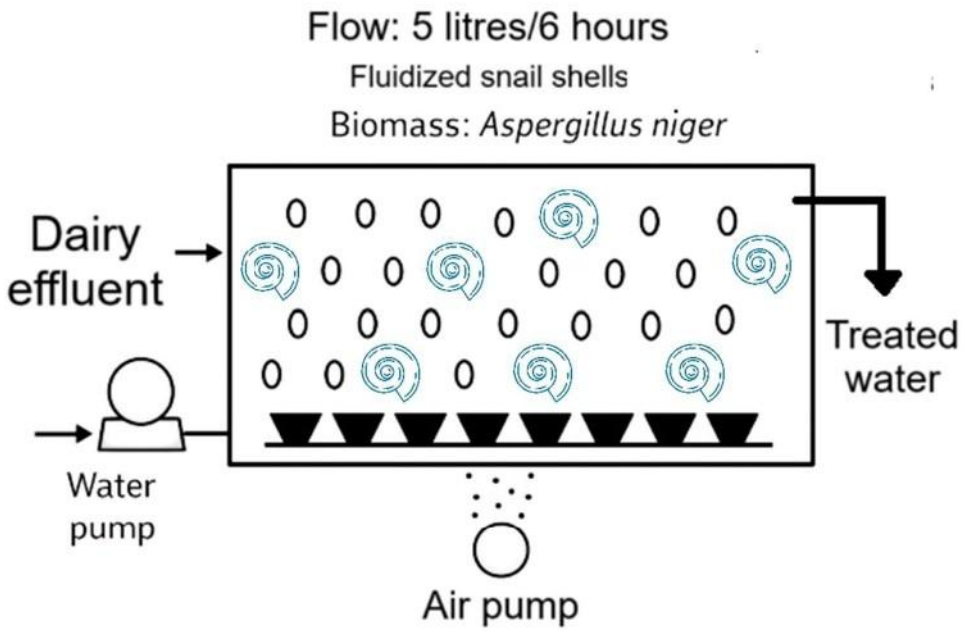


Figure 2. Schematic representation of the semi continuous-flow MBBR system using fluidized snail shells and *Aspergillus niger* for dairy effluent treatment

2.4. Analytical Methods for Pollution Removal Monitoring and Biomaterial Characterization

Samples were collected during each analytical cycle to assess the performance of the biofilm reactor in removing organic pollution from dairy effluent. All experiments were conducted in triplicate at minimum.

Temperature (T°)

In the continuous-flow MBBR process applied to dairy effluent treatment, water temperature plays a key role in determining overall system efficiency. It directly affects the solubility of dissolved oxygen, which is essential for the aerobic metabolism of *Aspergillus niger*, and influences the rate of the enzymatic reactions in organic matter degradation. Temperature was measured in situ using a Testo 950 thermometer fitted with a Pt100 Class B1/10 probe to monitor the reactor environment precisely. It is well established that a 10°C increase can double or even triple the rate of biochemical reactions [8]. But, this acceleration may lead to a reduction in available oxygen, which could impair the activity of the biofilm developed on snail shell carriers. Therefore, maintaining an optimal temperature balance is essential to ensure efficient biodegradation and adequate oxygen supply within the system.

Hydrogen Potential (pH)

The pH was measured using a Fisher Scientific AB15 pH meter. This parameter is essential for maintaining the ionic balance of the medium, directly influencing microbial activity and the stability of biochemical reactions. A range between 6 and 9 is generally considered favourable for the development of aquatic organisms and for the performance of biological processes such as MBBR, particularly when using sensitive fungal biomass such as *Aspergillus niger* [9].

Chemical Oxygen Demand (COD)

Total COD was determined according to the NF T90-101 (2022) [22] standard, using acid digestion with potassium dichromate, followed by a two-hour reflux. This analysis quantifies the overall organic load of the effluent, including both carbon-based and nitrogenous compounds.

Biochemical Oxygen Demand over 5 Days (BOD_5)

BOD_5 was measured using a Hach Lange BOD meter (BOD Direct LQV158.98.00001), in accordance with the AFNOR NF T90-103 (1975) standard [23]. This parameter estimates the biodegradable fraction of the organic load. The COD/BOD_5 ratio was calculated to assess the biodegradability potential of the effluent.

Total Kjeldahl Nitrogen (TKN)

Organic and ammoniacal nitrogen (TKN) was determined in accordance with the NF EN 25663 (1997) [24] standard. In this method, sulphuric acid digests a substance in the presence of catalysts (K_2SO_4, $CuSO_4$), followed by distillation and acid–base titration using 0.1 M sodium hydroxide (NaOH).

The nitrogen concentration was calculated using the following formula (Eq. 1):

$$N\ (mg/L) = \frac{(V_B - V_{NaOH})x[NaOH]x14.01x1000}{Sample\ Volume\ (mL)} \qquad \text{(Eq. 1)}$$

Where:

- V_B is the volume of NaOH used for the blank (mL)
- V_{NaOH} is the volume used for the sample (mL)
- [NaOH] is the molar concentration of the titrant (mol/L)
- 14.01 is the molar mass of nitrogen (g/mol)

Total Phosphorus

Total phosphorus was determined following mineralization by acid digestion, in accordance with the DIN 38405-D11-1 standard (1993). The released orthophosphate reacted with ammonium molybdate to form a blue-coloured complex, which was quantified by spectrophotometric colourimetry at 880 nm [25].

Scanning Electron Microscopy (SEM) Observation

Shell samples were fixed in 1% glutaraldehyde and dehydrated through a graded ethanol series. They were stored in sterile containers until observation. The surface morphology and biofilm structure were examined using scanning electron microscopy (SEM), employing a Philips XL30 model. This technique enabled high-resolution visualization of the biofilm architecture and its adhesion to the carrier surface [26].

Contact Angle Measurement (Hydrophobicity)

Shells were characterized using contact angle goniometry (Visiodrop MCAT, GBX SC Instruments). Three methods were used: sessile drop, circle fitting, and dynamic profile. Four droplets were placed on each sample, and the mean contact angle was calculated [26].

Specific Surface Area Measurement (BET)

The specific surface area was determined using nitrogen adsorption at 77 K, based on the Brunauer–Emmett–Teller (BET) method [27]. A Coultronic 2100E surface area analyser was used for the measurements. Prior to analysis, the samples were degassed under vacuum to remove any physically adsorbed contaminants. The specific surface area (SSA) was calculated using the BET equation (Eq. 2):

$$S\ (m^2/g)\ =\ \frac{6.02\ x\ 10^{23} x\ V_m x S_m}{22\ 214\ x\ sample\ mass\ (g)} \qquad \text{(Eq. 2)}$$

Where:

- V_m is the monolayer volume (cm³ STP),
- $S_m = 16{,}2\ A^{o2}$ the cross-sectional area of a nitrogen molecule,
- 22 214 is the molar volume of gas at STP (cm³/mol)

3. Results and Discussion

3.1. Characterization of Raw Dairy Effluent

Table 2 summarizes the physico-chemical characterization of the raw effluent collected from the dairy cooperative. The results reveal a substantial organic and nutrient load, with average COD, BOD_5, and TKN concentrations markedly exceeding national discharge limits. The effluent presents an alkaline pH (~9.1), slightly above the regulatory threshold, and a high phosphorus content (45.6 g/L), pointing to a considerable risk of eutrophication. The COD/BOD_5 ratio of 1.79 indicates a readily biodegradable effluent, suitable for biological treatment using systems such as MBBR. These findings support the implementation of a focused and efficient treatment strategy, particularly in settings where conventional infrastructure is unavailable.

The raw effluent collected from the dairy cooperative exhibited a high organic and nutrient load, with an average COD of 3785 mg/L and a BOD_5 of 2105 mg/L. The COD/BOD_5 ratio of 1.79 indicates strong biodegradability, characteristic of effluents readily treatable via biological processes. This value, below the critical threshold of 3 [9], confirms that most of the organic matter is readily assimilated by microorganisms, thereby supporting the use of fixed-biofilm biological treatment systems.

Despite this biodegradability, the measured concentrations greatly exceed the Moroccan regulatory limits defined by decree no. 1607-06 (COD ≤ 125 mg/L, BOD_5 ≤ 40 mg/L, TKN ≤ 30 mg/L, P ≤ 2 mg/L). The effluent contains 2861 mg/L of total Kjeldahl nitrogen and 45.6 mg/L of total phosphorus, which pose a substantial eutrophication risk if discharged without appropriate treatment. These results are consistent with those reported by Rachiq *et al.* [34] in a dairy facility in Rabat, where COD values reached 11,000 mg/L, attributed to significant milk losses and high volumes of rinse water.

Table 2. Quantitative characterization of dairy effluent

Parameter	Mean value	Expected range	Admissible limit*	Regulatory reference
Temperature (°C)	21.4	20.0 – 25.0	≤ 30	Order No. 1607-06, Art. 13 [28]
pH	9.1	8.5 – 9.5	6.5 – 8.5	Order No. 1607-06, Art. 13 [28]
COD (mg/L)	3785	3500 – 4200	125	Order No. 1607-06, Annex 2 [28]
TKN (mg/L)	2861	2600 – 3100	30	CAR/PAP, 2002 [6]
BOD_5 (mg/L)	2105	1900 – 2300	40	Order No. 1607-06, Annex 2 [28]
Total phosphorus (Pt, g/L)	45.6	40.0 – 50.0	2	CAR/PAP, 2002 [6]
COD/BOD_5 ratio	1.79	1.6 – 1.9	—	—

***Note**: Limit values vary depending on whether the effluent is discharged directly into the natural environment, into a collective sewer network, or after treatment.

*Limits set by Joint Order No. 1607-06 of 11 July 2006 on thresholds for industrial wastewater discharges into receiving environments [28]

Studies conducted in various regions of Morocco and Tunisia confirm the wide variability of dairy effluent characteristics (Table 3). Pollutant loads depend on unit size, cleaning protocols, and product loss during processing. The COD/BOD_5 ratio remains below 3 across all reported cases. This indicates a high level of biodegradability.

Table 3. Quantitative characterization of selected dairy effluents in the Maghreb

Source of Effluent	pH	COD (mg/L)	BOD_5 (mg/L)	TKN (mg/L)	TP (mg/L)	Reference
Moroccan standards	6.5–8.5	500	100	30	10	[28]
Biological station inlet (northern dairy cooperative, M'diq)	8.5–12.5	5,5	2,85	75.93	23.5	[29]
Total effluent (LVRS Rabat–Salé)	6–9	117,000–122,900	55,000–63,000	4,400–13,600	13,000–34,000	[30]
Total effluent (Doukkala dairy unit)	3.5	6,780 ± 934	3,270 ± 813	170 ± 33	35 ± 7.15	[31,32]
Dairy effluent (Fès dairy unit, Morocco)	6.6–6.8	2,260–3,490	867–1,163	107–246	18–21	[33]
Industrial dairy unit (Rabat–Salé–Kénitra region, Morocco)	6.8	3,5	–	45.35	–	[34]
Cheese dairy effluents (Sousse region, Tunisia)	4–11	1,500–3,571	350–2,351	14–329	280	[35]
Total effluent (Casablanca dairy cooperative)	9.1 ± 0.3	3,785 ± 250	2,105 ± 180	2,861 ± 210	45.6 ± 4.2	Present study

Note: COD: chemical oxygen demand; BOD_5: biochemical oxygen demand over five days; TKN: total Kjeldahl nitrogen; TP: total phosphorus.

Effluent streams, whether from industrial or cooperative units, consistently exceed Moroccan standards for discharge. COD, BOD_5, nitrogen, and phosphorus levels are frequently high. These values reflect an acute risk of pollution when untreated effluent is released into the environment. Data from the M'diq cooperative [29] and the Rabat–Salé unit [30] illustrate this concern. In these cases, COD and nitrogen concentrations are exceptionally elevated. Similar patterns appear in Fès [33] and Casablanca (present study), where nitrogen loads are especially significant. The situation in Tunisia [35] offers comparable evidence, underlining that this challenge extends beyond Morocco. Such findings support the need for effective biological treatment systems. Among available options, Moving Bed Biofilm Reactors (MBBR) using natural carriers—such as snail shells—offer a practical solution. These systems combine performance with affordability. They also promote circular economy principles and reduce reliance on synthetic materials. Their use enables better water reuse and supports local adaptation strategies.

3.2. Temporal Evolution of Pollutant Removal from Dairy Effluent Treated Biologically with Aspergillus *niger* Using Snail Shells and Kaldnes K3 as Carriers

Figure 3 shows the temporal evolution of removal rates for BOD_5, COD, total Kjeldahl nitrogen (TKN), and total phosphorus during the treatment of dairy effluent by *Penicillium chrysogenum*, using two types of carriers: snail shells and Kaldnes K3.

BOD_5 – Evolution of Biodegradability

The five-day biochemical oxygen demand (BOD_5) reflects microbial activity in response to biodegradable organic matter. The results show a clear increase in BOD_5 removal over time, reaching 73.3% with K3 and 84.8% with snail shells after 72 hours. This 11.5% advantage in favour of snail shells suggests improved fungal colonization, probably because their rougher, more hydrophilic surface promotes cell adhesion and stable biofilm formation [26,36,37].

The rapid growth phase between 24 and 48 hours aligns with enhanced enzymatic activity, particularly fungal hydrolases and oxidases, breaking down complex carbon substrates. The superior performance of snail shells can be explained by their ability to support a more stable biofilm, allowing for better retention of active biomass [38].

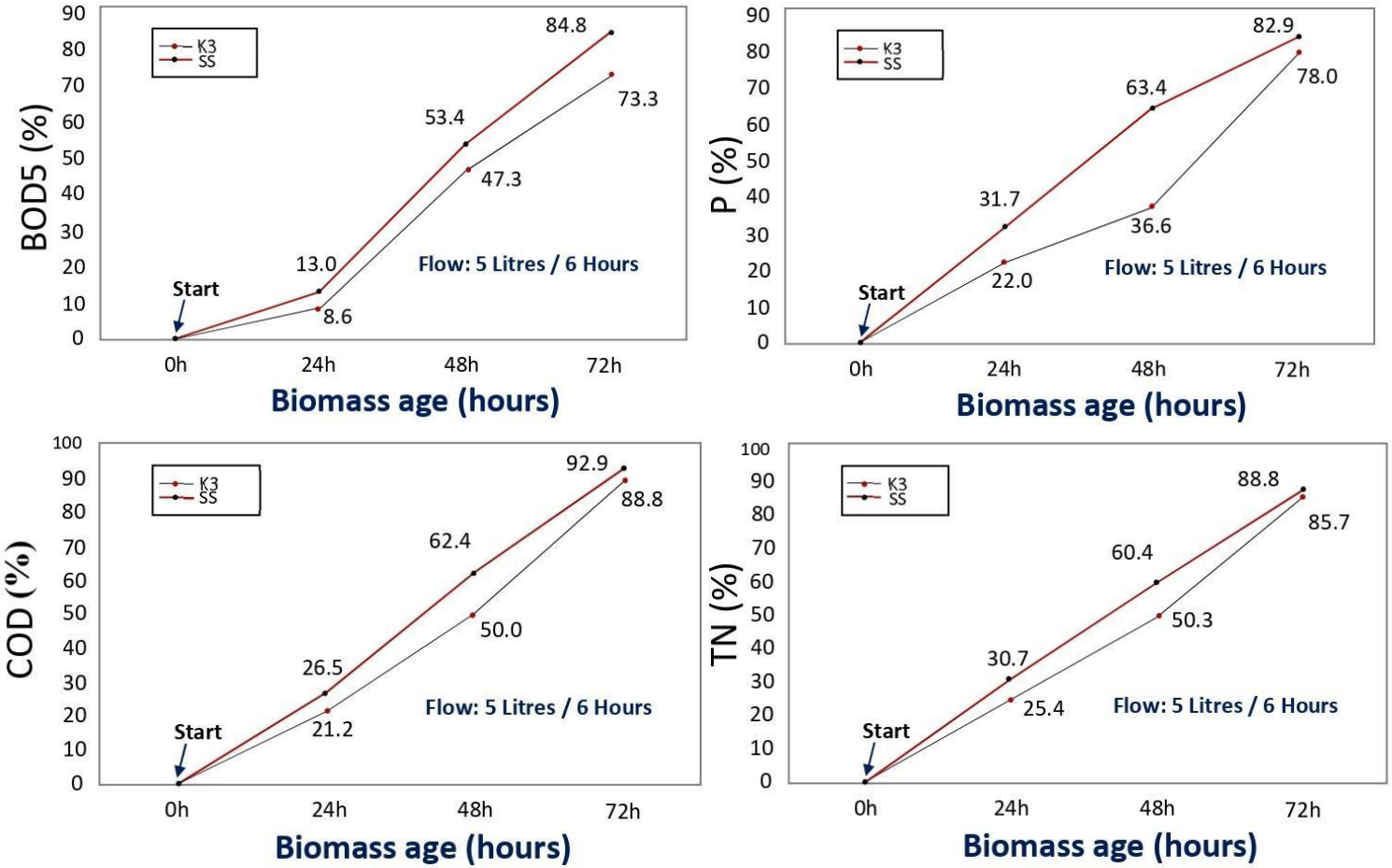


Figure 3. Temporal evolution of BOD_5, COD, TKN, and total phosphorus removal efficiencies during the treatment of dairy effluent using *Penicillium chrysogenum* on two types of biofilm carriers (snail shells and Kaldnes K3).

COD – Total Organic Matter Content

The decrease in chemical oxygen demand (COD) reflects the overall efficiency of the process in removing organic matter. After 72 hours, removal rates were high: 92.9% with snail shells and 88.8% with K3. From 48 hours onwards, the curve shows a clear advantage for the shells, indicating their ability to support a dense and metabolically active biofilm. Charef *et al.* [9] confirmed that the type of carrier directly affects the biodegradation rate in MBBR systems. Snail shells serve not only as structural support but may also enhance biological activity by locally modifying pH or nutrient conditions on their surface, thereby stimulating fungal action [8].

TKN – Total Kjeldahl Nitrogen Removal

Organic and ammoniacal nitrogen was reduced through fungal assimilation and partial nitrification. Removal efficiency increased over time, reaching 88.8% with snail shells and 85.7% with K3 at 72 hours. Although the difference is modest, it supports the assumption that carrier type influences biomass adhesion, stability, and effectiveness.

Fathi *et al.* [8] reported that the carbon-to-nitrogen ratio strongly affects biomass composition and nitrification rate. In this study, snail shells appear to optimize these ratios, enhancing the conversion of organic nitrogen.

Phosphorus – Total Phosphorus Removal

Phosphorus levels declined steadily over time, reaching 82.9% removal with snail shells compared to 78.0% with K3. This difference is noteworthy, as *Penicillium chrysogenum* is known for its ability to accumulate phosphorus intracellularly in the form of polyphosphates. Natural carriers appear to enhance this capability [8,9], especially when *Aspergillus niger* is used as the biomass. The porous structure of snail shells probably facilitates additional physico-chemical adsorption of phosphorus alongside biological uptake. This dual mechanism was previously demonstrated by Belghyti *et al.* [39] in real effluent systems. Figure 4 confirms that the presence of a carrier—particularly snail shells—strongly influences biofilm formation, which lies at the core of the treatment performance. Fungal biofilms developed on the shells benefit from a biocompatible surface and favourable topography, both of which enhance adhesion [26,40].

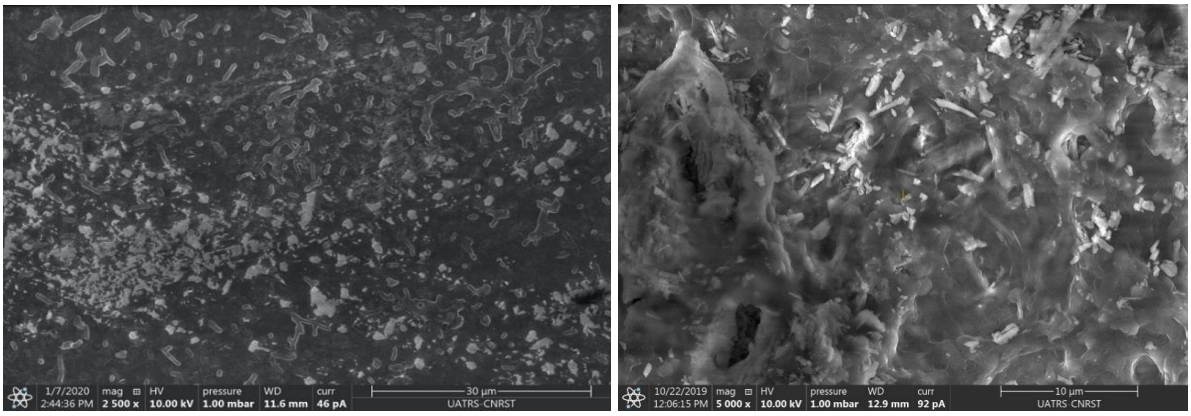
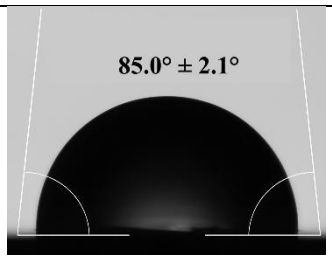
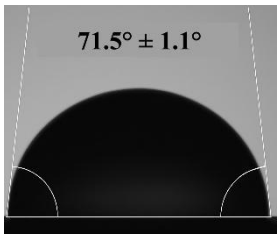


Figure 4. Comparative SEM micrographs of biofilms developed on Kaldnes K3 (left, ×2500) and snail shell support (right, ×5000) in continuous MBBR treating dairy effluent.
The images highlight differences in surface morphology and biofilm structure: sparse and patchy colonization on the synthetic K3 media versus dense, multilayered biofilms embedded in EPS on the naturally rough snail shell matrix

On the Kaldnes K3 support (×2500), the surface appears relatively smooth and uniform, with dispersed microcolonies forming scattered clusters. The biofilm shows limited structural complexity, with individual fungal cells and extracellular polymeric substances (EPS) loosely spread across the synthetic surface. The uniformity of the polymer restricts spatial anchorage and limits biofilm thickness. In contrast, the snail shell surface (×5000) presents a more irregular and porous micro-topography, which encourages extensive microbial colonization. The biofilm is denser and more structured, with multilayered cell clusters embedded in a fibrous EPS matrix. The rough texture and natural heterogeneity of the shell provide protective niches, supporting better adhesion and biofilm maturity. These morphological distinctions suggest that natural calcium carbonate-based supports, such as snail shells, offer a more favourable microenvironment for biofilm development than synthetic carriers [36,40]. Increased surface roughness, porosity, and chemical compatibility probably enhance microbial attachment and metabolic activity in the reactor. Table 5 compares the specific surface area and water contact angle of natural snail shells (CE) and synthetic Kaldnes K3 media. The K3 support showed a slightly higher specific surface area (5120 ± 45 m²/kg) than CE (4985 ± 60 m²/kg). Greater differences emerged in wettability: the contact angle for CE reached $85.0° \pm 2.1°$, compared to $71.5° \pm 1.1°$ for K3, indicating that snail shells display more hydrophilic behaviour.

Table 5. Specific surface area and water contact angle of snail shell (CE) and Kaldnes K3 support materials used in continuous MBBR treatment of dairy effluent.

Carrier type	Snail shells (CE)	Kaldnes K3 (K3)
Specific surface area (m²/kg)	4985 ± 60	5120 ± 45
Water contact angle (°)		

Although a lower contact angle is generally associated with higher hydrophilicity, the elevated contact angle measured on CE suggests a reversal in surface polarity. This may result from the presence of amyloid-like hydrophobins secreted by *Aspergillus niger*. These amphiphilic proteins modify surface energy and support microbial adhesion on rough and chemically active substrates [41]. The outer organic layer of the snail shell, the periostracum, further enhances colonization by providing a heterogeneous and reactive interface. This combination of micro-roughness, biochemical affinity, and variable polarity contributes to the development of dense and structured biofilms. Previous studies have also reported improved microbial adhesion on mollusc shells [26,38,40]. In particular, CE supports showed better performance in removing suspended solids and phosphorus. This may be linked not only to their physical features but also to the synergistic effect between fungal secretions and the natural composition of the support. These results confirm that natural calcium carbonate-based media such as snail shells represent a promising and low-cost alternative to synthetic carriers, especially when combined with filamentous fungi like *A. niger*, which display strong biofilm-forming capacities.

Discussion

Recent literature underlines the growing concern about the environmental burden caused by dairy industry effluents, which are often rich in nutrients, organic pollutants, and potentially inhibitory compounds such as sterilizing agents and alkaline detergents [27,37]. These components not only challenge treatment efficiency but may also impair microbial metabolism. Previous studies in batch systems—such as [8,10,20]—have demonstrated the feasibility of natural carriers like sardine scales, snail shells or mixed algal-fungal biofilms for COD and

nutrient removal, but they typically used either synthetic or partially diluted effluents and did not assess the long-term impact of effluent toxicity on biofilm resilience.

In contrast, our study operates under semi-continuous mode without effluent recirculation, mimicking decentralized low-tech systems more prone to fluctuating pollutant loads. Importantly, the use of real, undiluted dairy wastewater—collected directly from a cooperative outlet—exposes the fungal biomass to a wide spectrum of residual biocontaminants, including disinfectants, surfactants, and residual antibiotics. This setup allows for a more realistic evaluation of treatment robustness and the fungal biofilm's ability to adapt, colonize, and maintain performance over time. Notably, we investigated the effect of biofilm age, which is rarely considered in earlier works, to illuminate colonization dynamics and metabolic stability across operational phases.

Compared to prior works using fixed-bed [10] or batch fluidized-bed systems [8], our configuration showed superior and more stable performance, with COD and phosphorus removal rates consistently above 90% and 80%, respectively, despite the lack of recirculation. This indicates a promising ecological and resilient alternative for decentralized applications, particularly in rural or under-resourced regions where synthetic supports and complex control systems may be unavailable

Conclusion

The analysis clearly shows that snail shells, as natural biomedia, outperform Kaldnes K3 in most of the parameters assessed. Their effectiveness relies on:

- improved fungal colonization because of their surface topography and hydrophilicity;
- greater specific surface area supporting biomass adhesion and retention;
- enhanced metabolic synergy between the natural support and the fungal biomass.

These findings argue for replacing synthetic plastic carriers with valorized waste-derived biomaterials, contributing to a circular, sustainable, and efficient water treatment model.

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Ethics Approvals: This study was conducted in full accordance with ethical principles.

Data Availability: The data that support the findings of this study are available from the corresponding author upon reasonable request.

Code availability: Not applicable

Conflict of interest: All authors declare no conflicts of interest

References

[1] Sraïri M.T., Benyoucef M.T., Kraiem K., 2013, The dairy chains in North Africa (Algeria, Morocco and Tunisia): from self-sufficiency options to food dependency?, *SpringerPlus* **2(**162). https://doi.org/10.1186/2193-1801-2-162

[2] Akesbi, N., 2012, Une nouvelle stratégie pour l'agriculture marocaine : Plan Maroc Vert. *New Medit: Mediterranean Journal of Economics, Agriculture and Environment= Revue Méditerranéenne d'Economie Agriculture et Environment* **11**(2), 12. https://nokkade.wordpress.com/wp-content/uploads/2021/01/akesbi-najib-le-pmv-ou-la-nouvelle-strategie-agricole-du-maroc-medit-2012.pdf

[3] Addessi, L., 1994, Human disturbance and long-term changes on a rocky intertidal community. *Ecological applications* **4**(4), 786-797. https://doi.org/10.2307/1942008

[4] Ahmad, M., & van der Steen, P., 2022, Enhancing the governance of industrial wastewater using cleaner production and water footprint principles: A case study of two dairy companies in Palestine. *Desalination and Water Treatment* **275**, 339-349. https://doi.org/10.5004/dwt.2022.29136

[5] Cheng F., Pang J., Berggren S., Tanvar H., Mishra B., Arlos M.J., 2024, Treating Waste with Waste: Activated Bauxite Residue (ABR) as a Potential Wastewater Treatment, *ACS Omega* **9**(45): 45251–45262. https://doi.org/10.1021/acsomega.4c06699

[6] Plan Bleu., 2005, *Méditerranée : Les perspectives du Plan Bleu sur l'environnement et le développement. Résumé*. Centre d'activités régionales du Plan Bleu – PNUE/PAM. https://planbleu.org/sites/default/files/publications/red_resume_fr.pdf

[7] Aitcheikh, A., Boutaleb, N., Bahlaouan, B., El Omari, H., El Jaafari, A., Lazar, S., & El Antri, S., 2016, Snail shells: a new ecological packing for moving bed reactor MBBR in the biological treatment of dairy effluent. *Global Journal of Bio-Science and Biotechnology 5*, 492-497.

[8] Fathi, A., Boutaleb, N., Bahlaouan, B., Bennani, M., Lazar, S., & El Antri, S., 2021, Filamentous fungi and natural supports as a carrier in moving bed biofilm reactors for ecological treatment of halieutic industrial effluent. *Desalination and Water Treatment* **237**, 37-44. https://doi.org/10.5004/dwt.2021.27737

[9] Charef, I., Fathi, A., Ozi, F. Z., Asbai, Z., Radi Benjelloun, G., Waddi, K., Bahlaouan, B., El Antri, S., & Boutaleb, N., 2024, The use of mixed biomass alga–fungi in mutualistic relationship and natural marine-origin carrier in MBBR reactor for an ecological treatment of effluents from fish processing industry in Morocco. *Desalination and Water Treatment* **317**, 100020. https://doi.org/10.1016/j.dwt.2024.100020

[10] Aitcheikh, A., Boutaleb, N., Bahlaouan, B., Bennani, M., Lazar, S., & El Antri, S., 2018, Utilisation d'un lit fixe d'origine naturelle pour le traitement biologique d'effluents

laitiers. *Environnement, Ingénierie & Développement* **78**, Article 7756. https://doi.org/10.4267/dechets-sciences-techniques.3881

[11] Shete, B. S., & Shinkar, N. P., 2013, Dairy industry wastewater sources, characteristics & its effects on environment. *International Journal of Current Engineering and Technology* **3**(5), 1611-1615. https://inpressco.com/wp-content/uploads/2013/11/Paper31611-1615.pdf

[12] Ikhlef, S., & Basu, O. D., 2017, Influence of backwash regime on biofilter performance in drinking water treatment. *Journal of Chemical Technology & Biotechnology* **92**(7), 1777-1784. https://doi.org/10.1002/jctb.5178

[13] Nhung, N. T. H., Long, V. D., & Fujita, T., 2023, A critical review of snail shell material modification for applications in wastewater treatment. *Materials* **16**(3), 1095. https://doi.org/10.3390/ma16031095

[14] Defrawy, E., & Shaalan, H. F., 2003, Techno-economic assessment of biological treatment and water reuse of effluent from the food industries. *International Journal of Environmental Studies* **60**(2), 111-122. https://doi.org/10.1080/00207230304741

[15] Zou, J.-L., Xu, G.-R., Pan, K., Zhou, W., Dai, Y., Wang, X., Zhang, D., Hu, Y.-C., & Ma, M., 2012, Nitrogen removal and biofilm structure affected by COD/NH_4^+–N in a biofilter with porous sludge-ceramsite. *Separation and Purification Technology* **94**, 9–15. https://doi.org/10.1016/j.seppur.2012.03.019

[16] Ravindran, V., Kim, S. H., Badriyha, B. N., & Pirbazari, M., 1997, Predictive modeling for bioactive fluidized bed and stationary bed reactors: application to dairy wastewater. *Environmental Technology* **18**(9), 861-881. https://doi.org/10.1080/09593331808616606

[17] Potortì, A. G., Messina, L., Licata, P., Gugliandolo, E., Santini, A., & Di Bella, G., 2024, Snail shell waste threat to sustainability and circular economy: Novel application in food industries. *Sustainability* **16**(2), 706. https://doi.org/10.3390/su16020706

[18] Ahmad T., Aadil R.M., Ahmed H., Rahman U.U., Soares B.C.V., Souza S.L.Q., Pimentel T.C., Scudino H., Guimarães J.T., Esmerino E.A., Freitas M.Q., Almada R.B., Vendramel S.M.R., Silva M.C., Cruz A.G., 2019, Treatment and utilisation of dairy industrial waste: a review. *Trends in Food Science and Technology* **88**. 361–372. https://doi.org/10.1016/j.tifs.2019.04.003

[19] Bhuvanendran, R. K., Jagadeesan, B. K., Karthigeyan, J., Bhuvaneshwari, S., Vallinayagam, S., & Prasannakumari, A. S. N., 2024, Remediation and management techniques for industrial dairy wastewater and sludge: a review. *Journal of Material Cycles and Waste Management* **26**(5), 2634-2655. https://doi.org/10.1007/s10163-024-02017-2

[20] Fathi A., Khalki Y., Bahlaouan B., El Bouqdaoui K., Charef I., Boutaleb F., Bennani M., El Antri S., Boutaleb N., 2025, Implementation of nature-based biofilm carriers for sustainable bioremediation: A novel MBBR approach to treat fishery effluents in the Greater Casablanca Region, *Natural Built Social Environment Health* **1**(4): 80–95. https://doi.org/10.63095/NBSEH.25.195556

[21] Ledezma-Villanueva, A., Robledo-Mahón, T., Gómez-Silván, C., Angeles-De Paz, G., Pozo, C., Manzanera, M., Calvo, C., & Aranda, E. (2022). High-throughput microbial community analyses to establish a natural fungal and bacterial consortium from sewage sludge enriched with three pharmaceutical compounds. *Journal of Fungi* **8**(7), 668. https://doi.org/10.3390/jof8070668

[22] AFNOR, 2021, *NF T90-101 : Qualité de l'eau – Détermination de la demande chimique en oxygène (DCO)*, 11 p., 1re édition, février 2021 (Paris : Association Française de Normalisation). https://www.boutique.afnor.org/fr-fr/norme/nf-t90101/qualite-de-leau-determination-de-la-demande-chimique-en-oxygene-dco/fa199063/260997

[23] MELCCFP, 2023, *Méthode d'analyse MA. 315 – DBO 1.1 (révision 6) : Détermination de la demande biochimique en oxygène – méthode électrométrique*, 14 février 2023, 17 p. (Québec : Ministère de l'Environnement, de la Lutte contre les changements climatiques, de la Faune et des Parcs). Disponible en ligne : www.environnement.gouv.qc.ca

[24] AFNOR. Qualité de l'eau – Détermination de l'azote Kjeldahl. Norme NF EN 25663, Association Française de Normalisation, Paris, 1997. https://www.boutique.afnor.org/fr-fr/norme/nf-en-25663/qualite-de-leau-dosage-de-lazote-kjeldahl-methode-apres-mineralisation-au-s/fa029815/13570

[25] DIN 38405-D11-1, 1993, German standard methods for the examination of water, wastewater and sludge – Chemical analysis (group D) – Part D11: Determination of phosphorus (D 11-1). Deutsches Institut für Normung e.V., Berlin. https://www.analytik-jena.com/knowledge/standards-norms-productfinder/standards/din-38405/

[26] Boutaleb, N., 2007, Étude de la formation de biofilms sur les surfaces de matériaux couramment utilisés dans les canalisations d'eau potable [PhD thesis, Université de Bretagne Sud]. http://www.theses.fr/2007LORIS099

[27] Brunauer S., Emmett P.H., Teller E., 1938, Adsorption *of gases in multimolecular layers*. *Journal of the American Chemical Society* **60**(2), 309–319. https://doi.org/10.1021/ja01269a023

[28] Ministère de l'Intérieur, Ministère de l'Aménagement du Territoire, de l'Eau et de l'Environnement, & Ministère de l'Industrie, du Commerce et de la Mise à niveau de l'Économie, 2006, Arrêté conjoint n° 1607-06 du 29 joumada II 1427 (25 juillet 2006) fixant les valeurs limites spécifiques de rejet des eaux usées domestiques des agglomérations urbaines. *Bulletin Officiel*, n° 5448, 17 août 2006. https://faolex.fao.org/docs/pdf/mor66777.pdf

[29] El Ghammat, A., Riffi, K. T., & Zerrouk, M. H., 2019, A study of the performance of a sequential bioreactor plant for the treatment of dairy effluents. *LARHYSS Journal* **37**, 7–21. https://larhyss.net/ojs/index.php/larhyss/article/view/624/634

[30] Louaste, B., Boudine, L., Eloutassi, N., & Chaouch, M., 2014, Traitement biologique de l'effluent liquide issu de l'industrie laitière par des champignons exogènes. *International Journal of Innovation and Applied Studies* **7**(4), 1551–1559. http://www.ijias.issr-journals.org/abstract.php?article=IJIAS-14-188-03

[31] Hamdani A., Moufti A., Mountadar M., Assobhei O., 2005, Évolution de la qualité physico-chimique et bactériologique d'un effluent laitier sur un cycle annuel. *Environnement, Ingénierie & Développement* **37**, 1–10. https://doi.org/10.4267/dechets-sciences-techniques.1880

[32] Hamdani A., Chennaoui M., Assobhei O., 2004, Mountadar M. Characterisation and treatment by coagulation–decantation of dairy effluent. *Lait* **84**(3), 317–328. https://doi.org/10.1051/lait:2004005

[33] Lhanafi S., Abbaz M., Elhaouti R., Azougarh Y., Benafqir M., Ettaleb S., Ez-Zahery M., Aba-Aaki R., Chebli B., El Bari H., El Alem N., 2017, *Characterisation and*

anaerobic treatment of biological and physicochemical sludge from a Moroccan dairy industry. *Journal of Water and Environmental Sciences* **1**(1), 49–58. http://revues.imist.ma/?journal=jwes

[34] Rachiq T., Samghouli N., Mabrouki J., El-Moustaqim K., Rahmani M., Al-Jadabi N., El Hajjaji S., Rahal S., 2022, Study *and modelling of dairy effluents treatment using design of experiments methodology*. *Desalination and Water Treatment* **261**, 131–140. https://doi.org/10.5004/dwt.2022.28524

[35] M'Sadak Y., Yousfi M., 2024, Characterisation and valorisation potential of dairy effluents from cheese production: Review of the state of the art and perspectives of new technologies. *Environmental and Water Sciences, Public Health & Territorial Intelligence* **8**(1), 1075–1090. https://doi.org/10.48421/IMIST.PRSM/ewash-ti-v8i1.46624

[36] Radi Benjelloun, G., Bahlaouan, B., Rizki, H., Waddi, K., Asbai, Z., Bennani, M., Foughal, T., El Antri, S., & Boutaleb, N., 2024, Effect of food environment on the ability of microorganisms to form biofilms. *Journal of Food Safety* **44**(2). https://doi.org/10.1111/jfs.13120

[37] Benjelloun, G. R., Chouhbi, O., Bahlaouan, B., Bennani, M., El Antri, S., & Boutaleb, N., 2025, Biofilms in the Food Industry: Adhesion Mechanisms, Control Strategies, and Mastery. *Natural Built Social Environment Health* **1**(1). https://doi.org/10.63095/NBSEH.25.650223

[38] Aitcheikh A., Boutaleb N., Bahlaouan B., El Jaafari A., Taiek T., Bennani M., Lazar S., El Antri S., 2014, Dairy wastewater treatment in moving bed biofilm reactor using sardine's scales as biomass support. *International Journal of Engineering Research and Technology* **3**(11). https://www.ijert.org/research/dairy-wastewater-treatment-in-moving-bed-biofilm-reactor-using-sardines-scales-as-biomass-support-IJERTV3IS110126.pdf

[39] Belghyti, D., Guamri, Y.E., Ztit, G., Ouahidi, M., Joti, M., Harchrass, A., Amghar, H., Bouchouata, O., Kharrim, K.E., Bounouira, H., 2009. Caractérisation physico-chimique des eaux usées d'abattoir en vue de la mise en oeuvre d'un traitement adéquat : cas de Kénitra au Maroc. *Afrique Science: Revue Internationale des Sciences et Technologie* **5**. https://doi.org/10.4314/afsci.v5i2.61730

[40] Louanjli F.A., Bahlaouan B., Silkina A., Benjelloun G.R., Boutaleb F., Tesse R., El Antri S., Boutaleb N., 2025, Plasticulture film coextruded with essential oils: sustainable protection of salad crops. *International Journal of Environmental Studies* **82**(1), 432–447. https://doi.org/10.1080/00207233.2024.2368443

[41] Maeda, H., Yamagishi, R., Ishida, E.H., Kasuga, T., 2019, Wettability and dynamics of water droplet on a snail shell. *Journal of Colloid and Interface Science* **547**, 111–116. https://doi.org/10.1016/j.jcis.2019.03.096

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Impact of irrigation water sources on growth and physiological traits in tomato (*Solanum lycopersicum*)

Lamiaa Belasri [1a] ☑, Ayoub Mardi [1b], Nihad Chakri [2c], Mehdi El Mellouki [1d], Mourad Arabi [3e], Fouad Amraoui [2f], Btissam El Amrani [2g], Samah Ait Benichou [1h]

[1] Health and Environment Laboratory, Department of Biology, Ain Chock Science Faculty, Hassan II University of Casablanca (https://ror.org/001q4kn48), Morocco.

[2]Association for Action-Research for Sustainable Development, Faculty of Sciences, Aïn Chock Hassan II University of Casablanca (https://ror.org/001q4kn48), Morocco

[3]Laboratory for Improvement of Agricultural Production, Biotechnology and Environment (LAPABE)/ Water, Environment and Health Team, Faculty of Science, Mohamed I University (https://ror.org/01ejxf797), PB 717 60000, BV M6, Oujda, Morocco

[a]***ORCID***: *0009-0005-0988-6869*, ***Email***: *lamiaabelasri@gmail.com*

[b]***ORCID***: *0009-0004-0366-7270*, ***Email***: *mardiayoub19991@gmail.com*

[c]***ORCID:*** *0000-0002-1510-0253*, ***Email***: *n.chakri2009@gmail.com*

[d]***ORCID:*** *0009-0002-3328-7354*, ***Email***: *mehdielmellouki7@gmail.com*

[e]***ORCID:*** *0000-0002-2179-663X*, ***Email***: *m.arabi@ump.ac.ma*

[f]***ORCID:*** *0000-0001-6012-0694*, ***Email***: *amraoui_f@hotmail.com*

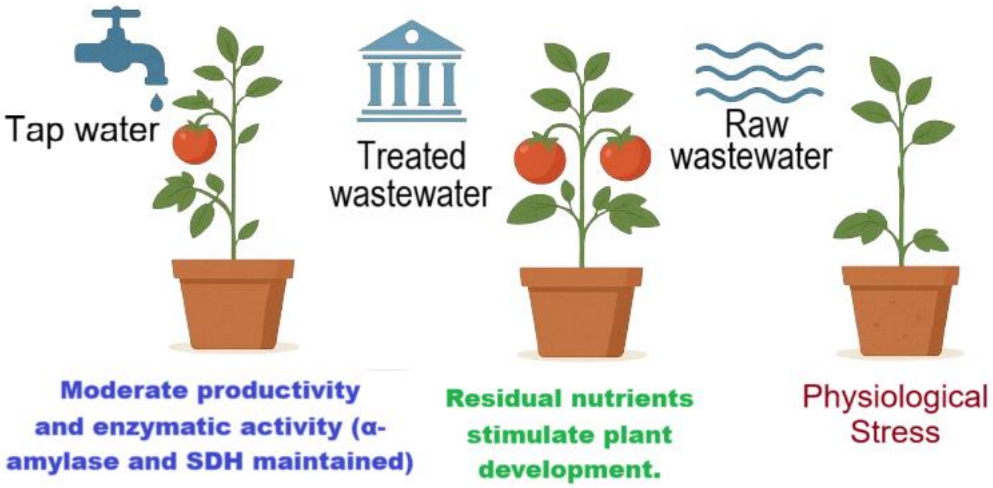
[g]***ORCID:*** *0000-0002-2940-3503*, ***Email***: *elamrani.btissam@gmail.com*

[h]***ORCID:*** *0000-0003-4423-2893*, ***Email***: *aitbenichous@gmail.com*

☑ **Corresponding author:** *Lamiaa Belasri;* ***Email address***: *lamiaabelasri@gmail.com*

Graphical Abstract

This study shows the effects of three irrigation water sources; tap water, treated wastewater, and raw wastewater; on the physiological and metabolic responses of tomato plants. The image points to improved growth and enzymatic activity, especially α-amylase and succinate dehydrogenase (SDH), in plants irrigated with treated wastewater. Raw wastewater causes stress, with visible declines in plant health. The visual reflects two aims: encouraging the safe reuse of treated effluents for sustainable farming, and showing the harm linked to untreated wastewater;



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Abstract: This study examined the effects of tap water (TW), treated wastewater (TWW), and raw wastewater (RWW) on *Solanum lycopersicum*. Raw wastewater showed high nitrite (42.57 ± 1.78 mg·L^{-1}) and BOD_5 (170 ± 12 mg·L^{-1}) levels. These values were lower in TWW (12.41 ± 0.56 mg·L^{-1} and 20 ± 4.5 mg·L^{-1}), which met Moroccan irrigation standards. Germination tests revealed higher α-amylase activity and germination index in RWW. This may reflect nutrient enrichment**.** After 90 days, plants irrigated with TWW showed the strongest vegetative growth, with taller stems (57.5 cm) and larger leaves. Microbiological analysis of tomato fruits showed minimal contamination across treatments. Succinate dehydrogenase activity was highest in TW-irrigated plants. This indicated optimal mitochondrial function**.** TWW produced moderate reductions in activity**.** RWW caused marked declines in both leaves and fruits**,** suggesting metabolic inhibition under stress. These findings show that TWW provides a useful balance between nutrient supply and plant health**,** supporting its suitability for sustainable irrigation.

Keywords: *Solanum lycopersicum*, Wastewater, Metabolic stress, Irrigation.

Introduction

The increasing global demand for freshwater, driven by population growth, urban expansion and climate change, has made water scarcity more severe in many parts of the world [1]. Agriculture, which uses nearly 70% of global freshwater, is especially exposed to these pressures [2]. In the Mediterranean region, several countries struggle to meet rising food needs. This is worse in areas with arid or semi-arid climates [3]. Morocco, once defined by a Mediterranean climate, now faces faster semi-aridification in key zones such as Casablanca-Settat, which is home to about 6.86 million people [4]. Agriculture remains central to Morocco's economy and society. It must now increase food production and manage water demand, as farming consumes nearly 80% of the country's freshwater [5].

In response to growing water scarcity, the reuse of treated wastewater is an alternative to standard irrigation sources. It conserves water and delivers essential nutrients, such as nitrogen and phosphorus. This practice supports circular economy aims by cutting reliance on synthetic fertilizers [6]. Concerns remain about the possible transfer of pathogens, heavy metals, and phytotoxic compounds to soil and crops [7]. In this context, the present study assesses the agronomic value of treated wastewater produced by a pilot decentralized treatment unit at the Faculty of Sciences Ain Chock (FSAC) in Casablanca, Morocco. This system uses an MBBR process followed by sand filtration to improve effluent quality [8]. The study analyses the physicochemical properties of the treated wastewater and examines its impact on seed germination, enzymatic activity, plant growth, and the microbiological safety of irrigated crops under controlled conditions.

Tomato (*Solanum lycopersicum* L.) was chosen as the test species for its agronomic, economic, and physiological importance. It is a strategic crop in Morocco, used both for local consumption and for export. Tomato is highly sensitive to water quality. It has high water needs and tends to accumulate salt and heavy metals. These traits make it a reliable bioindicator for assessing the suitability of reclaimed water for irrigation [9]. By comparing the effects of tap water, raw wastewater, and treated wastewater, this study aims to support the development of sustainable irrigation in water-limited regions such as Morocco.

Materials and methods

Site description and physicochemical assessment of wastewater

The treated wastewater used in this study came from a pilot decentralized treatment unit at the Faculty of Sciences Ain Chock (FSAC) in Casablanca, Morocco. This unit, developed by

Chakri *et al.* [8], was set up to offer sustainable wastewater treatment**.** The system combines a Moving Bed Biofilm Reactor (MBBR) with vertical sand filtration**,** which achieves high removal of organic and inorganic pollutants**.** Earlier studies confirmed the system's effectiveness and the suitability of the treated effluent for agriculture**.** Physicochemical analysis of the treated wastewater followed standard procedures [10,11]. The parameters tested included sulphates (SO_4^{2-}) using NF T 90-009, nitrites (NO_2^-) using NF T 90-013, and nitrates (NO_3^-) using NF ISO 7890-3/1988. Ammonium (NH_4^+) was tested by NF T 90-015. Orthophosphates (PO_4^{3-}) were analysed by NF T 90-023. Biological oxygen demand over five days (BOD_5) and chemical oxygen demand (COD) were measured using standard instrumental and dichromate reflux methods**,** based on NF T 90-101. pH, electrical conductivity (EC), suspended solids (SS), and turbidity were assessed using calibrated multiparameter probes, gravimetric filtration, and nephelometry. All measurements were carried out in triplicate, with blanks and standards included for quality control. The results showed that the treated wastewater met the required criteria for irrigation reuse. It provided a consistent source for tomato cultivation trials.

Plant material

Tomato (*Solanum lycopersicum*), part of the Solanaceae family, was selected as the model species for its dual role. It is a staple in Moroccan diets, eaten both raw and cooked. It also has high nutritional value, being rich in phosphorus and in vitamins A and C [12]. *S. lycopersicum* has high water needs throughout its growth, which makes it a relevant choice for studies on alternative irrigation [13].

Germination test

Germination tests were carried out using a modified version of the Zucconi [14] phytotoxicity assay, in line with OPPTS 850.4200 [15]. Seeds of *Solanum lycopersicum* L. were commercially sourced and selected for uniform size and intact shape, with no pre-treatment. Twenty seeds were placed evenly on Whatman No. 1 filter paper in sterile Petri dishes. Raw or treated wastewater was used to moisten the seeds in the test groups. Tap water was used in the control group under identical conditions. All Petri dishes were sealed and kept in the dark at 20–25 °C. After 72 hours, germinated seeds were counted, and radicle length was measured. Each treatment was tested in triplicate to ensure statistical consistency**.**

α-Amylase activity was analysed to assess metabolic response during germination**.** The extraction followed a modified protocol based on Berbezy [16]. Germinated seeds were

homogenized in 50 mM Tris-HCl buffer (pH 7.5). The homogenate was centrifuged, and the supernatant was used as the crude enzyme extract.

Enzymatic activity was quantified by incubating 500 µL of extract in a mixture containing 100 mM potassium phosphate buffer (pH 6.5), 1% soluble starch, and 1% NaCl. The reaction was stopped by adding 2 N NaOH and 3,5-dinitrosalicylic acid. Absorbance was measured at 520 nm using a spectrophotometer. Total protein in the extract was measured using the Bradford method [17], with bovine serum albumin as the standard.

Greenhouse cultivation conditions and experimental design

The soil used in this experiment was the same as in our previous study. It had known physicochemical properties and proved suitable for agriculture [18]. The experiment took place in a greenhouse, using cylindrical polyethylene pots (27 cm diameter × 40 cm height). A base layer of fine gravel was added to improve drainage, reduce the risk of oxygen shortage, and limit fungal growth in the root zone. The pots were then filled with the prepared soil. *Solanum lycopersicum* seeds were sown directly, three per pot.

This trial tested the effects of irrigation using treated and untreated wastewater from the FSAC decentralized treatment unit on tomato growth. Twelve pots were randomly assigned to three groups. The control group (C) received tap water. The treated wastewater group (TW) was irrigated with effluent from the FSAC system. The untreated wastewater group (UW) received raw influent from the same source. All treatments were applied in equal volume and frequency to keep soil moisture uniform across the trial.

At the end of the growth period, several morphometric traits were measured to assess treatment effects. Plant height was measured from the base to the apical meristem. Fruit length and width were also recorded to evaluate how water quality affected reproductive growth and biomass use.

Mitochondrial extraction and succinate dehydrogenase activity assay

Mitochondria were isolated using a modified protocol based on the Romani method [19]. Fresh tomato tissues were homogenized in extraction buffer containing 0.25 M sucrose, 50 mM potassium phosphate buffer (pH 7.2), 6 mM EDTA, 10 mM β-mercaptoethanol, 0.5% polyvinylpolypyrrolidone, and 1 $mg \cdot mL^{-1}$ bovine serum albumin. The homogenate was filtered to remove debris, then centrifuged in steps to isolate the mitochondrial fraction.

Succinate dehydrogenase (SDH) activity was measured using a modified version of the Frenkel and Patterson method [20]. The reaction mixture contained 100 mM potassium phosphate buffer (pH 7.2), 10 mM potassium cyanide, 6 mM phenazine methosulphate, 20 mM sodium

succinate, and 0.2 mM dichlorophenol indophenol (DCIP). Mitochondrial extract was added to the mixture, and SDH activity was tracked by measuring the reduction of DCIP at 600 nm with a spectrophotometer.

SDH specific activity was calculated as enzymatic rate per milligram of total protein. Protein content was measured using the Bradford assay, with bovine serum albumin as the standard.

Bacteriological analysis

Microbiological analysis of *Solanum lycopersicum* fruits examined contamination by total coliforms, faecal coliforms, *Clostridium* spp., and *Salmonella* spp. [21]. Total and faecal coliforms were counted using the multiple-tube fermentation method [22]. Detection of *Salmonella* spp. used the Most Probable Number technique [23]. Clostridium spores were quantified following protocols from APAT-IRSA C.N.R. and APHA [24,25].

Statistical analysis

Statistical analysis was carried out using GraphPad Prism. Results are shown as means ± standard error of the mean (SEM). Two-way ANOVA was used to assess differences in morphological, physiological, and biochemical traits of *Solanum lycopersicum* under different irrigation treatments (tap water, untreated wastewater, and treated wastewater). Differences were considered significant at $p < 0.05$.

Results and Discussion

Quality characteristics of water samples used for irrigation

Table 1 shows the physicochemical values of the three irrigation waters. Nitrite (NO_2^-) rose from 0.06 ± 0.02 mg.L^{-1} in tap water to 42.57 ± 1.78 mg.L^{-1} in raw wastewater. After treatment, levels dropped to 12.41 ± 0.56 mg.L^{-1}. This remains well above the usual threshold for urban wastewater (<1 mg.L^{-1}) but stays within the Moroccan limit for irrigation water (30 mg.L^{-1}). This reduction shows partial treatment efficiency and incomplete nitrification. Nitrate (NO_3^-) levels stayed low in all samples, from 0.01 ± 0.02 mg.L^{-1} in tap water to 1.93 ± 0.72 mg.L^{-1} in raw wastewater. After treatment, levels dropped to 0.58 ± 0.14 mg.L^{-1}. These values are below typical urban wastewater concentrations and do not pose a risk for irrigation reuse.

Ammonium (NH_4^+) increased from 0.11 ± 0.02 mg.L^{-1} in tap water to 35.15 ± 2.75 mg.L^{-1} in raw wastewater, then fell to 15.68 ± 0.93 mg.L^{-1} after treatment. Sulphate (SO_4^{2-}) levels also rose, reaching 188 ± 5.16 mg.L^{-1} in raw wastewater. Treated water showed a reduction to 100 ± 23 mg.L^{-1}, below the 250 mg.L^{-1} irrigation limit.

Table 1: Physicochemical characteristics of the water samples

Physicochemical parameters	Unit	Tap water	Treated wastewater	Raw wastewater	Usual range of urban wastewater*,**	ILV**
NO_2^-	mg.L^{-1}	0.06±0.02	12.41±0.56	42.57±1.78	<1*	30
NO_3^-		0.01±0.02	0.58±0.14	1.93±0.72	<1*	-
NH_4^+		0.11±0.02	15.68±0.93	35.15±2.75	20-80*	-
PO_4^{3-}		0.88±0.07	1.14±0.21	4.33±0.63	2**	-
SO_4^{2-}		88±5.16	100±23	350±15	-	250
BOD_5		0	20±4.5	170±12	200-400	40*

* Limit values according to the guidelines for treated water intended for irrigation [26]
** ILV: Irrigation Limit Value [27]

Biochemical oxygen demand over five days (BOD_5) increased from 0 mg.L^{-1} in tap water to 170 ± 12 mg.L^{-1} in raw wastewater, and dropped to 20 ± 4.5 mg.L^{-1} after treatment. This indicates a major drop in biodegradable organic matter.

In summary, while some values remain higher than usual for urban wastewater, the treated water meets Moroccan thresholds for irrigation reuse in terms of nitrites, sulphates, and BOD_5.

Influence of raw and treated wastewater on seed germination

Germination tests showed clear differences in seed response under the three irrigation treatments (Figure 1). Seeds irrigated with raw wastewater had the highest germination index. Those given treated wastewater showed slightly lower values. Seed weight also increased under raw wastewater, followed by treated wastewater, compared to the control.

Raw wastewater probably provided extra nutrients and organic matter, which boosted seed metabolism during germination. A similar result was reported in a previous study. Rice seeds treated with municipal wastewater had a higher germination index than those irrigated with treated water [28]. The effect was linked to higher levels of dissolved nutrients and minerals in raw wastewater, which may act as natural biostimulants during early seed growth. Our findings differ from Ravindran *et al.* [29], who found a higher germination index in tomato seeds irrigated with treated wastewater than with raw effluent. This contrast may reflect variation in wastewater composition, source, or treatment method, showing the need to consider the physicochemical profile of the water used.

El Kafz *et al.* [30] showed that olive mill wastewater at high concentration was phytotoxic to tomato seeds. Dilution was needed to reduce toxicity. When treated properly, the same

wastewater improved seed germination. This agrees with our results: moderate use of treated wastewater supported germination, although less effectively than raw wastewater in this case. In summary, raw wastewater enhanced early seed development under controlled conditions, though it may carry risks. Treated wastewater was safer but had a milder effect.

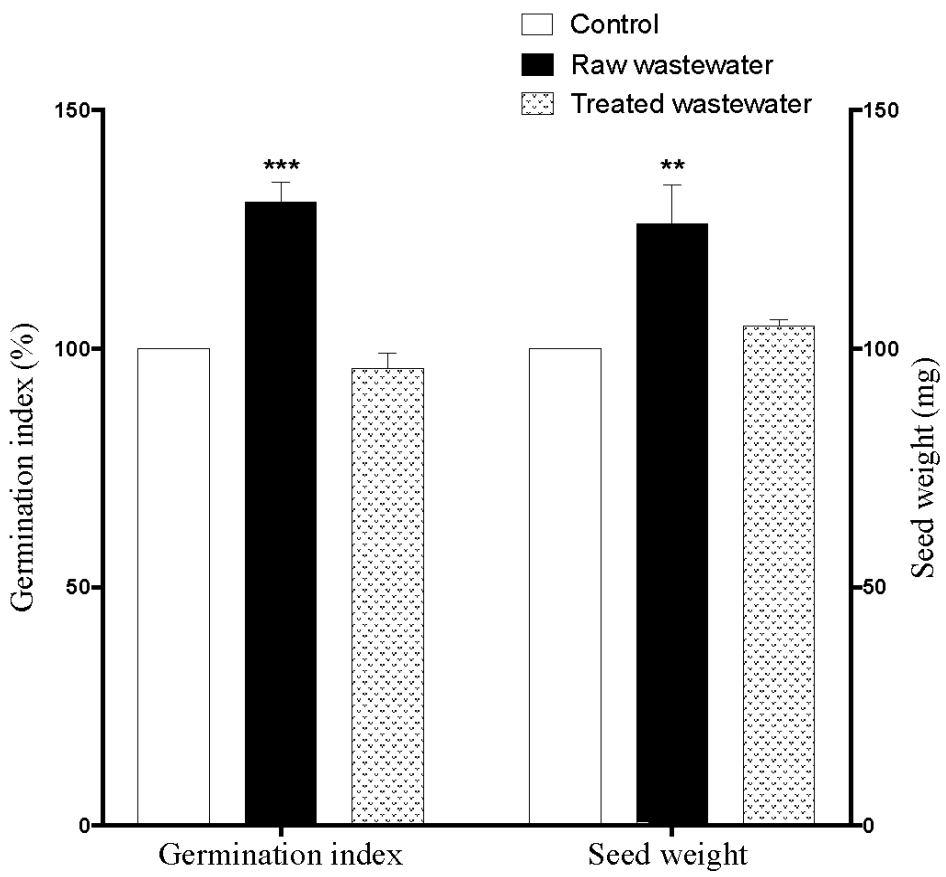

Figure 1. Effect of different irrigation types on seed germination index and seed weight. **Control**: Tap water; **Raw wastewater**: untreated effluent; **Treated wastewater**: effluent after treatment. Data are expressed as mean ± SD. **p < 0.01: very significant (**)**; p < 0.001: highly significant (***)

Variation of α-amylase activity in tomato seeds

To clarify the effect of irrigation on seed germination, α-amylase activity was measured in germinated tomato seeds [31]. This enzyme breaks down starch during germination.

Figure 2 shows that α-amylase activity differed across treatments. Seeds irrigated with raw wastewater showed the highest activity. Activity was lower with tap water and treated wastewater. This increase aligns with the higher germination index seen under raw wastewater. Raw wastewater appears to stimulate reserve mobilization in tomato seeds, possibly through bioavailable nutrients or mild stress signals that activate the enzyme [32].

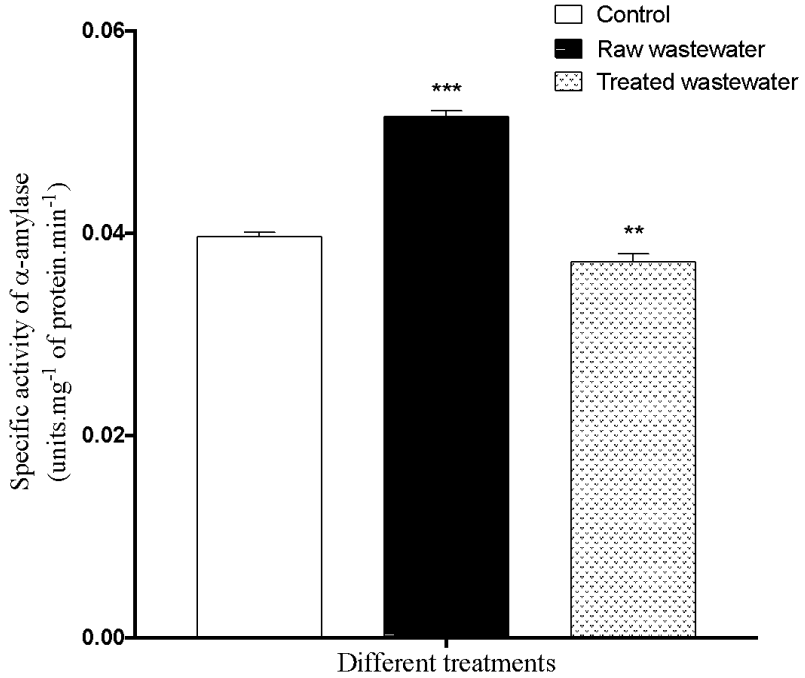

Figure 2. Effect of irrigation type on the specific activity of α-amylase (units mg^{-1} protein min^{-1}). Data are expressed as mean ± SD. **p < 0.01: very significant (**)**; p < 0.001: highly significant (*****)**

These results agree with Abdennbi *et al.* [32], who found increased α-amylase activity in seeds exposed to olive mill wastewater**.** Their study showed that wastewater can stimulate enzyme activity during early growth**.** Belasri *et al.* [16] also found a clear link between germination and α-amylase activity in *Medicago sativa* seeds treated with different leachate concentrations**.** Enzyme activity followed the same pattern as germination**.** In our study, the match between germination index and α-amylase activity supports the link between reserve mobilization and irrigation water quality**.**

Effects of raw and treated wastewater on the plant growth

Figures 3 and 4 show that irrigation with different water sources affected tomato plant morphology**.** Stem height and leaf size both changed**.** Over 90 days, stem height increased in all treatments. Plants irrigated with treated wastewater grew the tallest, reaching 57.5 cm by day 90.

wastewater (37 cm), which showed the least growth**.** This agrees with Muscarella *et al.* [33], who found that treated wastewater increases tomato height**.** The effect was linked to higher nutrient levels, especially nitrogen and phosphorus**,** which support vegetative growth.

Leaf length and width were also greatest in plants irrigated with treated wastewater**,** in line with stem growth. Ammonium (NH_4^+) and phosphate (PO_4^{3-}) in the treated water may have promoted cell division and expansion**,** leading to larger leaves**.**

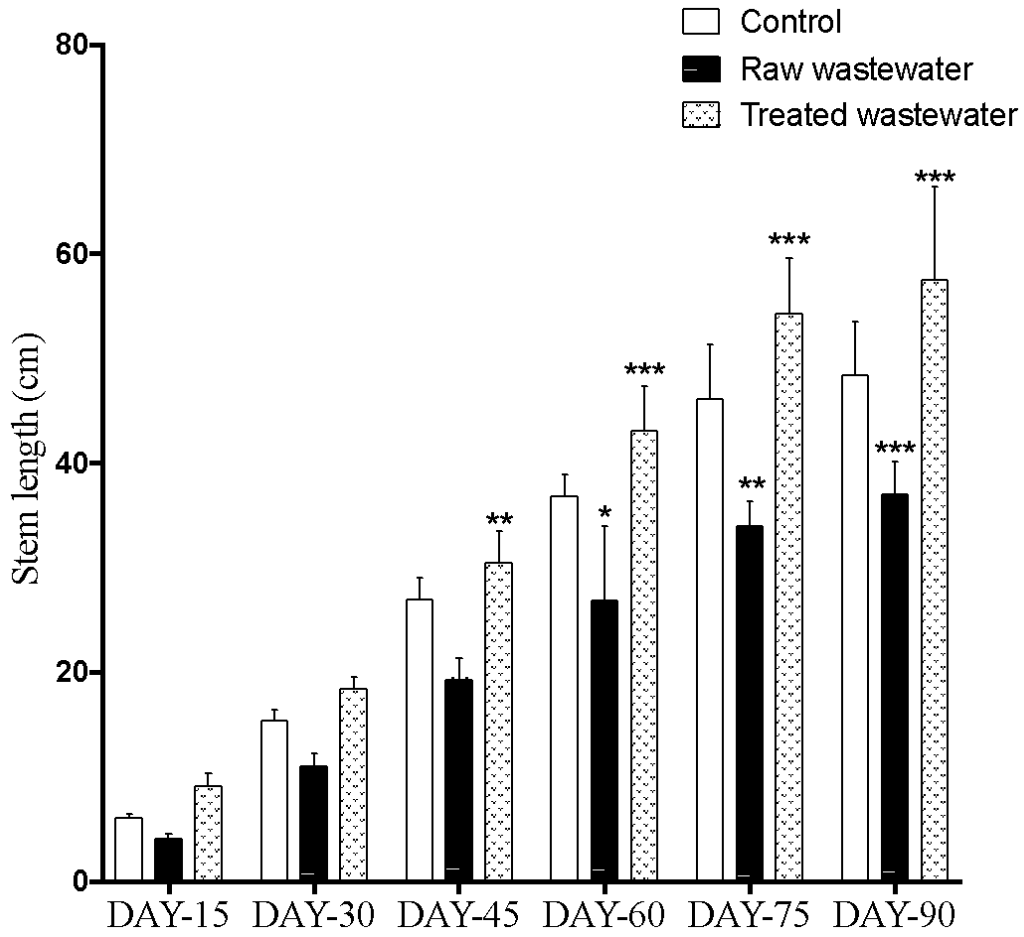

Figure 3. Temporal evolution of stem length in *Solanum lycopersicum* plants irrigated with tap water, control), treated wastewater, and raw wastewater. Values represent means ± SD (n = 10). * $p < 0.05$ (significant). ** $p < 0.01$ (very significant); ***$p < 0.001$ (highly significant).

These plants were significantly taller than those irrigated with tap water (48.35 cm) and raw Plants irrigated with raw wastewater had the smallest leaves, suggesting phytotoxic effects from untreated effluent. High nitrite (NO_2^-) and BOD_5 levels likely caused stress, reducing metabolic efficiency and limiting photosynthesis, which restricted foliar development [34].

Tap water produced intermediate growth, with moderate leaf size and stem height. The absence of both pollutants and extra nutrients explains this pattern. Tap water is safe, but lacks the fertilizing potential of treated wastewater, which may increase biomass when combined with fertilizer [35].

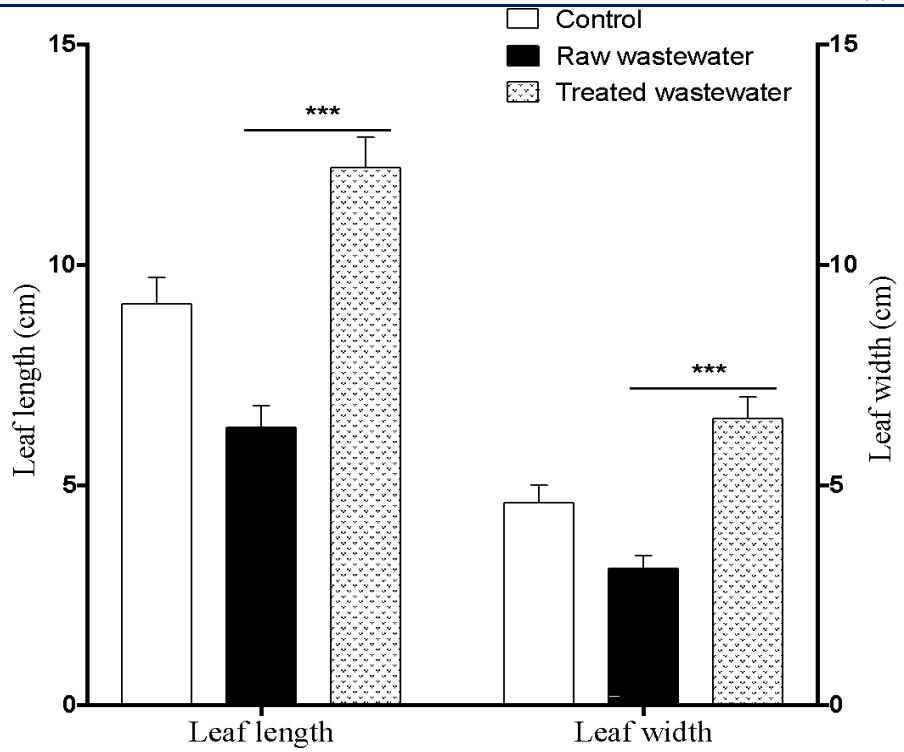

Figure 4. Final measurements of leaf length and leaf width in *Solanum lycopersicum* plants irrigated with tap water, treated wastewater, and raw wastewater. ***$p < 0.001$ (highly significant).

Microbiological characterization of harvested tomatoes

Bacteriological analysis was done to assess the sanitary quality of tomato fruits irrigated with different water sources. Tests were performed by an accredited agri-food laboratory in Casablanca, Morocco. The analysis covered tomatoes irrigated with tap water, treated wastewater, and raw wastewater.

Bacteriological analysis of tomato fruits irrigated with tap water, treated wastewater, and raw wastewater showed low microbial counts across all treatments (Table 2). Clostridium, faecal coliforms, and total coliforms were below 10 CFU/g in both control and treated wastewater fruits. Raw wastewater fruits had a slightly higher total coliform count ($<4.10^1$ CFU/g), but were still low. Salmonella was not detected in any sample.

Table 2. Bacteriological parameters in tomato fruits samples irrigated with tap water (control), treated wastewater, and raw wastewater.

Parameters	Units	Control	Treated wastewater	Raw wastewater
Clostridium [24, 25]	ufc/g	<10	<10	<10
Faecal Coliform [22]		<10	<10	<10
Total Coliform [22]		<10	<10	$<4.10^1$
Salmonella [23]	*spp/25g*	Absent	Absent	Absent

These findings agree with Ouansafi *et al.* [34], who reported no pathogenic bacteria in tomatoes irrigated with treated wastewater. Orlofsky *et al.* [36] also found low faecal indicators and no major pathogens in similar conditions. These studies show that with proper treatment and careful practices, treated wastewater carries low contamination risk. Raw wastewater raised coliform levels slightly, but counts stayed within safety limits for fresh produce. No Salmonella was found [37]. Under the study conditions, microbial loads remained low and did not present a food safety risk.

Enzymatic activity of succinate dehydrogenase in leaves and fruits

SDH activity in *Solanum lycopersicum* leaves and fruits varied with tissue type and irrigation source (Figure 5).

SDH is a mitochondrial enzyme in the tricarboxylic acid cycle and electron transport chain. It indicates mitochondrial function and metabolic state [38]. Activity was higher in leaves than in fruits across all treatments. Leaf tissues support photosynthesis and growth, requiring sustained energy. Fruits prioritize storage over respiration, so enzyme activity was lower. This matches previous findings in tomato and other solanaceous plants, where photosynthetic organs had higher SDH activity than reproductive tissues [39]. Plants irrigated with tap water had the highest SDH activity, especially in leaves. This points to healthy mitochondrial function under non-stress conditions.

Treated wastewater caused a moderate drop in SDH, mainly in leaves. This may reflect mild stress from residual elements, such as trace metals, despite the nutrients in reclaimed water [40]. In fruits, SDH activity remained higher than in the raw wastewater group, suggesting partial stress mitigation. Leaf SDH activity dropped by more than 60% under raw wastewater. Fruit activity was very low (0.0024 ± 0.0018 IU·mg^{-1} protein·min^{-1}). This sharp decline reflects toxic effects from high salinity (SO_4^{2-}) and nitrogen compounds (NO_2^-).

These disrupt mitochondrial enzymes and redox stability [41]. Earlier studies also showed that raw wastewater reduced mitochondrial function and respiration enzyme activity [18,34]. Standard deviation fell under raw wastewater, especially in fruits, suggesting a uniform stress response. This supports SDH activity as a sensitive marker of stress in response to irrigation water quality.

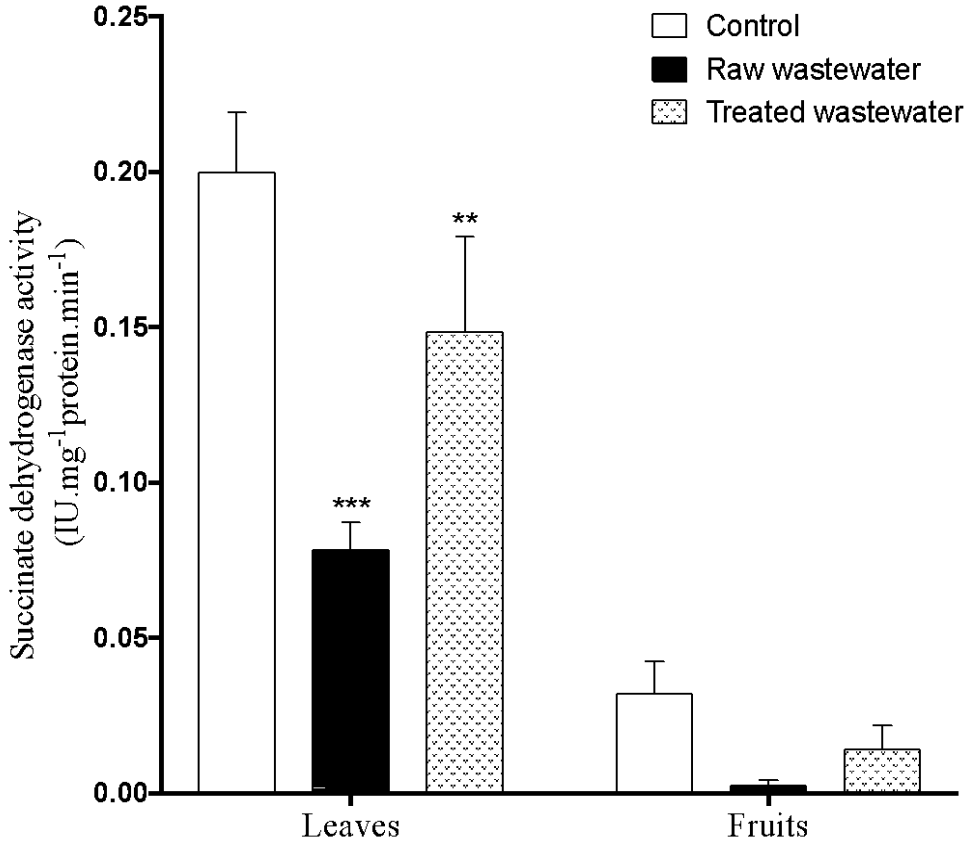

Figure 5. The enzymatic activity of SDH in leaves and fruits of tomato plants. ** $p < 0.01$ (very significant); ***$p < 0.001$ (highly significant).

Conclusion

This study assessed the agronomic value of treated wastewater from a pilot decentralized system at the Faculty of Sciences Ain Chock (FSAC), Casablanca**.** In water-scarce regions such as Morocco, reusing treated effluent can conserve freshwater and improve soil fertility**.** Physicochemical analysis showed that treatment reduced nitrites, ammonium, and organic matter to levels within national irrigation standards**.** Nitrite levels remained higher than in tap water but stayed within safe limits**,** demonstrating effective treatment. Microbiological results showed that raw wastewater boosted germination and enzyme activity but carried greater risks of phytotoxicity and contamination. Treated wastewater was safer and supported healthy early growth**.** Tomatoes irrigated with treated wastewater grew taller and had larger leaves than those irrigated with tap water or raw wastewater. Nutrients in the treated water improved development and yield**.** Microbiological testing confirmed the safety of fruit from treated wastewater plots**.** Fruits irrigated with raw wastewater showed signs of contamination risk**.** This underlines the need for proper treatment to ensure both crop productivity and food safety**.** Treated wastewater from the FSAC unit provides a sustainable option for irrigation in dry

regions**.** It supports resource recovery, environmental protection, and plant growth**.** Regular water quality checks remain essential**.** More research is needed to test other crops and field conditions before scaling up use in agriculture**.**

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Author Contributions

All authors contributed to the study's conception, design, data collection, and analysis. The first draft of the manuscript was written by Lamiaa Belasri, with all authors providing feedback on previous versions. All authors read and approved the final manuscript.

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Data Availability

All data generated in this study are included in the submitted manuscript.

Consent for publication

All authors have approved and consented to publish this paper.

Competing interests

The authors declare no competing interests.

References

[1] He, C., Liu, Z., Wu, J., Pan, X., Fang, Z., Li, J., & Bryan, B. A., 2021, Future global urban water scarcity and potential solutions. *Nature Communications* **12**(1), 4667. https://doi.org/10.1038/s41467-021-25026-3

[2] FAO. 2017. *The future of food and agriculture – Trends and challenges*. Rome: Food and Agriculture Organization of the United Nations (Rome: FAO). Available at:

https://openknowledge.fao.org/server/api/core/bitstreams/2e90c833-8e84-46f2-a675-ea2d7afa4e24/content

[3] Claro, A., Fonseca, A., Fraga, H., & Santos, J., 2024, Future Agricultural Water Availability in Mediterranean Countries under Climate Change: A Systematic Review. *Water* **16**(17), 2484. https://doi.org/10.3390/w16172484

[4] Casablanca-Settat Regional Investment Center (RIC), 2018, Socioeconomic data of the Casablanca-Settat Region. https://www.hcp.ma/Les-comptes-regionaux-de-l-annee-2018_a2585.html

[5] Et-Touile, H., 2023, Water Scarcity Impacts On Food Production in Morocco. *International Journal of Strategic Management and Economic Studies* **2**(5), 1640–1653. https://doi.org/10.5281/zenodo.8355193

[6] Ungureanu, N., Vlăduț, V., & Voicu, G., 2020, Water scarcity and wastewater reuse in crop irrigation. *Sustainability* **12**(21), 9055. https://doi.org/10.3390/su12219055

[7] Yadav P., Singh R.P., Gupta R.K., Pradhan T., Raj A., Singh S.K., Kaushalendra, Pandey K.D., Kumar A., 2023, Contamination of soil and food chain through wastewater application,

In: Luiz Fernando Romanholo Ferreira, Ajay Kumar, Muhammad Bilal (Eds) *Advances in Chemical Pollution, Environmental Management and Protection*, Volume 9, 2023, pp. 109–132 (Amsterdam: Elsevier). DOI: https://doi.org/10.1016/bs.apmp.2022.11.001

[8] Chakri, N., Amrani, B. E., & Berrada, F., 2021, Modeling and optimization of wastewater treatment, from the Ain Chock faculty in Morocco, using the vertical flow filter filled with pozzolana. *Desalination and Water Treatment* **234**, 376–385. https://doi.org/10.5004/dwt.2021.27598

[9] Peco, J., Pérez–López, D., Centeno, A., Moreno, M., Villena, J., & Moratiel, R., 2023, Comparison of physiological and biochemical responses of local and commercial tomato varieties under water stress and rehydration. *Agricultural Water Management* **289**, 108529. https://doi.org/10.1016/j.agwat.2023.108529

[10] Association française de normalisation (AFNOR), 1999, *Recueils des normes AFNOR. Collection of AFNOR Standards*, Tomes 1 à 4 (Paris : AFNOR).

[11] Rodier, J., Legube, B., & Merlet, N., 2009, *L'Analyse de l'eau*, 9ème édition, entièrement mise à jour (Paris: Dunod).

[12] Yang, Z., Li, W., Li, D., & Chan, A., 2023, Evaluation of Nutritional Compositions, Bioactive Components, and Antioxidant Activity of Three Cherry Tomato Varieties. *Agronomy* **13**(3). https://doi.org/10.3390/agronomy13030637

[13] Júnior, A., De Souza Vilela, M., Carmona, R., Peixoto, J., Da Silva, N., Clara, J., Saba, E., & De Jesus Da Silva Neto, A., 2024, Nutritional quality of tomato in response to different fertilization

doses and conduction systems. *Contribuciones A Las Ciencias Sociales*. https://doi.org/10.55905/revconv.17n.7-347

[14] Zucconi, F., Pera, A., Forte, M., & DeBertolli, M., 1981, Evaluating Toxicity of Immature Compost. *Biocycle* **22**, 54–57. https://archive.org/details/sim_biocycle_1981_22_index/mode/2up

[15] US Environmental Protection Agency (USEPA), 1996, *Ecological effects test guidelines (OPPTS 850.4200): Seed germination/root elongation toxicity test*. https://nepis.epa.gov/Exe/ZyPURL.cgi?Dockey=P100RF5I.txt

[16] Belasri, L., Hmimid, F., Cherki, M., & Ait Benichou, S., 2024, Seasonal comparison of the effect of landfill leachate from Mediouna (Casablanca, Morocco) on germination and α-amylase activity in *Lens culinaris* and *Medicago sativa*. *Euro-Mediterranean Journal for Environmental Integration* **9**, 1301–1309. https://doi.org/10.1007/s41207-024-00511-5

[17] Bradford, M. M., 1976, A rapid and sensitive method for quantitation of microgram quantities of protein utilizing the principle of protein-dye binding. *Analytical Biochemistry* **72**, 248–254. https://doi.org/10.1016/0003-2697(76)90527-3

[18] Belasri, L., Guenaou, I., Hmimid, F., & Ait Benichou, S., 2024, Assessing the impact of leachate irrigation on *Medicago sativa* (alfalfa) growth, enzymatic responses, and heavy metal accumulation. *Environmental Science and Pollution Research* **31**, 61033–61048. https://doi.org/10.1007/s11356-024-35307-1

[19] Romani, R. J., Yu, I. K., & Fisher, L., 1969, Isolation of tightly coupled mitochondria from acidic plant tissues. *Plant Physiology* **44**, 311–312. https://doi.org/10.1104/pp.44.2.311

[20] Frenkel, C., & Patterson, M., 1973, Effect of carbon dioxide on activity of succinic dehydrogenase in 'Bartlett' pears during cold storage. *Horticultural Science* **8**, 395–396. Available online: https://eurekamag.com/research/000/068/000068615.php

[21] Tallon, P., Magajna, B., Lofranco, C., & Leung, K. T., 2005, Microbial Indicators of Faecal Contamination in Water: A Current Perspective. *Water Air and Soil Pollution* **166**, 139–166. https://doi.org/10.1007/s11270-005-7905-4

[22] Rice E.W., Baird R.B., Eaton A.D., Clesceri L.S. (Eds.), 2012, *Standard Methods for the Examination of Water and Wastewater*, 22nd edition (Washington, DC: American Public Health Association, American Water Works Association, Water Environment Federation)

[23] El-Lathy, A. M., El-Taweel, G. E., El-Sonosy, M. W., Samhan, F. A., & Moussa, T. A., 2009, Determination of pathogenic bacteria in wastewater using conventional and PCR techniques. *Environmental Biotechnology* **5**(2), 73–80. https://bibliotekanauki.pl/articles/363166.pdf

[24] APAT-IRSA, C.N.R., 2003, *Metodi analitici per le acque. Manuali e linee guida 29/2003*. APHA, AWWA, WEF, 1995. *Standard Methods for the Examination of Water and Wastewater*. 19th ed., (Washington, DC: APHA), https://www.irsa.cnr.it/wp/?page_id=5435

[25] American Public Health Association, American Water Works Association, Water Pollution Control Federation, & Water Environment Federation (APHA, AWWA, WEF), 1998, *Standard Methods for the Examination of Water and Wastewater* (Vol. 3). 20th ed., (Washington, DC: APHA), https://www.abpsoil.com/images/Books/Standard-Methods-for-the-Examination-of-Water-and-Wastewater-20.pdf

[26] UNEP/MAP/MED POL/WHO, 2004, *Municipal Wastewater Treatment Plants in Mediterranean Coastal Cities (II)*, MAP Technical Report Series No. 157 (Athens: United Nations Environment Programme / Mediterranean Action Plan), 1810-6218. https://digitallibrary.un.org/record/530303/files/mts157eng.pdf?ln=en

[27] Government of Morocco, 2002, Joint decree of the Minister of Equipment and the Minister in charge of Land Use Planning, Environment, Urban Planning, and Housing No. 1276-01 of October 17, 2002, establishing the quality standards for water intended for irrigation. *Official Bulletin* No. 1276-01, 1–5. https://www.susana.org/downloads?documentID=3175

[28] Gassama, U. M., Puteh, A. B., & Bangura, R. S., 2021, Impact of different concentrations of municipal wastewater on rice seed germination and seedling performance. *Zenodo* **7**(11). https://doi.org/10.5281/zenodo.5759603

[29] Ravindran, B., Kumari, S., Stenström, T., & Bux, F., 2016, Evaluation of phytotoxicity effect on selected crops using treated and untreated wastewater from different configurative domestic wastewater plants. *Environmental Technology* **37**, 1782–1799. https://doi.org/10.1080/09593330.2015.1132776

[30] El Kafz, G., Cherkaoui, E., Benradi, F., Khamar, M., Nounah, A., & Azzouzi, S., 2023, Study of the Phytotoxicity of Olive Mill Wastewater on Germination and Vegetative Growth – Case of Tomato (*Solanum lycopersicum* L). *Ecological Engineering & Environmental Technology* **24**(5), 265–274. https://doi.org/10.12912/27197050/165817

[31] Guzmán-Ortiz, F. A., Castro-Rosas, J., Gómez-Aldapa, C. A., Mora-Escobedo, R., Rojas-León, A., Rodríguez-Marín, M. L., Falfán-Cortés, R. N., & Román-Gutiérrez, A. D., 2018, Enzyme activity during germination of different cereals: A review. *Food Reviews International* **35**(3), 177–200. https://doi.org/10.1080/87559129.2018.1514623

[32] Abdennbi, S., Trabelsi, L., Ahmed, G. B., Ayadi, M., Maktouf, S., Gargouri, K., Chaieb, M., & Mekki, A., 2024, Assessment of the germination power and α-amylase activity in the soil rhizospheric compartment amended with olive mill waste waters. *Environmental Monitoring and Assessment* **196**(12). https://doi.org/10.1007/s10661-024-13380-w

[33] Muscarella, S., Alduina, R., Badalucco, L., Capri, F., Di Leto, Y., Gallo, G., Laudicina, V., Paliaga, S., & Mannina, G., 2024, Water reuse of treated domestic wastewater in agriculture: Effects on tomato plants, soil nutrient availability and microbial community structure. *Science of the Total Environment* **922**, 172259. https://doi.org/10.1016/j.scitotenv.2024.172259

[34] Ouansafi, S., Bellali, F., Maaghloud, H., & Kabine, M., 2022, Treated wastewater irrigation of tomato: Effects on crop production, and on physico-chemical properties, SDH activity and microbiological characteristics of fruits. *Environmental Challenges* **8**, 100556. https://doi.org/10.1016/j.envc.2022.100556

[35] Marcińczyk, M., Ok, Y., & Oleszczuk, P., 2022, From waste to fertilizer: Nutrient recovery from wastewater by pristine and engineered biochars. *Chemosphere* **311**, 135310. https://doi.org/10.1016/j.chemosphere.2022.135310

[36] Orlofsky, E., Bernstein, N., Sacks, M., Vonshak, A., Benami, M., Kundu, A., Maki, M., Smith, W., Wuertz, S., Shapiro, K., & Gillor, O., 2016, Comparable levels of microbial contamination in soil and on tomato crops after drip irrigation with treated wastewater or potable water. *Agriculture Ecosystems & Environment* **215**, 140–150. https://doi.org/10.1016/j.agee.2015.08.008

[37] Committee on the Review of the Use of Scientific Criteria & Performance Standards for Safe Food, 2003, Scientific criteria to ensure safe food. *Grove/Atlantic Inc* (Washington, D.C.: The National Academies Press). https://doi.org/10.17226/10690

[38] Huang, S., Braun, H., Gawryluk, R., & Millar, A., 2019, Mitochondrial complex II of plants: Subunit composition, assembly, and function in respiration and signaling. *The Plant Journal* **98**(3), 405–417. https://doi.org/10.1111/tpj.14227

[39] Kolekar, S., Sankapal, P., Khare, K., & Chinnasamy, P., 2023, Assessment of recycled treated wastewater for sustainable tomato crop production: A comprehensive review. *Environmental Challenges* **13**, 100791. https://doi.org/10.1016/j.envc.2023.100791

[40] Belasri, L., Arabi, M., Sabri, S., Hmimid, F., & Benichou, S. A., 2024, Transfer of metals from the soil to *Medicago sativa* irrigated with municipal landfill leachate. *Journal of Ecological Engineering* **25**(8), 336–346. https://doi.org/10.12911/22998993/190349

[41] Che-Othman, M. H., Millar, A. H., & Taylor, N. L., 2017, Connecting salt stress signalling pathways with salinity-induced changes in mitochondrial metabolic processes in C3 plants. *Plant Cell & Environment* **40**(12), 2875–2905. https://doi.org/10.1111/pce.13034

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Hospital Solid Waste: Sources, Risks, and the Path to Sustainable Management

Khawla Waddi [a1], Selma Siham El Khayat [a,b,2], Sanaa Deblij [a,c,3], Imane Benjelloun [a4], Karima Jmaili [a5], Ghita Radi Benjelloun [a6], Meriem Mahmoudi [a7], Bouchaib Bahlaouan [c8], & Nadia Boutaleb [a9]☑

[a] *Hassan II University of Casablanca (https://ror.org/001q4kn48), Laboratory of Biotechnology, Agri-Food, Materials and Environment, Team: Biotechnologies, Resource Valorization, Quality, Health and Ecotoxicology, Faculty of Science and Technology Mohammedia, BP 146, Mohammedia 20650, Morocco*

[b] Nephrology Department, Ibn Rochd University Hospital (https://ror.org/03sbc8x80), Casablanca 20360, Morocco.

[c] *Higher Institutes of Nursing and Health Technical Professions (ISPITS) (https://ror.org/007h8y788), Laboratory of Care, Health and Sustainable Development 2S2D, Higher Institutes of the Nursing Professions and Techniques of Health ISPITS Casablanca 22500, Morocco.*

[1] ***ORCID**: 0000-0001-9820-2265;* **Email:** khawla.waddi@etu.fstm.ac.ma

[2] ***ORCID**: 0000-0003-4746-7516;* **Email:** selmasiham@yahoo.fr

[3] ***ORCID**: 0000-0002-5147-982X ;* **Email:** deblijfstm@gmail.com

[4] ***ORCID**: 0000-0002-5577-8413;* **Email:** i.benjelloun@hotmail.fr

[5] ***ORCID**: 0009-0009-3153-0825;* **Email:** karima.jmaili-etu@etu.univh2c.ma

[6] ***ORCID**: 0000-0002-9884-8119;* **Email:** ghita.radibenjelloun@etu.fstm.ac.ma

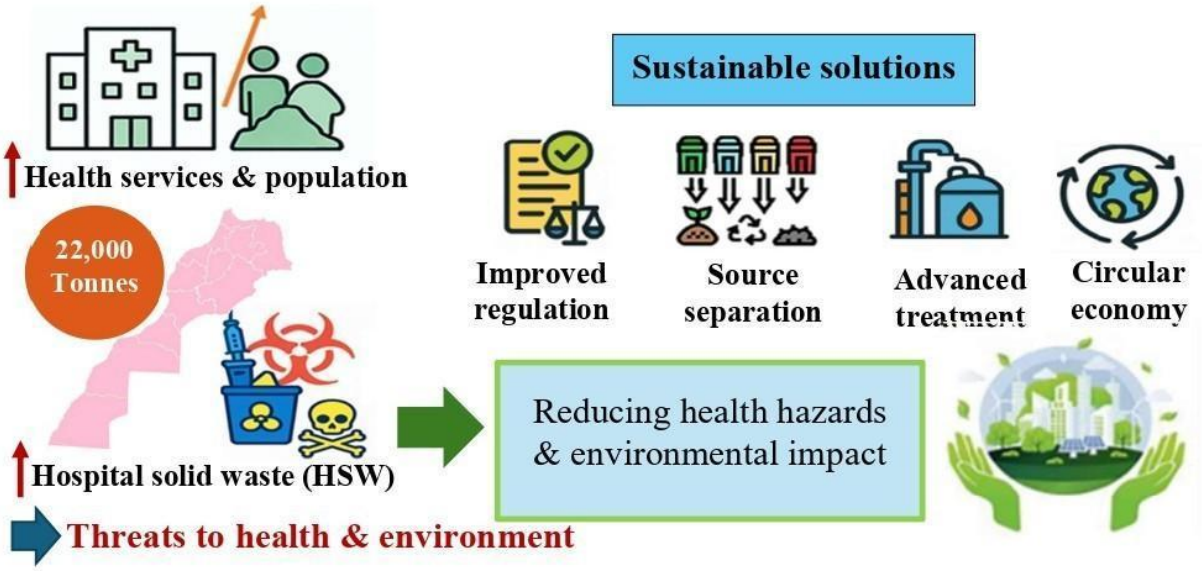
[7] ***ORCID**: 0009-0002-2682-2478;* **Email:** meriem.mahmoudi2-etu@etu.univh2c.ma

[8] ***ORCID**:* 0000-0002-0976-1274; **Email**: b.bahlaouan@ispitscasa.ac.ma

[9] ***ORCID**: 0000-0003-1628-4311;* **Email:** nadia.boutaleb@fstm.ac.ma

☑ ***Corresponding author:*** Nadia Boutaleb; ***Email***: nadia.boutaleb@fstm.ac.ma

The growth of health services and the population, combined with inadequate waste management systems, leads to the generation of more than 22,000 tonnes of hospital solid waste (HSW) each year in Morocco. Although most of this waste is non-hazardous, a significant proportion contains infectious, chemical, pharmacological, or radioactive agents that pose serious threats to human health and the environment. Sustainable solutions include improved regulation, source separation, advanced treatment methods, and the integration of circular economy principles. Applied together, these measures can reduce health hazards and environmental impact, contributing to a safer and more sustainable hospital waste management system.



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Abstract

The growth of healthcare services, population increase, and inadequate waste management systems have made hospital solid waste (HSW) a growing concern in developing nations. A considerable amount of hospital waste contains infectious, chemical, pharmacological, or radioactive agents that pose serious threats to human health and the environment, even though most of it is non-hazardous. Focusing on waste types, sources, associated risks, treatment methods, and current management practices, this analysis examines 2,350 scientific publications from 2000 to 2025. Morocco, which generates more than 22,000 tonnes of hospital waste each year, is used as a case study, revealing persistent issues such as inadequate segregation, insufficient training, and weak enforcement. The review also examines sustainable solutions, including improved regulation, source separation, advanced treatment methods, and circular economy approaches, to reduce health hazards and environmental impact.

Keywords: *Hospital, Solid, Waste, Management, Treatment, Risk.*

Introduction

Driven by the development of medical technologies [1], improved access to healthcare, and the rapid growth of population [2], urbanization, and manufacturing activities [3,4], developing countries are experiencing a marked increase in solid medical waste. This poses a major challenge for waste management and a growing threat to public health and the environment [5]. In many developing nations, the management of solid hospital waste has become a global concern. As healthcare services expand to meet the needs of growing populations [6], medical facilities generate more waste in various forms. Some present serious risks to human health and the environment. About 85% of hospital waste is categorized as non-hazardous, with the remaining 15% comprising toxic, infectious, or hazardous material [7]. Although it accounts for a smaller proportion, this fraction carries a significant risk to public health because it can transmit diseases such as HIV, hepatitis B and C, and multidrug-resistant bacterial infections [8].

Numerous medical procedures, including diagnosis, treatment, surgery, laboratory testing, biomedical research, and home-based care, generate hospital waste. Sharps, blood-stained materials, contaminated glassware, chemical compounds, and pharmaceutical residues are all included [9,10]. The World Health Organization (WHO) defines hospital solid waste as any solid material discarded during patient care, immunizations, biological testing, and medical observations [11]. Healthcare personnel, waste handlers, and the general public can be affected by extensive exposure and contamination resulting from improper handling of this waste [9,12]. The variety and hazardous nature of healthcare waste (HCW) require strict protocols for segregation, collection, treatment, and disposal [13]. Waste management systems in many low- and middle-income nations are either inadequate or poorly enforced [14,15]. Contributory factors include insufficient training for staff handling medical waste, weak regulatory frameworks, and limited financial and technological resources [16].

In parallel with its responsibility to care for patients and improve public health, the healthcare sector is increasingly generating waste that threatens environmental sustainability and human well-being [17,18]. The amount and complexity of healthcare waste are increasing as health systems intensify their efforts to reduce illness and expand access to care [18]. Comprehensive approaches that emphasise environmentally responsible disposal, safe handling, and effective treatment are required [19].

Hospital solid waste management is increasingly difficult in Morocco [20]. Persistent gaps in implementation, monitoring, and infrastructure remain despite national efforts to strengthen the

regulatory framework and waste management standards [21,22]. Morocco produces over 22,000 tonnes of hospital waste each year, of which about 6,000 tonnes are classified as hazardous, according to the Ministry of Energy, Mines, and Environment [23]. In addition, between 18% and 64% of healthcare institutions fail to manage or dispose of their medical waste correctly, according to a WHO report based on a 2002 survey in 22 low-income countries [24].

This review examines the current state of solid hospital waste management in Morocco, highlighting the hazards to human health and the environment, current practices, constraints, and opportunities for more integrated and sustainable waste management strategies.

Bibliometric Insights into Solid Hospital Waste

A bibliometric analysis was conducted using PubMed, Scopus, Web of Science, Google Scholar, and ScienceDirect to examine research on solid hospital waste from 2000 to 2025. The generation, classification, environmental impact, and treatment of hospital solid waste were the main focus of this multi-database approach, ensuring a comprehensive and representative study of global research output on the subject.

The number of publications has increased steadily over the past 20 years, with a marked rise after 2020, linked in part to the COVID-19 pandemic and the resulting growth in medical waste. Research frequently addresses hazardous waste management, environmental and human health risk assessments, disposal technologies, regulatory frameworks, and sustainable treatment methods.

Asia, particularly China and India, has made the largest contribution to research output, followed by North America and Europe, including the United States and Italy. Recent years have also seen a noticeable increase in studies from Latin America and Africa, reflecting growing concern over the environmental and public health impacts of hospital waste in low-income regions.

Significant gaps remain, notably in the behaviour of healthcare professionals, the application of monitoring systems, and the integration of circular economy principles into waste management. These findings highlight the urgent need for interdisciplinary research, capacity building, and stronger policy enforcement, particularly in low- and middle-income countries.

Search Strategy

A comprehensive search strategy was implemented to identify relevant literature, targeting five major databases: PubMed, Scopus, Web of Science, Google Scholar, and ScienceDirect (Table 1). Identical keyword sets were applied across all databases to ensure consistency and maximize coverage. The eligibility criteria restricted the search to publications from 2000 to 2025.
The review focused on qualitative and quantitative research on solid hospital waste, including waste generation, classification, treatment technologies, regulatory frameworks, environmental and health impacts, and sustainable management approaches.

Table 1. Research approach for systematic review process.

Database	Research Approach
PubMed	Title-Abstract-Keywords search using ("hospital waste" OR "healthcare waste" OR "medical waste") AND ("solid waste" OR "hazardous waste") AND ("waste management" OR "treatment" OR "disposal")
Scopus	Title-Abstract-Keywords search using ("hospital waste" OR "healthcare waste" OR "medical waste") AND ("solid waste" OR "hazardous waste") AND ("waste management" OR "treatment" OR "disposal")
Web of Science	Title-Abstract-Keywords search using ("hospital waste" OR "healthcare waste" OR "medical waste") AND ("solid waste" OR "hazardous waste") AND ("waste management" OR "treatment" OR "disposal")
Google Scholar	Keyword search using "hospital solid waste management", "healthcare waste disposal", "medical waste treatment"
ScienceDirect	Title-Abstract-Keywords search using ("hospital waste" OR "healthcare waste") AND ("solid waste management" OR "hazardous waste treatment")

Selection Criteria

The PRISMA statement formed the basis for the selection criteria. The aim was to identify recent literature on solid hospital waste management, including treatment technologies such as pyrolysis, autoclaving, and incineration, environmental impacts, policy frameworks, and waste issues linked to pandemics. This process produced a comprehensive database of research articles published in reputable journals over the past 25 years (2000–2025). Establishing clear inclusion and exclusion criteria was essential to maintain focus, originality, and avoid selection bias in the study. Articles published before 2000 were excluded. A total of 18,200 records were

removed, as the search was largely limited to publications in English and French. The remaining 2,350 records were retained for full-text review.

Quality Assessment

The review focused exclusively on original research articles and review papers to ensure the inclusion of high-quality, peer-reviewed scientific literature. A stringent screening process was applied to remove duplicate records and preserve data integrity. Only research directly related to solid hospital waste management, such as treatment methods, environmental impacts, legal frameworks, and pandemic-associated issues, was included in the scope of analysis. To avoid thematic dilution, studies not directly related by keywords and outside the primary focus, including clinical case reports, pharmacology, and unrelated biomedical topics, were excluded. Figure 1 summarizes the PRISMA statement-based selection process.

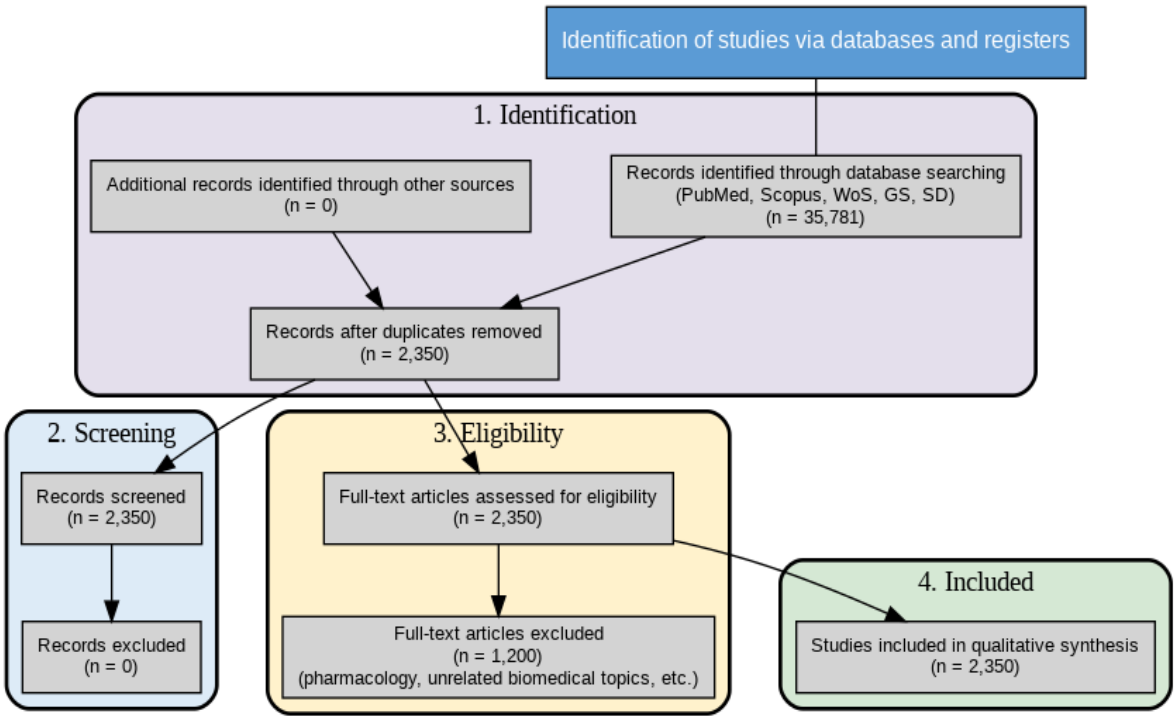

Figure 1. PRISMA flow diagram depicting the identification, screening, eligibility, and inclusion of studies in the systematic review.

Geographical Distribution of Publications

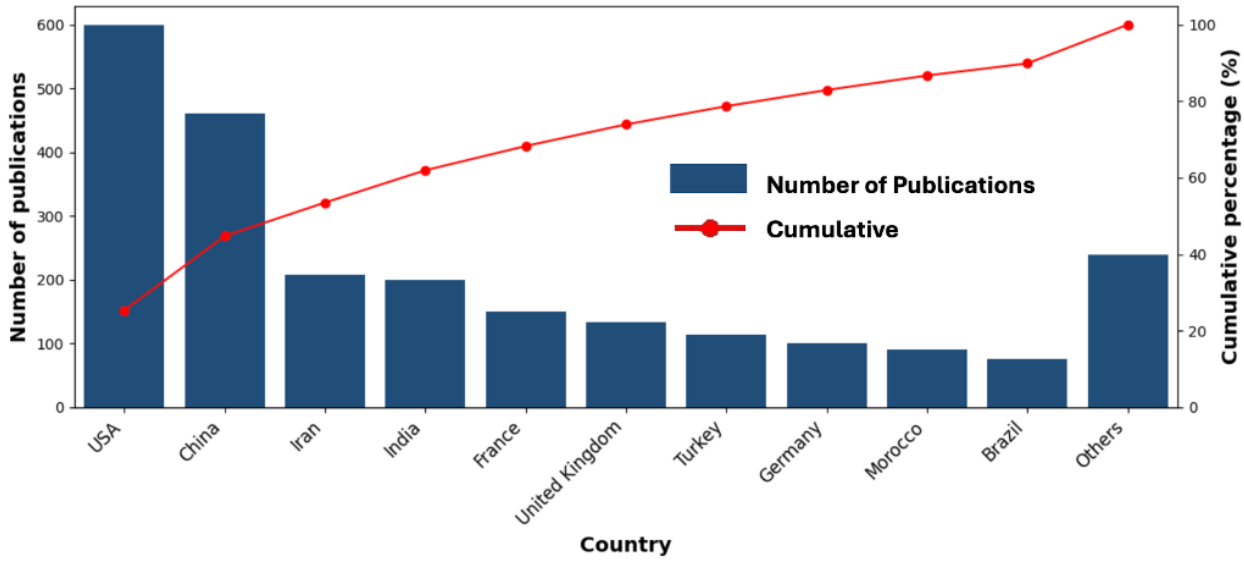

Figure 2. Pareto chart of publication distribution of reviewed papers by country.

The publication distribution of the 2,370 reviewed articles reflects a dynamic and global interest in Solid Hospital Waste research, covering its characterization, environmental impact, and toxicological assessment. Figure 2 shows the geographical distribution of publications. The United States leads individual countries in documented research output, with approximately 600 publications, reflecting strong academic infrastructure and governmental support for environmental and public health studies. China follows with about 460 publications, demonstrating growing investment in pollution control technologies and wastewater treatment innovations.

India, with roughly 200 publications, shows increasing commitment to managing hospital waste and associated health risks. With over 208 articles, Iran also demonstrates the expansion of regional research. The United Kingdom with 134 publications and Turkey with 113 publications are also notable contributors.

In France (150 publications) and Germany (100 publications), research is largely driven by regulatory frameworks and advanced analytical capabilities that enable detailed environmental assessments.

Morocco records close to 90 publications, highlighting its active role in addressing regional environmental concerns and developing capacity in hospital waste monitoring and management. Brazil, contributing about 75 publications, reflects Latin America's growing awareness and academic investment in the field.

The category of other countries, representing 240 publications, shows that a significant share of research originates from a broad range of nations on all continents. This confirms the global nature of the issue and the collaborative work of the international scientific community to face the environmental and health challenges linked to hospital solid waste.

Citation Trend Analysis (2000–2025)

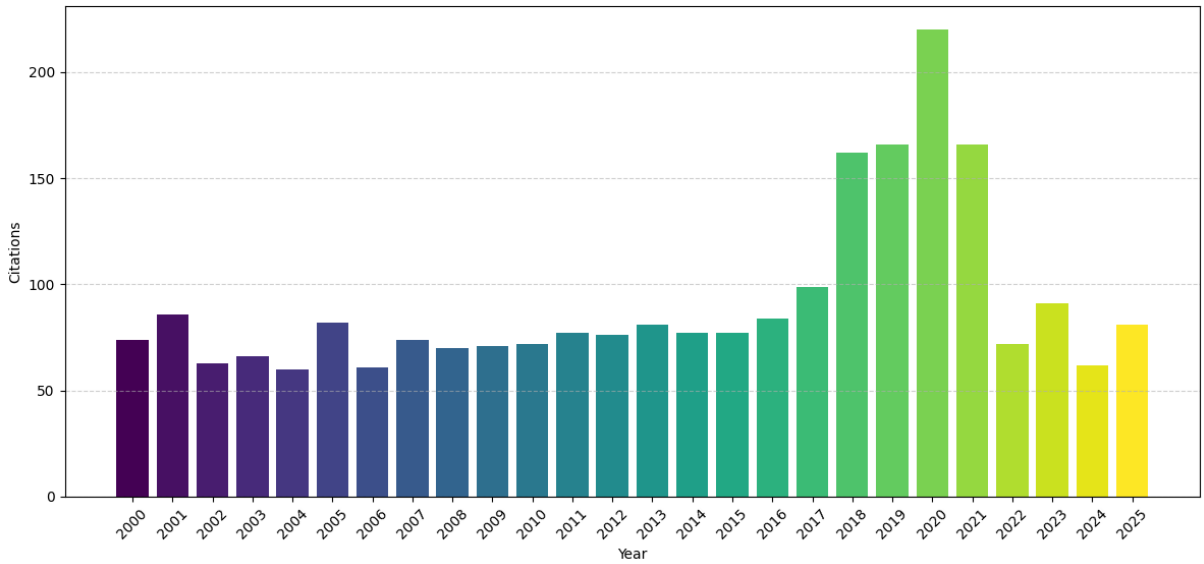

Figure 3. Citation trend for Hospital Solid Waste.

The citation trend in Figure 4 shows the evolving scholarly interest in hospital solid waste research over the past two decades. From 2000 to 2016, the annual citation count remained relatively stable, ranging from about 60 to 85 citations per year. A marked increase occurred after 2017, with citations rising to about 100 in 2018 and peaking at more than 210 in 2020. This peak points to a surge in attention, probably linked to growing global awareness of the environmental and public health impacts of hospital solid waste.

A modest decline followed, with citation numbers between 70 and 90 from 2021 to 2025, yet the overall upward trajectory since the mid-2010s remains clear. The sustained citation activity after 2020 indicates that hospital solid waste continues to be a critical topic in environmental pollution, particularly in the context of emerging contaminants and antimicrobial resistance.

This growing interest is connected to the global push for improved water quality management, especially in urban environments, and to rising concerns over micropollutants and pharmaceuticals in hospital discharges. It also reflects advances in analytical techniques, toxicological risk assessment, and wastewater treatment innovations to minimize the ecological footprint of healthcare facilities.

Definition, Sources, and Types of Hospital Waste

Definition of Hospital Waste

Healthcare waste (HCW) refers to all forms of solid or liquid waste generated through healthcare delivery, whether in hospitals, clinics, laboratories, research institutions, or home-based care settings [11,18,25]. It includes waste produced during biological testing on human beings or animals, medical diagnosis, treatment, vaccinations, and research [26]. This category covers both general non-hazardous components and hazardous fractions that may be chemically, biologically, or radiologically dangerous [9,27]. A considerable portion of HCW contains potentially hazardous materials, such as pathogens or toxic chemicals, which can threaten human health, workplace safety, and environmental integrity, even though most of it is similar in nature to household waste [11,26–28].

The volume of HCW is increasing as healthcare systems expand and medical interventions increase, with the need for efficient management from source segregation to disposal [9,10,18]. Improper treatment of such material can lead to serious consequences, including the spread of infections, environmental degradation, and heightened risks to public health [18,26,28].

Table 2. Terminology and Classification of Healthcare Waste in Scientific Literature (2000–2025).

Year	Database	Term Used	Definition	Authors / Reference
2001	PubMed	Biomedical waste	Any waste generated during the diagnosis, treatment or immunization of human beings or animals.	Zile Singh *et al.*[29]
2004	Sciences Direct	Medical waste	General waste and special waste.	Lee *et al.* [30]
2005	PubMed	Infectious waste	Infectious waste and non-infectious waste.	Miyazaki and Une [31]
2006	PubMed	Medical waste	Tissues and other waste.	Jang *et al.* [32]
2007	Sciences Direct	Hospital waste	Infectious and municipal waste.	Tsakona *et al.* [33]
2008	Scopus	Health care waste	General waste and medical waste.	Shinee *et al.* [34]
2008	PubMed	Hospital waste	General waste, medical waste, and sharps.	Nemathaga *et al.* [35]
2009	Sciences Direct	Medical waste	Infectious waste and general medical waste.	Cheng *et al.* [36]

2009	Sciences Direct	Hospital waste Healthcare waste	General waste and hazardous waste.	Sawalem *et al.* [37]
2009	Sciences Direct	Healthcare waste	Hazardous and non-hazardous waste.	Mohamed *et al.* [38]
2010	PubMed	Medical waste Hospital waste	Domestic waste and hazardous waste.	Abd El-Salam [39]
2010	ScienceDirect	Medical waste	Solid or semi-solid waste generated in healthcare settings.	Askarian M. *et al.* [39]
2015	Google Scholar	Biomedical waste / Health care waste	BMW: Any solid or fluid waste from diagnosis or treatment. HCW: total waste stream from healthcare facilities.	Himabindu *et al.* [40]
2019	Google Scholar	Health care waste	Biomedical waste is identified under many terminologies like hospital waste, healthcare waste etc.	Alshebli *et al.* [41]
2022	Web of Science	Health care waste	Waste generated by healthcare activities	Levchenko *et al.* [42]
2023	PubMed	Healthcare waste (HCW)	All types of waste generated from healthcare facilities, whether hazardous or harmless…	Karpinsja *et al.* [43]
2024	ScienceDirect	Biomedical waste	Any waste assembled during human or animal diagnosis, treatment, or immunization.	Pourmadadi *et al.* [44]
2025	ScienceDirect	Medical waste Healthcare waste	Healthcare waste includes all materials from healthcare organizations, both infectious and non-infectious.	Devebakan *et al* [45]

Types of Hospital Waste

The category of hospital waste is not uniform; it includes various types with differing levels of hazard [23]. For safe management, treatment, and disposal, medical waste must be accurately identified and classified [46]. The diversity of this waste reflects the range of medical activities, including diagnostic, therapeutic, laboratory, and research-related procedures [47]. The main categories of hospital waste are presented in Table 3 and in Figures 4 and 5, with examples and related references to illustrate their characteristics and potential hazards.

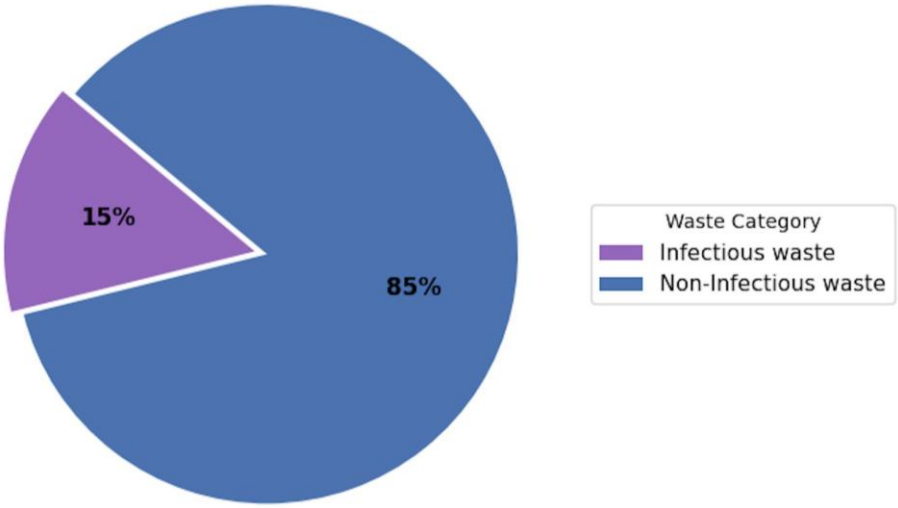

Figure 4. Distribution of Healthcare Waste types.

Table 3. Classification of Hospital Waste: Categories, Examples.

Category	Examples	Authors / Reference
Infectious waste	Lab cultures and stocks of infectious agents; wastes from isolation wards; tissues, materials or equipment that have been in contact with infected patients.	Hossain *et al.* [10]
Pharmaceutical waste	Expired or unnecessary pharmaceuticals and drugs.	
Pathological waste containing human tissues or fluids	Body parts, human foetuses, blood, other body fluids	
Chemical waste	Solid, liquid and gaseous chemicals from diagnostic and experimental work; cleaning materials.	
Radioactive waste	Radioactive substances including used liquids from radiotherapy or laboratory work.	
Sharps	Needles, syringes, blades, broken glass, scalpels, etc.	
Sharps waste	Used or unused sharps (e.g., hypodermic or intravenous needles; auto-disable syringes; infusion sets; scalpels; pipettes; knives; blades; broken glass)	WHO [23]
Infectious waste	Waste suspected to contain pathogens and that poses a risk of disease transmission (see section 2.1.2) (e.g., waste contaminated with blood and other body fluids; laboratory cultures and microbiological stocks;	

	materials in contact with patients infected with highly infectious diseases in isolation wards).	
Pathological waste	Human tissues, organs or fluids; body parts; foetuses; unused blood products	
Pharmaceutical waste, cytotoxic waste)	Expired or no longer needed pharmaceuticals; items contaminated by pharmaceuticals; cytotoxic waste containing substances with genotoxic properties (e.g., cytostatic drugs used in cancer therapy).	
Chemical waste	Laboratory reagents; film developer; disinfectants; solvents; waste containing heavy metals (batteries, broken thermometers, pressure gauges).	
Radioactive waste	Unused liquids from radiotherapy or laboratory research; contaminated glassware; sealed sources.	
Non-hazardous or general health-care waste	Waste that does not pose any biological, chemical, radioactive or physical hazard.	
Radioactive waste	Liquids, gases and solid products contaminated by radionuclides from radio-therapeutic or diagnostic materials emitting ionising radiation	
Pathological waste	Organs, human tissues, body fluids such as blood, whether infected or not but considered hazardous for disposal reasons.	
Anatomical waste	Recognizable human body parts (infected or not) requiring precautionary disposal.	Sherani *et al.* [48]
Pharmaceutical waste	Unused, expired, spilt or contaminated pharmaceutical products such as vaccines and drugs.	
Sharps waste	Syringes, needles, broken ampoules, blades, disposable scalpels; highly dangerous as they may be infected or cause puncture wounds.	

Infectious waste	Waste generated from hospitals containing pathogens or toxins (faeces, vomit, urine, blood, sputum, pus, saliva, microbial cultures).	
Chemical waste	Discarded reagents, solvents, disinfectants and heavy metals from hospital procedures or cleaning.	
Genotoxic/ cytotoxic waste	Wastes generated from oncology or radiotherapy drugs with mutagenic, cytotoxic or carcinogenic effects.	
Chemical Waste	Laboratory reagents, film developer, expired disinfectants, solvents, heavy metals (batteries, thermometers, pressure gauges), gas cylinders and aerosol cans.	Padder *et al.* [25]
Pathological Waste	Human tissues including placentas, body parts, blood and foetuses. Anatomical waste as a sub-group includes recognizable body parts.	
Hazards from Infectious Waste	Infectious wastes may contain pathogenic microorganisms transmitted via punctures or mucous membranes. Particular concern for HIV, HBV, HCV infections via contaminated sharps	
Medical wastes such as sharps	Needles, scalpels, blades.	Devebakan *et al.* [45]
Biological wastes	Blood, infected tissues.	
Chemical wastes	Pharmaceuticals, laboratory chemicals.	

Figure 5. Hospital waste classification according to type and origin.

Sources of Hospital Waste

Hospital waste originates from a range of activities, including patient care, diagnostics, research, and facility maintenance [23]. These sources include inpatient and outpatient departments, surgical theatres, intensive care units, laboratories, pharmacies, imaging services, and administrative areas [46]. Each department generates specific types of waste according to its function, such as infectious waste from surgical wards, chemical waste from laboratories, pharmaceutical waste from pharmacies, and radioactive waste from diagnostic imaging facilities [43,49]. Besides, cleaning services, kitchens, laundry units, and general maintenance also produce waste [43]. The diversity of sources adds to the complexity of hospital waste management and underlines the need for systematic segregation and disposal practices to reduce risks to health and the environment [43] (Table 4 and Figure 5).

Table 4. Sources of Hospital Waste.

Sources	Respective performance specifications	Reference
Major sources of health-care waste	**Hospitals:** University hospital ; General hospital ; District hospital.	WHO [23]
	Other health-care facilities : Emergency medical care services ; Health-care centres and dispensaries ; Obstetric and maternity clinics ; Outpatient clinics ; Dialysis centres ; Long-term health-care establishments and hospices ; Transfusion centres ; Military medical services ; Prison hospitals or clinics	
	Related laboratories and research centres: Medical and biomedical laboratories ; Biotechnology laboratories and institutions ; Medical research centres.	
	Mortuary and autopsy centres	
	Animal research and testing	
	Blood banks and blood collection service	
	Nursing homes for the elderly	
Minor sources of health-care waste	**Small health-care establishments** First-aid posts and sick bays Physicians' offices ; Dental clinics ; Acupuncturists ; Chiropractors.	
	Specialized health-care establishments and institutions with low waste generation: Convalescent nursing homes ; Psychiatric hospitals ; Disabled persons' institutions.	
	Activities with intravenous or subcutaneous interventions : Cosmetic ear-piercing and tattoo parlours ; Illicit drug users and needle exchanges	
	Funeral services	
	Ambulance services	
	Home treatment	
Major sources of health-care waste	**University / General / National Referral Hospital:** ● Special service for complicated health problems ● Teaching, research and development ● Outpatient clinic enterprise ● Operational supply of emergencies and other interferences (Birth assistance, surgery including traumatology, urology), and etc.	Bidlingmaier *et al.*[27]
	District Hospital: Like University Hospital but without: ● Special service for complicated health problems ● Teaching, research and development	
	Rural-, Primary Hospital (mainly in villages and remote areas): Curative supply acutely and chronically patients, so far as no medical authority is necessary (generally about 80 % all illness - and welfare cases) ● Pregnant woman precaution ● Birth support and family planning ● Infant welfare service (inclusively inoculating and growth control), and etc.	
	Health-care centres, clinics and dispensaries: Like Rural Hospital but without: ● Supervision of minor health posts and centres,	

	● Stationary treatment, laboratory test, X-ray and simple operations	
	Other special health-care facilities: ● Emergency medical care services, obstetric and maternity clinics, outpatient clinics, dialysis centre, first-aid posts and sick bays, transfusion centres, military medical services; ● Related laboratories and research centres, mortuary and autopsy centres, animal research and testing, Blood banks and blood collection services, nursing homes for the elderly.	
Minor sources of health-care waste	**Small health-care facilities** ● Dental clinics ● Physicians' offices ● Acupuncturists	
	Chiropractors Specialized health-care facilities and institutions with low waste generation ● Psychiatric hospitals ● Convalescent nursing homes ● Institutions for disabled persons	
	Non-health activities involving intravenous or subcutaneous interventions ● Cosmetic ear-piercing and tattoo parlours ● Illicit drug users	
	Funeral services	
	Ambulance services	
	Home treatment	
Hospitals and clinics, particularly those providing acute services	Operating Theatres, Maternity ward, Accident & Emergency, Mortuary, Intensive Care, Isolation Wards, Pharmacy, Pathology Laboratories and other research facilities	Hossain *et al.* [10]
Other sources	Ambulance services, public health laboratories, blood donation centers and blood banks, practice centre of doctors, dentists, veterinary surgeons, immunization/vaccination clinics and hospitals, clinics and nursing homes providing community care, care of the elderly and services related to mental health and learning disabilities	

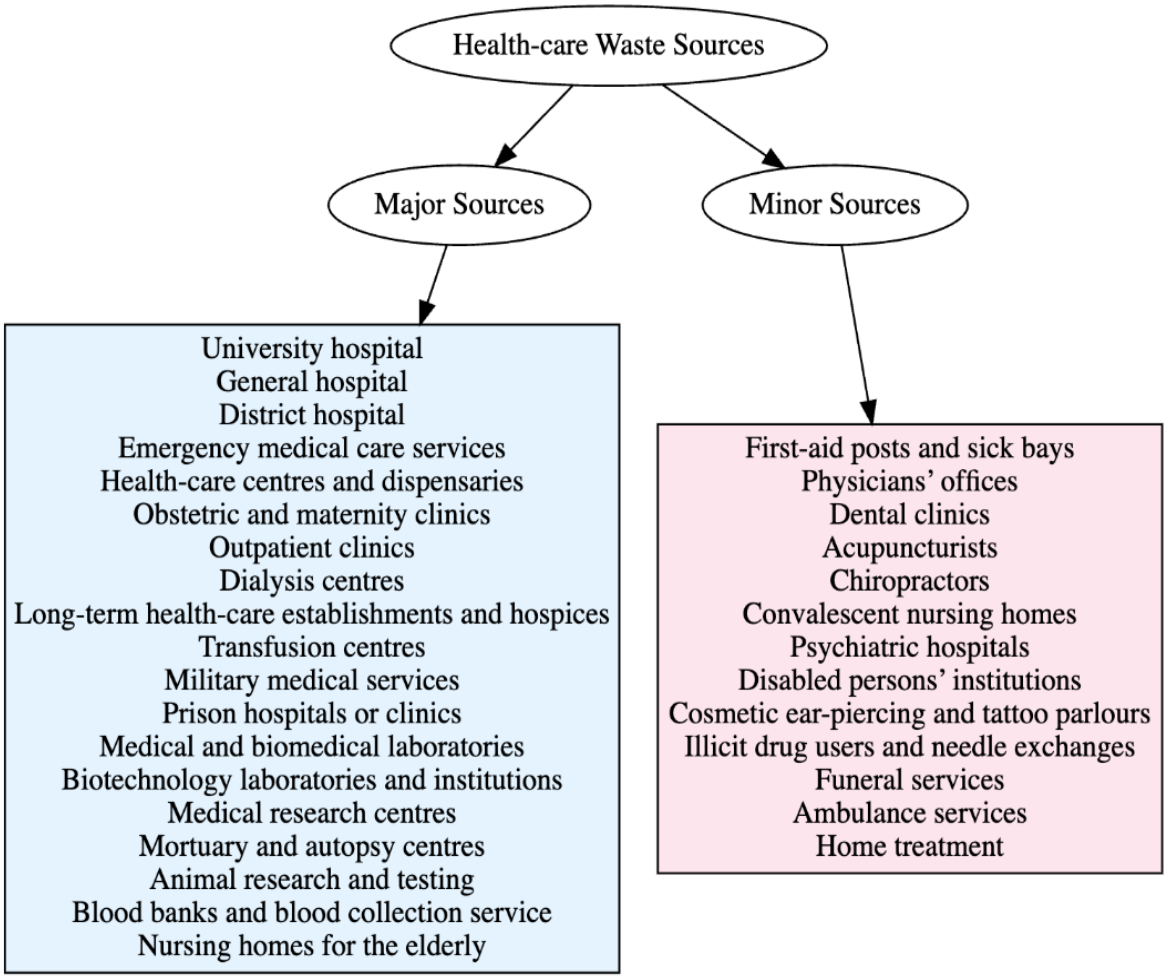

Figure 6. Sources of Hospital Waste.

Solid Waste Management

Hospital solid waste represents a major fraction of the total waste generated by healthcare institutions and must be carefully identified and managed because of potential health and environmental risks [50]. It includes contaminated materials, sharps, anatomical parts, expired medications, and chemically hazardous products. These materials are often inadequately segregated, creating additional risks for healthcare professionals, waste handlers, and the public [51,52]. A comprehensive classification of hospital solid waste types is essential for safe handling, efficient treatment, and sustainable disposal [10]. Table 5 summarizes the main categories of hospital solid waste, with examples and references [10].

Table 5. Main Categories of Hospital Solid Waste in Healthcare Facilities.

Category	Examples	Physical State
Infectious waste	Blood-soaked materials, swabs, surgical gloves, microbiological cultures, wastewater	Solid or liquid
Pathological waste	Human tissues, organs, body parts, placentas, foetuses	Solid (some liquid content)
Sharps waste	Needles, syringes, scalpels, broken glass	Solid
Pharmaceutical waste	Expired drugs, discarded medicines, vaccine vials, contaminated packaging	Solid or liquid
Cytotoxic/genotoxic waste	Waste from cancer treatments: chemotherapy drugs, contaminated materials	Solid or liquid
Chemical waste	Disinfectants, solvents, reagents, heavy metal-containing devices (e.g., thermometers, batteries)	Solid or liquid
Radioactive waste	Radioactive liquids from therapy/labs, contaminated materials, sealed sources	Solid or liquid
Non-hazardous/general waste	Paper, packaging, food waste, office waste, kitchen/laundry waste	Solid
Anatomical waste	Recognizable human body parts	Solid
Body fluids and excreta	Blood, urine, vomit, faeces from infected patients	Liquid

Healthcare Solid Waste Generation

Hospital solid waste generation varies across regions, healthcare settings, and economic conditions, yet it remains a large component of total healthcare waste. A detailed study in Peru reported that a hospital produced 92.77 kg/day, with 62% being biocontaminated (solid) waste and 7.7% sharps [53]. Globally, hospital solid waste generation per bed per day ranges from 0.016 to 3.23 kg in low-income settings [54], whereas Iran reports an average of 3.5 kg (range: 2.67–4.80) [55]. A meta-analysis found that national averages range from 0.24 kg/bed/day in India to 6.03 kg/bed/day in Ethiopia [56], with similar patterns observed in Pakistan and Brazil. Reviews indicate that 85% of healthcare waste is non-hazardous solid waste and 15% is toxic [43].

During the COVID-19 pandemic, some hospitals experienced daily waste increases of 33–42 kg per bed [57]. Long-term trends indicate a 2–3% annual growth in HCW, linked to improved isolation practices and greater reliance on single-use supplies [58]. These findings confirm that solid hospital waste is a significant and increasing environmental burden, reinforcing the need for context-specific waste segregation and management strategies.

Hospital Solid Waste Generation and Influencing Factors

Hospital solid waste is intrinsically varied, containing both hazardous and non-hazardous fractions [59]. Pathogenic, toxic, and potentially pathogenic materials require particular attention because of their impact on health and the environment [33]. A typical hospital produces a range of waste types, including general municipal waste (paper, food residues), pathological waste (tissues and body parts), microbiological and pharmaceutical waste, sharps, chemical and genotoxic substances, and materials contaminated with blood or heavy metals [37]. Although radioactive waste is not generated in all healthcare facilities, its possible presence requires special treatment [59]. Understanding these categories is essential for developing safe and effective waste management strategies [10].

Several key factors influence hospital solid waste generation, including facility type and size, availability of medical equipment, use of disposable items, and patient volume [60]. The economic, social, and cultural background of the patient population also affects waste output [61]. Public hospitals, particularly those with high outpatient turnover, tend to produce more waste than private facilities [62]. Studies show that when measured per bed, the quantity of clinical waste is similar between public and private hospitals, suggesting that poor segregation practices may inflate clinical waste figures in some facilities [63].

Waste generation rates vary not only with healthcare facility characteristics but also with a country's economic status. Developed countries generate considerably more per-bed waste than low-income countries [10]. According to WHO data, hospitals in North America generate 7–10 kg per bed per day, compared with 3 kg in South America. Western European hospitals typically produce 3–6 kg, Eastern European facilities 1.4–2 kg. In Asia, higher-income countries report about 2.5 kg per bed per day, whereas lower-income nations average 1.8–2 kg [23]. These differences reflect the influence of disposable materials, higher standards of care, and advanced medical infrastructure in wealthier economies.

In many developing countries, clinical waste is not effectively prioritized and is often mixed with general waste at disposal. Even if clinical waste starts as a small fraction, lack of segregation can cause cross-contamination, turning all mixed waste into clinical waste [10]. Effective waste management strategies must consider the source, volume, and composition of the waste [10]. Reducing waste at its origin and enforcing strict segregation at source will improve the safety and efficiency of clinical waste management [10].

Risk Related to Solid Hospital Waste

Solid healthcare waste is considered both dangerous and environmentally harmful [64]. Individuals exposed to this type of waste, either directly in healthcare settings or indirectly through improper handling, face varying degrees of risk [65]. More than two million healthcare workers worldwide are exposed to infectious pathogens during their daily tasks [43]. The risks associated with HCW are particularly acute in low- and middle-income countries, where waste management systems are often inadequate [43]. It is estimated that over 5.2 million people, including more than 4 million children, die each year from diseases caused directly or indirectly by improperly managed medical waste [43].

Persons at Risk

Anyone who comes into contact with hazardous healthcare waste may face substantial risks, whether inside or outside healthcare facilities, from improper handling and mismanagement. The most vulnerable groups include physicians, nurses, auxiliary healthcare workers, and hospital maintenance staff; patients receiving care in hospitals or at home; visitors to medical facilities; and workers in associated support services such as laundry, waste collection, and transportation [11,23,65]. Individuals working in waste disposal plants, including incinerator operators and informal waste pickers, are also at increased risk. Scattered and small-scale sources of medical waste, such as home-based healthcare activities (e.g. dialysis) or unsafe disposal practices related to intravenous drug use may also be dangerous [11,65].

When hazardous healthcare waste is dumped or abandoned, it poses a threat to public safety. Small, dispersed sources of medical waste require specific attention, as they are often overlooked [11]. These include infectious and pharmaceutical waste from home-based healthcare operations such as home dialysis or insulin administration, as well as contaminated single-use products like discarded needles [11]. Improper disposal linked to illicit intravenous drug use further increases the risk to the wider community [11].

Table 6. Categories of Persons at Risk and Associated Hazards from Solid Hospital Waste.

Category of Persons at Risk	Main Type of Exposure	Potential Hazards	Reference
Healthcare personnel	Direct handling of sharp, infectious, or chemical waste	Needle-stick injuries, bloodborne infections (HIV, Hepatitis B/C), exposure to toxic substances	[23,27,65]
Waste management staff	Collection, segregation, and transport without adequate protection	Infections, intoxications, physical injuries, exposure to contaminated aerosols	[23,27,65]
Patients and visitors	Accidental contact with poorly stored or disposed waste	Risk of infection, injuries, or indirect environmental contamination	
Workers at treatment/disposal facilities	Handling waste at incinerators, landfills, or recycling sites	Exposure to toxic emissions (e.g., dioxins), chemical burns, respiratory issues, mechanical hazards	[23,27,65]
Informal waste pickers (scavengers)	Unauthorized retrieval of items from medical waste without PPE	Severe infections, chemical exposure, injuries from sharps or contaminated materials	[23,27,65]
General public	Indirect exposure to environmental contamination (air, water, soil)	Long-term health impacts (e.g., cancer, endocrine disruption), spread of infectious diseases	[23,27,65]

Nature and Impact of the Risks

All individuals exposed to hospital solid waste (HSW) face potential health risks such as accidents and infections. These groups include medical staff, patients, hospital waste workers, and the general public [23]. The initial stages of HSW management, including collection and segregation, are critical points of exposure [23]. To reduce risks, the WHO recommends a colour-coded segregation system based on waste type [23]. For example, non-hazardous waste and small amounts of anatomical waste are collected in black bins; anatomical, sharps, infectious, and radioactive wastes are collected in yellow bins; pharmaceutical, chemical, and heavy metal wastes are collected in brown bins [23].

Colour-coding systems vary widely among low- and middle-income countries. In India, the Biomedical Waste Management Rules (2016) specify yellow, red, blue, and white bins for different waste categories, but Botswana and South Africa use other colour schemes [56]. Non-compliance with WHO guidance can result in poor handling, including mixing hazardous and non-hazardous waste, which increases health risks for workers [66].

Hospital solid waste is often non-hazardous in its raw state, but the presence of infectious organisms and toxic substances creates significant health hazards. Studies report higher rates of hepatitis B (HBV) and hepatitis C (HCV) among municipal solid waste workers (MSWWs) and hospital solid waste workers (HSWWs) in several developing countries [67]. In Iran, HBV prevalence among exposed MSWWs was estimated at 6.2%, considerably higher than in unexposed workers. Similar infection rates have been recorded in Greece, Egypt, Brazil, Thailand, Ethiopia, and Libya. Risk factors include low education, substance misuse, and

previous medical procedures. Co-infection with HBV and HCV adds further health complications [66,67].

Research indicates that hospital and municipal waste workers are up to four times more likely to contract viral diseases than the general population. The risk of infection after a single unvaccinated exposure ranges from 6% to 30% [68]. Preventive measures include health education, strict personal hygiene, use of protective equipment, vaccination programmes, and stronger industrial safety standards [68].

Healthcare waste can contain hazardous microorganisms capable of infecting patients, healthcare workers, and the public [65]. It also increases the likelihood of introducing drug-resistant bacteria into the environment [65]. Other risks include radiation burns, injuries from sharps, pharmaceutical poisoning (particularly antibiotics and cytotoxic medicines), and contamination from hazardous elements such as mercury and dioxins released during waste incineration [65].

Infectious waste and Sharps

Infectious healthcare waste presents a significant risk to human health because it can contain obligate or facultative pathogens in concentrations high enough to cause disease. Materials contaminated with human blood, bodily fluids, or tissues fall into this category [23,27]. Such materials are more likely to originate from isolation wards, surgical procedures on infected patients, laboratory cultures, haemodialysis equipment, and infected laboratory animals. HIV and the hepatitis B and C viruses are among more than 30 bloodborne pathogens that can be transmitted through improper handling of this waste [25,43]. Microorganisms can enter the body through cuts, punctures, mucous membranes, inhalation, or ingestion. Needle-stick injuries are a recognized route for serious infections [25], highlighting the importance of proper training and vaccination, especially against hepatitis B, for all personnel handling healthcare waste [11].

Sharps pose serious risks because they can cause cuts or puncture wounds [27]. Needles, scalpels, blades, cannulas, infusion sets, and broken glass can all transmit infectious diseases, even if only slightly contaminated with blood or other human fluids. Sharps are classified as highly hazardous healthcare waste because of their potential to cause injury and infection, regardless of visible contamination [27,43]. Their correct management is essential for reducing occupational health risks and limiting the spread of disease [27,43].

Chemical and Pharmaceutical Waste

Healthcare facilities frequently use a wide range of chemical and medicinal substances, many of which are hazardous to human health and the environment [27]. Pharmacists, anaesthetists, nurses, auxiliary staff, and maintenance personnel may be exposed to harmful compounds in the form of vapours, aerosols, or liquids. Such exposures can cause respiratory problems, skin disorders, or mucosal irritation [27]. To reduce these risks, harmful substances should be replaced with safer alternatives wherever possible [27]. Appropriate personal protective equipment (PPE) must be provided, and staff should receive comprehensive training in safe handling practices. Adequate ventilation must be ensured in all spaces where hazardous compounds are stored or used [27].

There are no extensive studies linking disease outbreaks to chemicals or pharmaceuticals from HCW, yet several incidents of poisoning and injury have been recorded as a result of poor management of such substances [11,43]. Many chemicals and medicines, particularly those that are expired or no longer required, often go to landfills [11,43]. These substances can cause acute harm if inhaled, ingested, or absorbed through the skin or mucous membranes [11,43]. Formaldehyde and other corrosive, flammable, or reactive chemicals can cause severe injuries to the eyes, skin, and respiratory system [11,43].

Pharmaceutical residues are frequently detected in groundwater, surface water, and soils following improper disposal, such as discarding unused or expired drugs into lavatories. Commonly detected pharmaceuticals include antibiotics, hormones, nonsteroidal anti-inflammatory drugs (NSAIDs), beta-blockers, lipid regulators, and antidepressants [43,69]. Long-term environmental exposure to these has been associated with acute and chronic toxicity in wildlife, behavioural changes, reproductive disorders, and cellular damage [43,69]. The development of antibiotic-resistant microorganisms resulting from prolonged environmental exposure to drug residues is alarming [43,69]. This underlines the urgent need for effective decontamination of pharmaceutical and chemical waste before landfill disposal, to prevent harmful interactions between environmental bacteria and active pharmaceuticals that may lead to resistant microbial strains [43,70].

Genotoxic Waste

Genotoxic waste, particularly that derived from cytotoxic or anticancer medicines used in chemotherapy, poses serious risks to health and the environment [27]. Nurses, chemists, laboratory technicians, and those concerned with the preparation, transport, and disposal of

these wastes, are among the most vulnerable healthcare personnel [43]. Exposure occurs mainly through inhalation of aerosols or dust, dermal absorption, ingestion of contaminated food, and accidental injury from sharps [27]. Contact with patients undergoing chemotherapy can cause additional exposure through bodily fluids and excreta such as vomit, urine, and faeces [43].

Acute exposure often results in temporary symptoms such as dizziness, nausea, headaches, and skin irritation [43]. Most cytotoxic medicines are potent irritants capable of causing dermatitis, mucosal ulceration, and inflammation of the eyes, mouth, or skin on direct contact [27,43]. Prolonged or repeated occupational exposure has been linked to serious long-term effects, including an increased risk of spontaneous abortion and congenital abnormalities [71]. Traces of cytotoxic medicines have been detected in the urine of medical and pharmacy staff, indicating systemic contamination [71].

Cytotoxic substances are poorly biodegradable and often resist conventional wastewater treatment methods [71]. They can accumulate in aquatic environments, threatening species through bioaccumulation and biomagnification [43]. Chronic exposure in aquatic organisms, such as zebrafish, has been shown to cause DNA damage and alter gene expression, with potential impacts on entire populations [43].

To reduce these risks, genotoxic waste should be managed with extreme care, preferably through high-temperature incineration or secure storage in sealed containers. Chemical neutralization is effective only for small quantities [27]. Safe handling and disposal of these substances are essential for protecting human health and conserving the environment [27].

Radioactive waste

Radioactive waste from hospital settings includes solid items such as contaminated gloves, syringes, gowns, absorbent paper, packaging, and laboratory glassware exposed to radioactive substances during medical procedures or research activities [43]. Such waste can also be generated during patient care, particularly when patients are treated with open radionuclides, which can contaminate bedding, dressings, or personal belongings [43]. Although generally classified as low-level radioactive waste, incorrect segregation, handling, or disposal can lead to environmental contamination and pose risks to hospital staff, waste management personnel, and the public [27].

Treatment Technologies for Hospital Solid Waste

Thermal Processes

These technologies use heat to eliminate microorganisms while reducing waste volume.

- **Incineration:** is a high-temperature burning technique that reduces waste volume by up to 90% while destroying organic materials and germs. It works particularly well with pathological waste, some pharmaceutical waste (especially cytotoxic medicines), and trace chemotherapeutic waste. Modern incinerators operate at extremely high temperatures (850-1200°C or 1,800-2,000°F) and use modern flue gas treatment systems to limit dioxin, furan, and heavy metal emissions. Environmental concerns about air pollution remain, making it a less popular choice in some areas [51,72].
- **Autoclaving (Steam Sterilization)**: is one of the most popular and environmentally beneficial procedures. Waste is exposed to high-pressure, superheated steam (usually 121-134°C) for a set amount of time, which efficiently kills microorganisms. Autoclaves are adaptable and can handle a wide variety of infectious waste, including sharps, laboratory waste, and general infectious materials [10]. They are not appropriate for pathological, cytotoxic, or some chemical/pharmaceutical wastes. Some sophisticated autoclaves use shredding or suction to increase steam penetration and reduce volume [10].
- **Microwave Treatment:** This technology uses microwave energy to heat and disinfect waste. This is frequently shredded and combined with water to produce steam, which sterilizes the material [10,72]. It is effective for both contagious and soft trash, requires little energy, and emits few pollutants [10,72]. Like autoclaving, it is not appropriate for all forms of waste, such as pharmaceutical or chemical waste [10].
- **Dry heat/hot air systems:** use circulating hot air to sterilize garbage. They work at temperatures below 180°C and make no substantial changes to the waste's physical or chemical structure. It is critical to use caution when handling volatile compounds [73].
- **Pyrolysis and gasification:** are sophisticated thermal processes that include heating waste in the absence (pyrolysis) or in the presence of limited oxygen (gasification). They transform solid waste into combustible gases or liquid/solid leftovers that can be used to recover energy [72]. These technologies reduce volume more effectively and are potentially more environmentally beneficial than standard incineration, but they necessitate special facilities and highly trained workers.

- **Plasma Arc:** This is an extremely high-temperature technique that uses an electric arc to generate plasma, which degrades waste into its constituent elements. It is highly effective for a wide range of waste types, but it is a complicated and costly technique [73].
- **Frictional Heat Treatment:** This technology shreds and heats trash to 135-150°C, rendering it unrecognizable and decontaminated, using heat created by friction and collision with rotor blades, which is often augmented by resistance heaters [74].

Chemical processes

To neutralize microorganisms, these procedures make use of chemical disinfectants.

- **Chemical disinfection** is the process of mixing trash with industrial disinfectants (such as chlorine compounds, peracetic acid, ozone, sodium hydroxide, and calcium oxide). It is typically used for liquid waste, but solid items can be shredded to guarantee uniform contact with the chemicals. Though effective in killing or inactivating microorganisms, it may not provide true sterilization and may not deactivate all drugs or chemical substances. Chemical leftovers must also be properly managed [75].
- **Alkaline hydrolysis** combines a strong alkaline solution and heat to break down organic compounds such as animal tissues and some toxic substances. It is being investigated as an alternative to incineration for some types of pathological and pharmaceutical waste [73,75].

Irradiative processes.

- **Irradiation (Electron Beam or Gamma Irradiation):** This approach destroys germs by exposing medical waste to ionizing radiation (for example, from a cobalt source). It is effective in disinfecting waste and may permeate plastic bags, removing the requirement for pre-treatment. It is not common because of severe regulatory standards and the necessity for special facilities [73].

Biological Processes

These procedures use biological agents for waste decomposition, but are less applicable for general clinical solid waste because they can transmit pathogens.

- **Biodigesters/Composting (for specific waste types):** In some cases, such as disposal of placentas or soft waste mixed with food waste, biological processes like biodigesters or vermiculture (worm composting) can be employed for natural breakdown [76].

Table 7. Comparative Overview of Treatment Technologies for Hospital Solid Waste.

Technology	Treatment Method	Principle	Applicable Waste Types	Advantages	Limitations	Special Requirements
Thermal	**Incineration**	High-temperature combustion (850–1200°C)	Pathological, pharmaceutical (cytotoxic), chemotherapeutic	Up to 90% volume reduction, effective destruction of pathogens and organic matter	Air pollution, toxic emissions (dioxins, furans, heavy metals)	Advanced flue gas treatment systems
	Autoclaving (Steam Sterilization)	Pressurized steam at 121–134°C	Infectious waste, sharps, laboratory waste	Environmentally friendly, widely adopted, cost-effective	Not suitable for pathological, cytotoxic, or certain chemical waste	Shredding or vacuum systems may enhance efficiency
	Microwave Treatment	Microwave energy + moisture to generate steam	Infectious soft waste	Low emissions, energy-efficient, effective sterilization	Unsuitable for chemical/pharmaceutical waste	Pre-shredding and moisture addition required
	Dry Heat / Hot Air Systems	Circulating hot air below 180°C	Non-volatile contaminated materials	No chemical transformation, simple setup	Limited efficacy, not suitable for volatile compounds	Precise temperature control
	Pyrolysis / Gasification	Decomposition with no or limited oxygen	General hospital solid waste	Potential energy recovery, less polluting than incineration	High cost, complex operations	Specialized infrastructure, trained personnel
	Plasma Arc	Electric arc creates plasma to decompose waste	All types including complex/mixed waste	Very high efficiency, complete breakdown	Expensive, technologically demanding	High-voltage plasma torch systems
	Frictional Heat Treatment	Mechanical shredding + frictional heating (135–150°C)	Infectious, soft hospital waste	Disinfection and volume reduction combined	Less common, energy-consuming	Rotor blades and resistance heating
Chemical	**Chemical Disinfection**	Use of disinfectants (e.g., chlorine, ozone, PAA)	Primarily liquid waste; solid if shredded	Quick disinfection, adaptable	May not achieve full sterilization, chemical residues remain	Safe handling of hazardous chemicals
	Alkaline Hydrolysis	Heat + strong alkali to dissolve organic matter	Animal tissue, pharmaceutical waste	Environmentally safer alternative to incineration	Limited adoption, long processing time	Corrosion-resistant reactors
Irradiative	**Gamma or Electron Beam Irradiation**	Ionizing radiation (e.g., Co-60 source)	Infectious waste, sealed in plastic bags	No pre-treatment needed, deep penetration	Strict regulations, costly facilities	Licensed radioactive sources or accelerators
Biological	**Biodigestion / Composting**	Microbial or vermiculture decomposition	Organic soft waste (e.g., placentas, food-mixed waste)	Eco-friendly for specific waste types	Risk of pathogen transmission, not for general waste	Controlled biological conditions (temperature, humidity)

Conclusion

Solid hospital waste management is a major environmental and public health problem, particularly in developing nations such as Morocco. This paper emphasizes that urbanization, population growth, and health emergencies such as the COVID-19 pandemic are increasing the volume and complexity of medical waste. Implementation remains inadequate despite national efforts to strengthen regulatory frameworks, hindered by limited funding, insufficient training, and weak enforcement.

Many stakeholders, from healthcare workers to the public, are affected by the risks linked to hospital waste, including infections, chemical exposure, and environmental damage. The wide range of waste types, their diverse sources, and the variety of available treatment technologies (thermal, chemical, biological, and irradiative) mean that no single solution can address all situations. An integrated and tailored approach is essential.

Shortcomings in segregation, collection, and treatment remain significant risks in Morocco, where more than 22,000 tonnes of hospital waste are produced annually, a large share of which is hazardous. Achieving safer and more sustainable management requires investment in modern infrastructure, stronger legislation, adoption of circular economy principles, and effective training for relevant staff.

This review highlights the urgent need for interdisciplinary strategies and international cooperation to close gaps in knowledge and practice, and to ensure hospital waste management that protects both the environment and human health.

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References

[1] Islam, MT., Rafi, MA., Hasan, MJ., 2025, Knowledge, attitude and practice of health care workers on solid medical waste management in two urban hospitals of Bangladesh: a mixed-method study. *Journal of Health, Population and Nutrition* **44** (34). https://doi.org/10.1186/s41043-025-00748-y

[2] Nanda, S., Berruti, F., 2021, A technical review of bioenergy and resource recovery from municipal solid waste. *Journal of Hazardous Materials* **403** (123970). https://doi.org/10.1016/j.jhazmat.2020.123970

[3] Voukkali, I., Papamichael, I., Loizia, P., Zorpas, AA., 2024, Urbanization and solid waste production: prospects and challenges. *Environmental Science and Pollution Research* **31**, 17678–17689. https://doi.org/10.1007/s11356-023-27670-2

[4] Karamouz, M., Zahraie, B., Kerachian, R., Jaafarzadeh, N., Mahjouri, N., 2007, Developing a master plan for hospital solid waste management: A case study. *Waste Management* **27**, 626–638. https://doi.org/10.1016/j.wasman.2006.03.018

[5] Rashid, S., Sultan, H., Rashid, W., Talpur, BD., Supe Tulcan, RX., Khan, MT., Bohnett, E., Korai, M.S., Zhang, L., 2025, A critical review of opportunities and challenges of solid waste management in an emerging economy- evidence from Pakistan. *Environmental Development* **55** (101182). https://doi.org/10.1016/j.envdev.2025.101182

[6] Alighardashi, M., Moein, H., Dehghanpour, S., Mousavi, SA., Almasi, A., Mohammadi, P., 2024, Environmental assessment of hospital waste management practices: a study of hospitals in Kermanshah, Iran. *Results in Engineering* **23** (102658). https://doi.org/10.1016/j.rineng.2024.102658.

[7] Cayo-Rojas, C., Briceño-Vergel, G., Córdova-Limaylla, N., Huamani-Echaccaya, J., Castro-Mena, M., Lurita-Córdova, P., et al., 2023, Impact of a virtual educational intervention on knowledge and awareness of biomedical waste management among Peruvian dental professionals. *Scientific Reports* **13** (22346). https://doi.org/10.1038/s41598-023-49878-5.

[8] Hasan, MM., Rahman, MH., 2018, Assessment of healthcare waste management paradigms and its suitable treatment alternative: a case study. *Journal of Environmental and Public Health* **2018** (6879751). https://doi.org/10.1155/2018/6879751.

[9] Ranjbari, M., Shams Esfandabadi, Z., Shevchenko, T., Chassagnon-Haned, N., Peng, W., Tabatabaei, M., et al., 2022, Mapping healthcare waste management research: past evolution, current challenges, and future perspectives towards a circular economy transition. *Journal of Hazardous Materials* **422** (126724). https://doi.org/10.1016/j.jhazmat.2021.126724.

[10] Hossain, MdS., Santhanam, A., Nik Norulaini, NA., Omar, AKM., 2011, Clinical solid waste management practices and its impact on human health and environment – a review. *Waste Management* **31** (754–766). https://doi.org/10.1016/j.wasman.2010.11.008.

[11] Chartier, Y., Emmanuel, J., Pieper, U., Prüss, A., Rushbrook, P., Stringer, R., Townend, W., Wilburn, S., & Zghondi, R., 2014, *Safe management of wastes from health-care activities* (2nd ed.). (Geneva: World Health Organization).

[12] Kumar, AK., Ali, Y., Kumar, RR., Assaf, MH., Ilyas, S., 2025, Artificial intelligent and Internet of Things framework for sustainable hazardous waste management in hospitals. *Waste Management* **203** (114816). https://doi.org/10.1016/j.wasman.2025.114816.

[13] Azami-Aghdash, S., Sayadzadeh, M., Ashtari, A., Derakhshani, N., Sedaei, Z., Rezapour, R., 2023, Improving the hospital waste management at the Farabi hospital in Malekan - Iran: an action research study. *Heliyon* **9** (e17695). https://doi.org/10.1016/j.heliyon.2023.e17695.

[14] Fadaei, A., 2023, Comparison of medical waste management methods in different countries: a systematic review. *Reviews on Environmental Health* **38** (339–348). https://doi.org/10.1515/reveh-2021-0170.

[15] Chisholm, JM., Zamani, R., Negm, AM., Said, N., Abdel Daiem, MM., Dibaj, M., Akrami, M., 2021, Sustainable waste management of medical waste in African developing countries: a narrative review. *Waste Management Research* **39** (1149–1163). https://doi.org/10.1177/0734242X211029175.

[16] Tushar, SR., Alam, MdFB., Bari, ABMM., Karmaker, CL., 2023, Assessing the challenges to medical waste management during the COVID-19 pandemic: implications for the environmental sustainability in the emerging economies. *Socio-Economic Planning Sciences* **87** (101513). https://doi.org/10.1016/j.seps.2023.101513.

[17] Rupani, PF., Delarestaghi, RM., Abbaspour, M., Rupani, MM., EL-Mesery, HS., Shao, W., 2019, Current status and future perspectives of solid waste management in Iran: a critical overview of Iranian metropolitan cities. *Environmental Science and Pollution Research* **26** (32777–32789). https://doi.org/10.1007/s11356-019-06456-5.

[18] Abanyie, SK., Amuah, EEY., Douti, NB., Amadu, CC., Bayorbor, M., 2021, Healthcare waste management in the Tamale Central Hospital, northern Ghana: an assessment before the emergence of the COVID-19 pandemic in Ghana. *Environmental Challenges* **5** (100320). https://doi.org/10.1016/j.envc.2021.100320.

[19] Alam, O., Mosharraf, A., 2020, A preliminary life cycle assessment on healthcare waste management in Chittagong City, Bangladesh. *International Journal of Environmental Science and Technology* **17** (1753–1764). https://doi.org/10.1007/s13762-019-02585-z.

[20] Ech-chayeb, K., Auajjar, N., Hamama, S., Elmniai, A., Hicham, EL., Attarassi, B., 2022, Sustainable management and environment of the hospital wastes: a comparative study of two public hospitals in Morocco. *The Journal of Solid Waste Technology and Management* **48** (465–473). https://doi.org/10.5276/JSWTM/2022.465.

[21] Louzizi, T., Chakir, E., Sadoune, Z., 2025, A comprehensive review on solid waste management in Morocco: assessment, challenges and potential transition to a circular economy. *Euro-Mediterranean Journal for Environmental Integration* **10** (1281–1296). https://doi.org/10.1007/s41207-024-00662-5.

[22] Dahchour, A., Hajjaji, SE., 2020, Management of solid waste in Morocco. *Waste Management in MENA Regions* **13** (33). https://doi.org/10.1007/978-3-030-18350-9_2.

[23] Rushbrook, P., & Zghondi, R. (2005). *Better health care waste management: An integral component of health investment*. World Health Organization, Regional Office for the Eastern Mediterranean, Regional Centre for Environmental Health Activities (CEHA), & The World Bank, Middle East and North Africa Region (Amman: World Health Organization).

[24] Chauiyakh, O., Et-tahir, A., Kettani, K., Chaouch, A., Bessi, H., 2021, Evaluation of the bacteriological risk of solid medical and pharmaceutical waste from a Moroccan hospital center. *Research Journal of Pharmacy and Technology* **14** (2983–2988). https://doi.org/10.52711/0974-360X.2021.00522.

[25] Padder, AH., 2019, Health care waste management. *International Journal of Trend in Scientific Research and Development* **3** (908). https://doi.org/10.31142/IJTSRD23109.

[26] Pratyusha, K., Gaikwad, NM., Phatak, AA., Chaudhari, PD., 2012, Review on: waste material management in pharmaceutical industry. *International Journal of Pharmaceutical Sciences Review and Research* **16** (121–129). https://www.globalresearchonline.net/journalcontents/v16-2/27.pdf

[27] Bidlingmaier, W., Jager, E., & Stolze, R., 2016, *Management and treatment of health-care waste* (Manuscript for students). (Weimar: Bauhaus Universität Weimar, Projekt Orbit). Retrieved from https://orbit-online.net/images/orbit-downloads/2_Students/2_2_Medical_Waste/en/2_2_Medical-Waste-Treatment-with-Figurs.pdf

[28] Khobragade, DS., 2019, Health care waste: avoiding hazards to living and non-living environment by efficient management. *Fortune Journal of Health Sciences* **2** (14–29).

[29] Singh, Z., Bhalwar, R., Jayaram, J., Tilak, V., 2001, An introduction to essentials of bio-medical waste management. *Medical Journal Armed Forces India* **57** (144–147). https://doi.org/10.1016/S0377-1237(01)80136-2.

[30] Lee, B-K., Ellenbecker, MJ., Moure-Ersaso, R., 2004, Alternatives for treatment and disposal cost reduction of regulated medical wastes. *Waste Management* **24** (143–151). https://doi.org/10.1016/j.wasman.2003.10.008.

[31] Miyazaki, M., Une, H., 2005, Infectious waste management in Japan: a revised regulation and a management process in medical institutions. *Waste Management* **25** (616–621). https://doi.org/10.1016/j.wasman.2005.01.003.

[32] Jang, Y-C., Lee, C., Yoon, O-S., Kim, H., 2006, Medical waste management in Korea. *Journal of Environmental Management* **80** (107–115). https://doi.org/10.1016/j.jenvman.2005.08.018.

[33] Tsakona, M., Anagnostopoulou, E., Gidarakos, E., 2007, Hospital waste management and toxicity evaluation: a case study. *Waste Management* **27** (912–920). https://doi.org/10.1016/j.wasman.2006.04.019.

[34] Shinee, E., Gombojav, E., Nishimura, A., Hamajima, N., Ito, K., 2008, Healthcare waste management in the capital city of Mongolia. *Waste Management* **28** (435–441). https://doi.org/10.1016/j.wasman.2006.12.022.

[35] Nemathaga, F., Maringa, S., Chimuka, L., 2008, Hospital solid waste management practices in Limpopo Province, South Africa: a case study of two hospitals. *Waste Management* **28** (1236–1245). https://doi.org/10.1016/j.wasman.2007.03.033.

[36] Cheng, YW., Sung, FC., Yang, Y., Lo, YH., Chung, YT., Li, K-C., 2009, Medical waste production at hospitals and associated factors. *Waste Management* **29** (440–444). https://doi.org/10.1016/j.wasman.2008.01.014.

[37] Sawalem, M., Selic, E., Herbell, J-D., 2009, Hospital waste management in Libya: a case study. *Waste Management* **29** (1370–1375). https://doi.org/10.1016/j.wasman.2008.08.028.

[38] Mohamed, LF., Ebrahim, SA., Al-Thukair, AA., 2009, Hazardous healthcare waste management in the Kingdom of Bahrain. *Waste Management* **29** (2404–2409). https://doi.org/10.1016/j.wasman.2009.02.015.

[39] Abd El-Salam, MM., 2010, Hospital waste management in El-Beheira Governorate, Egypt. *Journal of Environmental Management* **91** (618–629). https://doi.org/10.1016/j.jenvman.2009.08.012.

[40] A.H., M.M., T.H.U., 2015, A critical review on biomedical waste and effect of mismanagement. *International Journal of Engineering Research and Technology* **4** (81–88). https://doi.org/10.17577/IJERTV4IS030179.

[41] Alshebli, A., Almaki, A., Alosmani, F., Alghumwi, M., Bahshwan, S., Ibrahim, O., & Modawy, E. E., 2019, Healthcare waste management practices in Al Leith Hospital, Saudi Arabia. *International Journal of Scientific and Technological Research* **5**(12), 279–286. https://doi.org/10.7176/JSTR/5-12-30.

[42] Levchenko, A., Schweikart, SJ., 2022, How should regulations help health care organizations manage waste? *AMA Journal of Ethics* **24** (E959–E966). https://doi.org/10.1001/amajethics.2022.959.

[43] Janik-Karpinska, E., Brancaleoni, R., Niemcewicz, M., Wojtas, W., Foco, M., Podogrocki, M., et al., 2023, Healthcare waste—a serious problem for global health. *Healthcare (Basel)* **11** (242). https://doi.org/10.3390/healthcare11020242.

[44] Pourmadadi, M., Aslani, A., Holghoomi, R., Fathi-karkan, S., Rahdar, A., Kharaba, Z., et al., 2024, Harnessing bio-waste for biomedical applications: a new horizon in sustainable healthcare. *European Journal of Medicinal Chemistry Reports* **12** (100234). https://doi.org/10.1016/j.ejmcr.2024.100234.

[45] Devebakan, N., Gasim, N., Durmus, A., Babashova, S., 2025, Bayesian model averaging and augmented autoregressive distributed lag approach for modeling hospital waste amount. Evidence from Dokuz Eylul University hospital in Turkiye. *Cleaner Waste Systems* **11** (100302). https://doi.org/10.1016/j.clwas.2025.100302.

[46] Siru, D., 2011, *Technical guidelines on healthcare waste management*. Kingdom of Cambodia, Ministry of Health. Prepared as a WHO consultancy project, December 2011. (Phnom Penh: World Health Organization). https://niph.org.kh/niph/uploads/library/pdf/GL012_HCW_Guideline_Eng.pdf

[47] Rayner, W. E., 2005, *The management of infectious healthcare waste – The need for a new approach in the UK* (Master's thesis, University of Surrey, Guildford, United Kingdom). ProQuest Dissertations & Theses Global. https://www.proquest.com/dissertations-theses/management-infectious-healthcare-waste-need-new/docview/305379553/se-2

[48] Sherani, SH., 2020, Proper hospital waste management for the protection of human health and environment: a review. *Health Systems and Policy Research*. https://doi.org/10.21767/2254-9137.100105.

[49] Tsakona, M., Anagnostopoulou, E., Gidarakos, E., 2007, Hospital waste management and toxicity evaluation: a case study. *Waste Management* **27** (912–920). https://doi.org/10.1016/j.wasman.2006.04.019.

[50] Aziz, HA., Omar, FM., Halim, HA., Hung, Y-T., 2022, Health-care waste management. In: Wang, LK., Wang, M-HS., Hung, Y-T., editors. *Solid Waste Engineering and Management* **3**, 163–229. https://doi.org/10.1007/978-3-030-96989-9_4.

[51] Zikhathile, T., Atagana, H., Bwapwa, J., Sawtell, D., 2022, A review of the impact that healthcare risk waste treatment technologies have on the environment. *International*

Journal of Environmental Research and Public Health **19** (11967). https://doi.org/10.3390/ijerph191911967.

[52] Fetouhi, F. Z., & Bahloul, B**.**, 2017, *Suivi de la gestion des déchets hospitaliers dans les établissements de santé (EPH et EPSP) de la ville de Guelma* (Master's thesis, Université 8 Mai 1945 Guelma, Algérie). DSpace Université 8 Mai 1945 Guelma. http://dspace.univ-guelma.dz:8080/xmlui/handle/123456789/1730

[53] Suarez Rivadeneira, JE., Suarez Chavarry, EB., Ramirez ÍM., Camacho, WR., Calderón, EV., Astonitas, RP., et al., 2024, Generation rate of hospital solid waste from different services: a case study in the province of Bagua, northern Peru. *Heliyon* **10** (e31814). https://doi.org/10.1016/j.heliyon.2024.e31814.

[54] Diaz, LF., Eggerth, LL., Enkhtsetseg, S., Savage, GM., 2008, Characteristics of healthcare wastes. *Waste Management* **28** (1219–1226). https://doi.org/10.1016/j.wasman.2007.04.010.

[55] Alighardashi, M., Mousavi, SA., Almasi, A., Mohammadi, P., 2024, Hospital waste management system in Kermanshah: challenges, future and sustainable management with circular economy. *Scientific Reports* **14** (25671). https://doi.org/10.1038/s41598-024-76525-4.

[56] Ansari, M., Ehrampoush, MH., Farzadkia, M., Ahmadi, E., 2019, Dynamic assessment of economic and environmental performance index and generation, composition, environmental and human health risks of hospital solid waste in developing countries; a state of the art of review. *Environment International* **132** (105073). https://doi.org/10.1016/j.envint.2019.105073.

[57] Singh, M., Karimi, N., Ng, KTW., Mensah, D., Stilling, D., Adusei, K., 2022, Hospital waste generation during the first wave of COVID-19 pandemic: a case study in Delhi. *Environmental Science and Pollution Research International* **29** (50780–50789). https://doi.org/10.1007/s11356-022-19487-2.

[58] Kaposi, A., Nagy, A., Gomori, G., Kocsis, D., 2024, Analysis of healthcare waste and factors affecting the amount of hazardous healthcare waste in a university hospital. *Journal of Material Cycles and Waste Management* **26** (1169–1180). https://doi.org/10.1007/s10163-024-01890-1.

[59] Ali, M., Wang, W., Chaudhry, N., Geng, Y., 2017, Hospital waste management in developing countries: a mini review. *Waste Management Research* **35** (581–592). https://doi.org/10.1177/0734242X17691344.

[60] Wilhemina, A., Amedumey, P., Raphael, GBH., 2022, Solid waste management in hospitals: a comparative assessment in some selected hospitals in Obuasi Municipality of Ghana. *Cleaner Waste Systems* **3** (100025). https://doi.org/10.1016/j.clwas.2022.100025.

[61] Minoglou, M., Gerassimidou, S., Komilis, D., 2017, Healthcare Waste Generation Worldwide and Its Dependence on Socio-Economic and Environmental Factors. *Sustainability* **9**, 220. https://doi.org/10.3390/su9020220

[62] Ali, M., Wang, W., Chaudhry, N., Geng, Y., Ashraf, U., 2017, Assessing knowledge, performance, and efficiency for hospital waste management—a comparison of government and private hospitals in Pakistan. *Environmental Monitoring and Assessment*, **189**, 181. https://doi.org/10.1007/s10661-017-5903-9

[63] Tesfahun, E., Kumie, A., Legesse, W., Kloos, H., Beyene, A., 2014, Assessment of composition and generation rate of healthcare wastes in selected public and private hospitals of Ethiopia. *Waste Management Research* **32**, 215–220. https://doi.org/10.1177/0734242X14521683

[64] Wafula, S.T., Musiime, J., Oporia, F., 2019, Health care waste management among health workers and associated factors in primary health care facilities in Kampala City, Uganda: a cross-sectional study. *BMC Public Health* **19**, 203. https://doi.org/10.1186/s12889-019-6528-4

[65] Padmanabhan, K. K., & Barik, D., 2019, Health hazards of medical waste and its disposal. In D. Barik (Ed.), *Energy from toxic organic waste for heat and power generation* (Woodhead Publishing Series in Energy, pp. 99–118) (Cambridge: Woodhead Publishing). https://doi.org/10.1016/B978-0-08-102528-4.00008-0

[66] Ansari, M., Ehrampoush, M.H., Farzadkia, M., Ahmadi, E., 2019, Dynamic assessment of economic and environmental performance index and generation, composition, environmental and human health risks of hospital solid waste in developing countries; A state of the art of review. *Environment International* **132**, 105073. https://doi.org/10.1016/j.envint.2019.105073

[67] Corrao, C.R.N., Del Cimmuto, A., Marzuillo, C., Paparo, E., La Torre, G., 2013, Association between Waste Management and HBV among Solid Municipal Waste Workers: A Systematic Review and Meta-Analysis of Observational Studies. *The Scientific World Journal* **2013**, 692083. https://doi.org/10.1155/2013/692083

[68] Ansari, M., Ehrampoush, M.H., Farzadkia, M., Ahmadi, E., 2019, Dynamic assessment of economic and environmental performance index and generation, composition, environmental and human health risks of hospital solid waste in developing countries; A state of the art of review. *Environment International* **132**, 105073. https://doi.org/10.1016/j.envint.2019.105073

[69] Doggalli, D.N., 2014, Hazards and Public Health Impacts of Hospital Waste. *The Journal of Applied Research* **4**, 384. https://doi.org/10.15373/2249555X/June2014/120

[70] Shaaban, H., Alghamdi, H., Alhamed, N., Alziadi, A., & Mostafa, A., 2018, Environmental contamination by pharmaceutical waste: Assessing patterns of disposing unwanted medications and investigating the factors influencing personal disposal choices. *Journal of Pharmacology and Pharmaceutical Research* ***1***(1), 003. https://www.thebiomedica.org/articles/jppr.003.pdf.

[71] Simegn, W., Dagnew, B., Dagne, H., 2020, Knowledge and associated factors towards cytotoxic drug handling among University of Gondar Comprehensive Specialized Hospital health professionals, institutional-based cross-sectional study. *Environmental Health and Preventive Medicine* **25**, 11. https://doi.org/10.1186/s12199-020-00850-z

[72] Sanito, R.C., Mujiyanti, D.R., You, S.-J., Wang, Y.-F., 2024, A review on medical waste treatment in COVID-19 pandemics: Technologies, managements and future strategies. *Journal of the Air & Waste Management Association* **74**, 72–99. https://doi.org/10.1080/10962247.2023.2282011

[73] Mazzei, H. G., & Specchia, S., 2023, Latest insights on technologies for the treatment of solid medical waste: A review. *Journal of Environmental Chemical Engineering* **11**(2), 109309. https://doi.org/10.1016/j.jece.2023.109309

[74] Memar, S., Dean, T., & Abeyrathna, P.**,** 2022, Management of medical waste: New strategies and techniques. In *Waste technology for emerging economies* (pp. 20). (Boca Raton: CRC Press). https://doi.org/10.1201/9781003132349

[75] Pinho, S. C.**,** 2015, *Disinfection of healthcare waste (HCW) by alkaline hydrolysis, its efficiency and emissions* (Doctoral dissertation, Universidade do Porto). (Porto: Universidade do Porto)

[76] Askarian, M., Heidarpoor, P., Assadian, O., 2010, A total quality management approach to healthcare waste management in Namazi Hospital, Iran. *Waste Management* **30**, 2321–2326. https://doi.org/10.1016/j.wasman.2010.06.020

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Peripheral Blood mRNA Profiling of SGCE and TOR1A in Myoclonus-Dystonia Syndrome: A Genetic Expression Study

Laila Rachad [1,a*], Hicham El Otmani [1,2,b], Khadija El Azhary [1,c], Nabil Zaid [3,d], Nadia El Kadmiri [1,4,e], Sellama Nadifi [1,f].

[1] *Laboratory of Medical Genetics and Molecular Pathologies, Faculty of Medicine and Pharmacy, Hassan II University of Casablanca (ROR: https://ror.org/001q4kn48), Casablanca, Morocco.*

[2] *Department of Neurology, Ibn Rochd University Hospital (ROR: https://ror.org/03sbc8x80), Casablanca, Morocco.*

[3] *Beaulieu-Saucier Pharmacogenomics Centre, Montreal Heart Institute (ROR: https://ror.org/03vs03g62), Montreal, QC, Canada.*

[4] *LBVE, Polydisciplinary Faculty of Taroudant, Ibn Zohr University (ROR: https://ror.org/006sgpv47), Taroudant, Morocco.*

[a] ***ORCID:*** *0000-0002-6856-182X,* ***Email****: laila.rachad@gmail.com*

[b] ***ORCID:*** *0000-0003-0870-1808,* ***Email****: hichamotmani@hotmail.com*

[c] ***ORCID:*** *0000-0002-7781-2352,* ***Email****: elazhary.khadija6m@gmail.com*

[d] ***ORCID****: 0000-0002-9272-6591,* ***Email****: zaidnabil@hotmail.com*

[e] ***ORCID:*** *0000-0002-7032-9704,* ***Email****: tresverre11@hotmail.com*

[f] ***ORCID****: 0000-0002-4272-1506,* ***Email****: ced.fmpc.gen@gmail.com*

*** Corresponding author:** Laila Rachad; ***Email address***: *laila.rachad@gmail.com*

Graphical Abstract

This study examined peripheral blood samples from patients with myoclonus–dystonia and healthy controls to profile mRNA expression of *SGCE* and *TOR1A*. Using real-time PCR, we identified significant overexpression of both genes in patients compared to controls, with a clear positive correlation between their expression levels. These findings indicate that *SGCE* and *TOR1A* expression changes may act as molecular biomarkers to distinguish affected patients from healthy subjects.

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Abstract: Myoclonus-Dystonia (M-D) is a rare autosomal-dominant movement disorder characterized by myoclonic jerks and dystonic symptoms. Myoclonus-Dystonia has been linked to mutations affecting the epsilon-sarcoglycan (SGCE, DYT11) gene. The syndrome has also been associated with mutations in the TOR1A (DYT1) gene. Herein we propose for the first time a link between the mRNA expression levels of SGCE and TOR1A. The main aim of this study was to detect the SGCE and TOR1A mRNA levels in peripheral blood of M-D patients and to explore the correlation between their mRNA levels. We have demonstrated that SGCE mRNA was highly expressed in peripheral blood of M-D patients compared to healthy controls (P = 0.04). We also observed that TOR1A mRNA levels were markedly higher in M-D patients than in healthy controls (P = 0.009). Furthermore, we have demonstrated a significant positive correlation between the SGCE and TOR1A mRNA levels in M-D patients (r = 0.659, p = 0.01). These findings suggest that the analysis of SGCE and TOR1A mRNA levels in peripheral blood could serve as a potential molecular biomarker for distinguishing M-D patients from healthy controls.

Keywords: Myoclonus-Dystonia, SGCE, TOR1A, Biomarker.

Introduction

Myoclonus-Dystonia (M-D), one of the combined dystonia syndromes, is a rare hereditary movement disorder clinically characterized by the presence of both myoclonus (rapid, involuntary jerks) and dystonia (muscle contractions that cause abnormal postures), which affect mainly the upper part of the body; lower limbs are occasionally involved [1]. Symptom onset is usually in the first two decades of life [2–5]. The disorder manifests with a range of symptoms that vary in severity, including tremors, bradykinesia and psychiatric abnormalities [6–7]. The vast majority of familial cases of M-D are linked to mutations in the SGCE gene. Inheritance follows an autosomal-dominant pattern with reduced penetrance on maternal transmission as a result of imprinting of the maternal allele [8]. Epsilon-sarcoglycan (SGCE, DYT11) is the major M-D gene located on chromosome 7q21-q31 and encodes the ε-sarcoglycan protein, a transmembrane glycoprotein within the dystrophin-glycoprotein complex (DGC) [9–11]. The DGC is composed of a number of transmembrane proteins that bind the cytoskeleton to the extracellular matrix in adult muscle fibres [12]. SGCE protein is found in striated and smooth muscle, heart and lung. In the brain, ε-sarcoglycan is strongly expressed in the midbrain monoaminergic neurons, cerebellar Purkinje cells, hippocampus and cortex [13]. The precise function of SGCE protein in the brain remains unknown [4,12,13]. Mutations of the SGCE gene are detected in about 30–50% of M-D cases; most are believed to cause a loss of function through frameshift and protein truncation before the transmembrane domain [9]. The pathophysiology of M-D is therefore not entirely clear [4]. Earlier reports indicated that M-D could also be linked to mutations in the TOR1A gene (DYT1), sometimes in combination with SGCE mutations [14–16].

Early-onset generalized torsion dystonia is a dominantly inherited movement disorder caused by a 3-bp deletion (ΔGAG) in the TOR1A gene that results in a loss of a glutamic acid residue (ΔE) in the carboxy-terminal region of the encoded protein torsinA [17]. This protein is a member of the AAA+ (ATPases associated with various cellular activities) superfamily of ATPases with an unknown biological function. This group of chaperone proteins is involved in protein folding, assembly of protein complexes, and transport of cargo in cells. TorsinA is localized in the contiguous lumen of the endoplasmic reticulum (ER) and nuclear envelope (NE) [17]. Previous studies revealed an association between TorsinA and SGCE protein, suggesting that TorsinA contributes to the quality control of SGCE [13,15,18]. In addition, since mRNA is translated into protein, one might presume that there is some correlation between the level of mRNA and that of protein. The present study aimed to detect the mRNA expression levels of SGCE and TorsinA in the peripheral blood of M-D patients and to explore the correlation between their mRNA levels.

Methods

Patients and samples

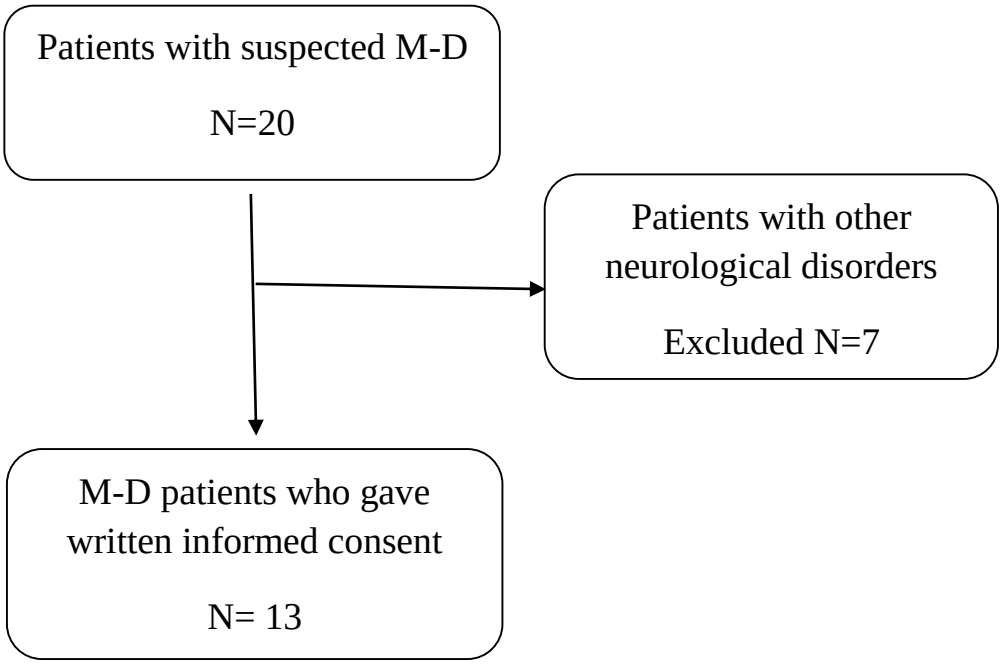
Patients and healthy control subjects were recruited at the Neurology Department of CHU IBN ROCHD (Casablanca, Morocco). All patients went through standardized neurological examinations performed by a movement disorder specialist and were diagnosed according to previously published diagnostic criteria. Psychiatric diagnoses were also made. The exclusion criteria were patients who had other neurological deficits or abnormal findings on electroencephalogram (EEG). After the neurological examination, 13 patients were included in the study. Table 1 shows clinical details of each patient. Our study also included 13 healthy control subjects who had no history of movement disorder. Figure 1 shows patient and control flow charts. Written informed consent was obtained from each patient. This study was approved by the Ethics Committee for Biomedical Research of the Faculty of Medicine and Pharmacy of Casablanca, Hassan II University, Casablanca, Morocco, under reference number 21/15. Peripheral blood samples were obtained from all patients and healthy controls. PBMCs were isolated by standard density centrifugation using Ficoll-Paque PLUS.

Table 1. Clinical features of M-D patients.

Case/sex	Age at onset (years)	Age at examination	Myoclonus distribution	Dystonia distribution	Alcohol sensitivity	Additional features
1/M	10	27	UL / C	UL / C / T	Yes	Depression
2/M	12	21	UL / C / Cr	UL / C / Wc	NK	OCD
3/M	12	20	UL / C	UL / C / Wc	NK	–
4/M	25	29	UL / C	Wc / N / T	Yes	Anxiety, Depression
5/F	7	25	UL / C / Cr	UL / C / Wc	NK	OCD
6/F	27	41	UL / C	C	NK	–
7/M	7	14	UL / C / Cr	UL / C / Wc	NK	–
8/M	15	18	UL / LL / C / T	UL / C / Wc	NK	–
9/M	Childhood	23	UL / LL / C / T	UL / LL / C	NK	–
10/M	3	17	UL / C	UL / LL / C / Wc	NK	–
11/M	Childhood	20	UL / C	UL	NK	–
12/M	Childhood	26	UL / C	C	NK	Anxiety
13/M	16	57	UL / C / N	UL / C / Wc	NK	OCD

UL = upper limbs; LL = lower limbs; C = cervical; Cr = cranial; N = neck; T = trunk; Wc = writer's cramp; NK = not known; OCD = obsessive–compulsive disorder.

M-D patients flow chart



Healthy controls flow chart

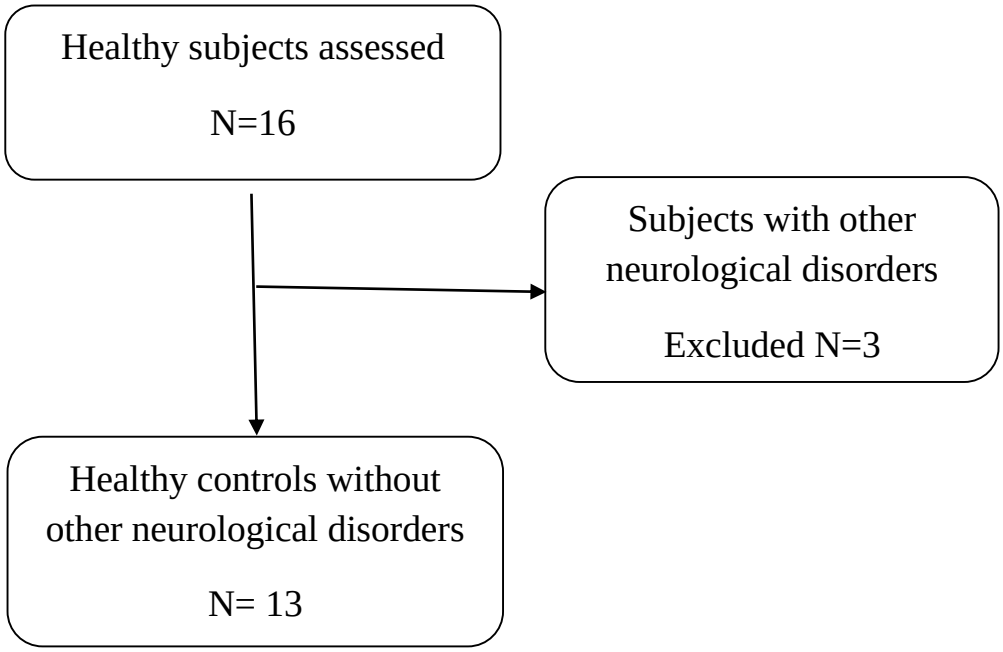


Figure 1. Flow charts of patients and controls

RNA Extraction and Reverse Transcription

Total ribonucleic acid RNA was extracted from PBMCs using TRIzol® Reagent (Invitrogen) according to the manufacturer's instructions. The quality and quantity of total RNA were determined by measuring the absorbance at 260–280 nm (ratio 1.8–2.1) using a spectrophotometer (GE Healthcare, UK), and stored at -80°C prior to analysis. The total RNA was reverse transcribed into cDNA using Random Hexamer (Invitrogen, 300 µg/µl) as a primer for denaturation, then the reverse transcription with: 10 nM dNTP (Invitrogen), DTT (0.1 M), recombinant RNasin, 5× first strand buffer, and SuperScript III RT (Invitrogen).

Quantitative analysis by Real-Time Polymerase Chain Reaction (RT-PCR)

To detect the mRNA expression levels of SGCE, TOR1A genes, and the housekeeping gene (β-ACTIN), quantitative PCR (qPCR) was carried out in duplicate using SYBR Green PCR Master Mix on the Applied Biosystems 7500 Fast Real-Time PCR System. Primers were designed as shown in Table 2. We analysed the relative quantification of SGCE and TOR1A mRNA expression levels using the comparative Ct method (2-ΔCt method) with β-ACTIN as the internal **control**

Table 2. Primers used for quantitative real-time PCR

Gene	Primer	Sequence (5'→3')
β-actin	Forward	5′-AGAGATGGCCACGGCTGCTT-3′
β-actin	Reverse	5′-ATTTGCGGTGGACGATGGAG-3′
SGCE	Forward	5′-ATGCAAACACCAGACATCCA-3′
SGCE	Reverse	5′-ACAGGGTGGAACACAGGAAG-3′
TOR1A	Forward	5′-TGGCCTTGTGTGTGTGTTTT-3′
TOR1A	Reverse	5′-CTTGGAGAGGCTGTTTCAGG-3′

Statistical Analysis

Statistical analysis was performed using SPSS software version 15.0.1 (Chicago, IL). Student's t-test and one-way ANOVA were applied to compare expression levels of SGCE and TOR1A mRNA among controls and M-D patients. Correlation between the SGCE and TOR1A mRNA levels was determined by Pearson's correlation coefficient. A criterion of p-value < 0.05 was considered significant [* $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$].

Results

Measurement of SGCE gene mRNA expression levels:

The results showed that M-D patients exhibited an overexpression of the SGCE gene compared to the control cases (**Figure 2**, $p = 0.04$).

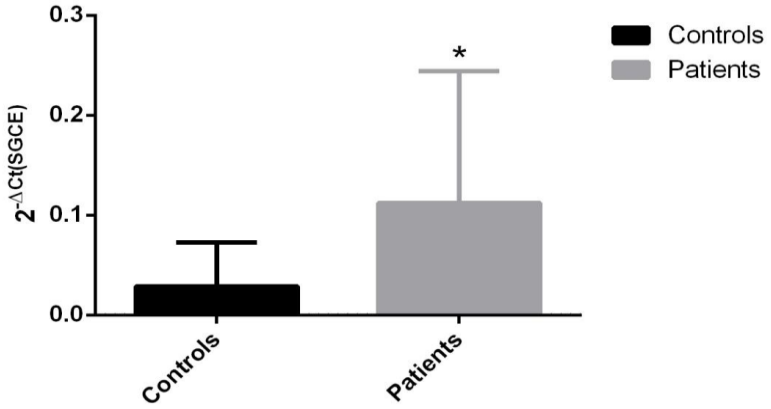


Figure 2. SGCE mRNA expression levels in peripheral blood of M-D patients and controls were determined using the quantitative RT-PCR.

Based on these data, it can be inferred that the overexpression of SGCE mRNA observed in M-D patients is correlated with the mutational load. A comparison was made between carriers of mutations and those without mutations.

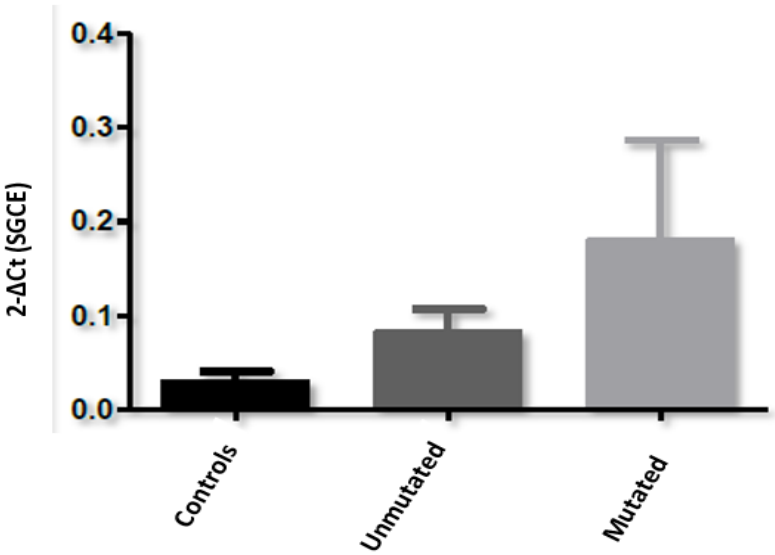
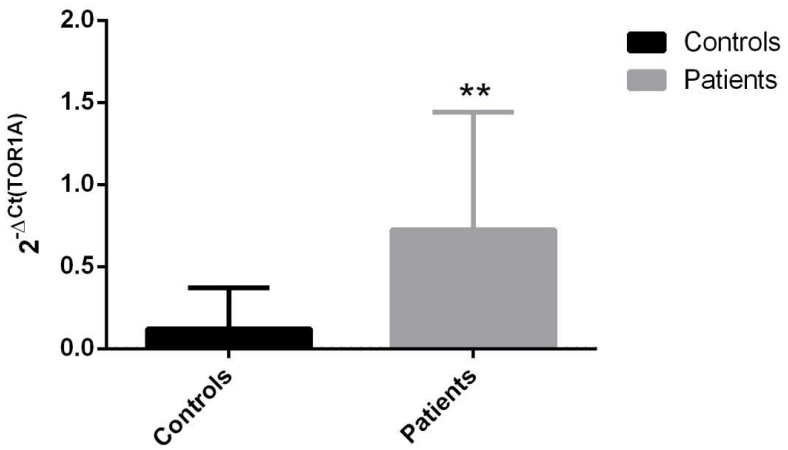


Figure 3. Comparison of SGCE Gene Expression Levels Between Mutated, Unmutated, and Healthy Controls

Our data showed higher SGCE mRNA levels in M-D patients carrying mutations compared to patients without mutations and control cases. A slight increase in mRNA levels was observed in patients without mutations compared with control cases. Comparison between the three groups highlighted a difference in their mRNA levels (Figure 3), but whether this difference is statistically significant remains unclear.

Measurement of TOR1A gene mRNA expression levels

As shown in Figure 4, overexpression of TOR1A mRNA was observed in M-D patients compared to their healthy counterparts (p = 0.009).



gure 4. mRNA expression levels of TOR1A in the peripheral blood of M-D patients and controls were determined using the quantitative RT-PCR (p = 0.009).

*A significant difference of SGCE and TOR1A mRNA expression levels was noticed respectively at *p < 0.05; **p < 0.01.*

The abnormal expression of the TOR1A gene could be related to the M-D phenotype. It is hypothesized that variations in the regulatory regions of the TOR1A gene may be associated with the development of the disease.

Comparison of SGCE and TorsinA mRNA levels in M-D patients

By comparing the expression levels of the two target genes, the result showed a lower expression rate of the SGCE gene compared to the TOR1A gene (Figure 5, p = 0.006).

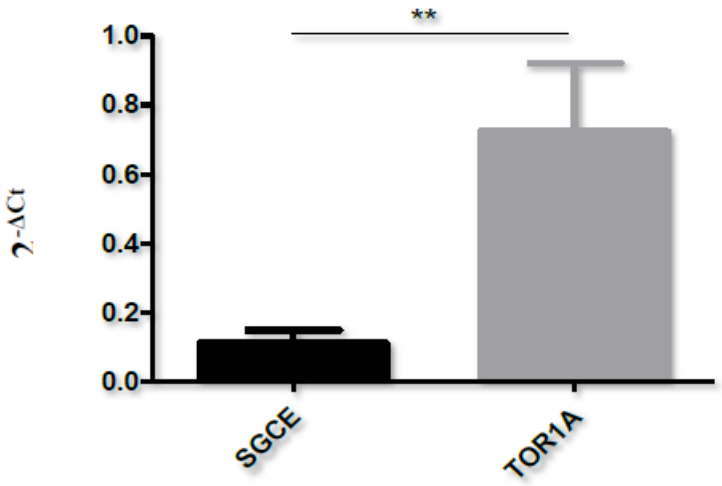


Figure 5. Comparison of SGCE and TOR1A gene expression levels.

Previous studies have revealed an association between TOR1A and SGCE. Since mRNA is translated into protein, it can be inferred that there is a correlation between mRNA levels and protein levels. To assess the association between SGCE and TOR1A, a correlation test was used.

Correlation analysis between SGCE and TOR1A mRNA levels in M-D patients

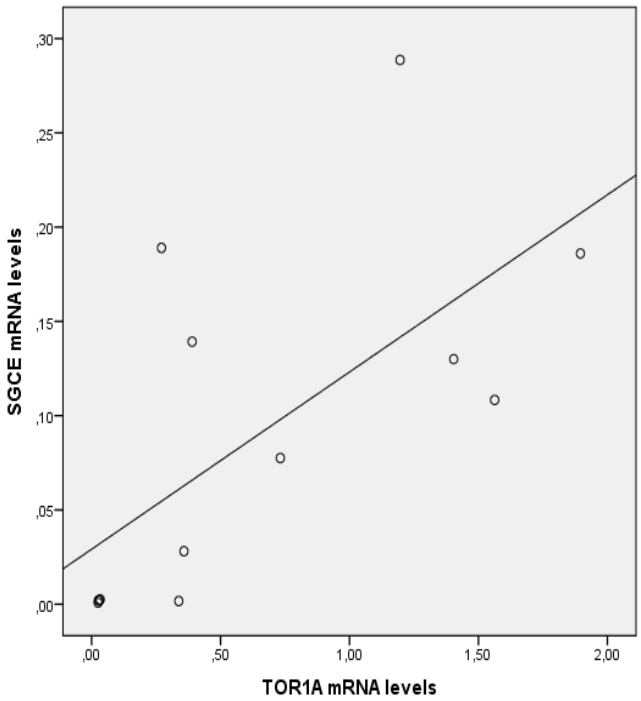


Figure 6. Correlation between SGCE and TOR1A mRNA expression levels in peripheral blood of M-D patients, determined using Pearson's correlation analysis (r = 0.659, p = 0.01).

In M-D patients, a significant positive correlation was found between SGCE and TOR1A mRNA levels in peripheral blood according to Pearson's correlation test (Figure 6, r = 0.659, p = 0.01)

Discussion

Although it is known that mutations in the SGCE gene cause M-D [9], the precise pathophysiology remains incompletely understood [4]. Three isoforms of SGCE have been reported, with exon 11b being the major brain-specific isoform, predominantly expressed in the cerebral cortex, cerebellum, and hippocampus [19]. The protein ε-sarcoglycan, a member of the transmembrane protein family, is localized to the plasma membrane in neurons, muscle, and transfected cells [20]. In the presence of missense mutations, ε-sarcoglycan fails to traffic to the plasma membrane and is retained intracellularly, polyubiquitinated, and degraded by the proteasome [13,20]. Previous studies have demonstrated that TorsinA, encoded by the TOR1A gene, forms a stable complex with mutant forms of ε-sarcoglycan, promotes its degradation, and plays a role in its quality control [13,17,18,21]. In this context, we propose for the first time a link between SGCE and TOR1A mRNA expression levels in patients with M-D.

Our results revealed significant overexpression of SGCE mRNA in M-D patients compared with controls ($p = 0.04$), suggesting that SGCE expression is altered in the context of M-D. This finding supports previous research linking SGCE expression levels to the pathogenesis of the disease. We observed higher SGCE mRNA levels in mutation carriers, which were significantly greater than in patients without mutations and in controls. This suggests that the mutational load may correlate with the overexpression of SGCE mRNA. A slight increase in mRNA levels was also observed in patients without mutations compared to controls, indicating possible subtle alterations in gene expression in this group. Despite these variations, the comparison between the three groups revealed a significant difference in SGCE mRNA levels (Figure 24), but whether this difference is statistically significant remains obscure and requires further investigation.

The elevated SGCE mRNA levels in M-D patients raise the possibility of overexpression of ε-sarcoglycan protein in key brain structures involved in motor function. Such overexpression may contribute to the pathophysiology of M-D by altering normal protein folding and trafficking processes. In this context, we hypothesize that mutations in SGCE lead to the retention of misfolded proteins within the endoplasmic reticulum (ER), where they are polyubiquitinated and degraded by the proteasome. This misfolding may be exacerbated in the presence of TorsinA, a protein known to organize the ER and the nuclear envelope. TorsinA may play a critical role in the quality control of SGCE in the ER, further supporting the idea of a functional interaction between the two proteins. The binding of TorsinA to mutant SGCE and its role in promoting its degradation have been well documented [13,15,18], and our findings of a significant correlation between the mRNA levels of SGCE and TOR1A ($r = 0.659$, $p = 0.01$) lend support to this interaction at the gene expression level.

Furthermore, the comparison of the expression levels of SGCE and TOR1A revealed lower expression of SGCE compared to TOR1A (Figure 27, $p = 0.006$), suggesting differential regulation of these two genes in the context of M-D. This result may imply that, although both genes are involved in the pathogenesis of M-D, their expression is not entirely coordinated. It is noteworthy that the relationship between SGCE and TOR1A expression could have implications for understanding the broader molecular mechanisms underlying the disease.

Based on these findings, we suggest that the overexpression of SGCE and the correlated expression of TOR1A may be indicative of a pathological process in M-D patients. This raises the possibility that the analysis of SGCE and TOR1A mRNA levels in peripheral blood could serve as a potential molecular biomarker for distinguishing M-D patients from healthy controls. Continual mutation testing of SGCE and TOR1A in M-D patients will be crucial in further elucidating the molecular basis of these expression changes and their relationship to disease progression.

Conflicts of interest

The authors declare no conflict of interest.

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References

[1] Hamami, F., Gerkensmeier, S., Münchau, A., & Weissbach, A., 2024, ε-sarcoglycan myoclonus-dystonia—overview of neurophysiological, behavioral, and imaging characteristics. *Dystonia* **3**, 11693. https://doi.org/10.3389/dyst.2024.11693

[2] Mencacci, N. E., Rubio-Agusti, I., Zdebik, A., Asmus, F., Ludtmann, M. H. R., Ryten, M., Plagnol, V., Hauser, A.-K., Bandres-Ciga, S., Bettencourt, C., Forabosco, P., Hughes, D., Soutar, M. M. P., Peall, K., Morris, H. R., Trabzuni, D., Tekman, M., Stanescu, H. C., Kleta, R., Carecchio, M., Zorzi, G., Nardocci, N., Garavaglia, B., Lohmann, E., Weissbach, A., Klein, C., Hardy, J., Pittman, A. M., Foltynie, T., Abramov, A. Y., Gasser, T., Bhatia, K. P., & Wood, N. W., 2015, A missense mutation in *KCTD17* causes autosomal dominant myoclonus-dystonia. *The American Journal of Human Genetics* **96**(6), 938–947. https://doi.org/10.1016/j.ajhg.2015.04.008

[3] Akarsu, E. O., Surmeli, R., & Yalcin, D., 2014, Myoclonus-dystonia syndrome: case report. *Northern Clinics of İstanbul* **1**(3), 187-190. https://jag.journalagent.com/nci/pdfs/NCI-28247-CASE_REPORT-OGUZ_AKARSU.pdf

[4] Rachad, L., El Kadmiri, N., Slassi, I., El Otmani, H., & Nadifi, S., 2017, Genetic aspects of myoclonus–dystonia syndrome (MDS). *Molecular Neurobiology* **54**(2), 939-942. https://doi.org/10.1007/s12035-016-9712-x

[5] Sarva, H., Miravite, J., Swan, M. C., Deik, A., Raymond, D., Severt, W. L., & Kopell, B. H., 2017, A Case of Myoclonus–Dystonia Responding to Low-frequency Pallidal Stimulation. *Tremor and Other Hyperkinetic Movements* **7**, 460. https://doi.org/10.7916/D82Z1BS4

[6] Hess, C. W., Raymond, D., de Carvalho Aguiar, P., Frucht, S., Shriberg, J., Heiman, G. A., Kurlan, R., Klein, C., Bressman, S. B., Ozelius, L. J., & Saunders-Pullman, R., 2007, Myoclonus-dystonia, obsessive-compulsive disorder, and alcohol dependence in *SGCE* mutation carriers. *Neurology* **68**(7), 522–524. https://doi.org/10.1212/01.wnl.0000253188.76092.06

[7] Kim, J.-Y., Lee, W.-W., Shin, C. W., Kim, H.-J., Park, S.-S., Chung, S. J., Cho, J. W., Ryu, H.-S., Son, T. O., & Jeon, B., 2017, Psychiatric symptoms in myoclonus-dystonia syndrome are just concomitant features regardless of the *SGCE* gene mutation. *Parkinsonism & Related Disorders* **42**, 73–77. https://doi.org/10.1016/j.parkreldis.2017.06.014

[8] Müller, B., Hedrich, K., Kock, N., Dragasevic, N., Svetel, M., Garrels, J., Landt, O., Nitschke, M., Pramstaller, P. P., Reik, W., Schwinger, E., Sperner, J., Ozelius, L., Kostic, V., & Klein, C., 2002, Evidence that paternal expression of the ε-sarcoglycan gene accounts for reduced penetrance in myoclonus-dystonia. *The American Journal of Human Genetics* **71**(6), 1303–1311. https://doi.org/10.1086/344531

[9] Zimprich, A., Grabowski, M., Asmus, F., Naumann, M., Berg, D., Bertram, M., Scheidtmann, K., Kern, P., Winkelmann, J., Müller-Myhsok, B., Riedel, L., Leube, B., Pilz, P., Fuchs, S., Dichgans, M., Gasser, T., & Wichmann, H. E., 2001, Mutations in the gene encoding ε-sarcoglycan cause myoclonus–dystonia syndrome. *Nature Genetics* **29**(1), 66–69. https://doi.org/10.1038/ng709

[10] Asmus, F., Zimprich, A., Tezenas Du Montcel, S., Kabus, C., Deuschl, G., Kupsch, A., Ziemann, U., Castro, M., Kühn, A. A., Strom, T. M., Vidailhet, M., Bhatia, K. P., Dürr, A., Wood, N. W., Brice, A., & Gasser, T., 2002, Myoclonus–dystonia syndrome: ε-sarcoglycan mutations and phenotype. *Annals of Neurology* **52**(4), 489–492. https://doi.org/10.1002/ana.10325

[11] Bhidayasiri, R., & Pulst, S. M., 2005, Dystonia (DYT) genetic loci. *European Journal of Paediatric Neurology* **9**(5), 367-370. https://doi.org/10.1016/j.ejpn.2005.05.002

[12] Waite, A. J., Carlisle, F. A., Chan, Y. M., & Blake, D. J., 2016, Myoclonus dystonia and muscular dystrophy: ε-sarcoglycan is part of the dystrophin-associated protein complex in brain. *Movement Disorders* **31**(11), 1694-1703. https://doi.org/10.1002/mds.26738

[13] Esapa, C. T., Waite, A., Locke, M., Benson, M. A., Kraus, M., McIlhinney, R. A. J., Sillitoe, R. V., Beesley, P. W., & Blake, D. J., 2007, *SGCE* missense mutations that cause myoclonus-dystonia syndrome impair ε-sarcoglycan trafficking to the plasma membrane: Modulation by ubiquitination and torsinA. *Human Molecular Genetics*, **16**(3), 327–342. https://doi.org/10.1093/hmg/ddl472

[14] Doheny, D., Danisi, F., Smith, C., Morrison, C., Velickovic, M., de Leon, D., Bressman, S. B., Leung, J., Ozelius, L., Klein, C., Breakefield, X. O., Brin, M. F., & Silverman, J. M., 2002, Clinical findings of a myoclonus-dystonia family with two distinct mutations. *Neurology* **59**(8), 1244–1246. https://doi.org/10.1212/WNL.59.8.1244

[15] Klein, C., Liu, L., Doheny, D., Kock, N., Müller, B., De Carvalho Aguiar, P., Leung, J., De Leon, D., Raymond, D., Bressman, S. B., Ozelius, L., & Breakefield, X. O., 2002, ε-sarcoglycan mutations found in combination with other dystonia gene mutations. *Annals of Neurology* **52**(5), 675–679. https://doi.org/10.1002/ana.10358

[16] Schüle, B., Kock, N., Svetel, M., Dragasevic, N., Hedrich, K., De Carvalho Aguiar, P., Liu, L., Kabakci, K., Garrels, J., Meyer, E.-M., Berisavac, I., Schwinger, E., Kramer, P. L., Ozelius, L. J., Klein, C., & Kostic, V., 2004, Genetic heterogeneity in ten families with myoclonus-dystonia. *Journal of Neurology, Neurosurgery & Psychiatry* **75**(8), 1181–1185. https://doi.org/10.1136/jnnp.2003.027177

[17] Yokoi, F., Yang, G., Li, J., DeAndrade, M. P., Zhou, T., & Li, Y., 2010, Earlier onset of motor deficits in mice with double mutations in Dyt1 and Sgce. *The Journal of Biochemistry* **148**(4), 459-466. https://doi.org/10.1093/jb/mvq078

[18] Granata, A., Schiavo, G., & Warner, T. T., 2009, TorsinA and dystonia: from nuclear envelope to synapse. *Journal of Neurochemistry* **109**(6), 1596-1609. https://doi.org/10.1111/j.1471-4159.2009.06095.x

[19] Ritz, K., van Schaik, B.D., Jakobs, M.E., van Kampen, A.H., Aronica, E., Tijssen, M.A., Baas, F., 2011, SGCE isoform characterization and expression in human brain: implications for myoclonus–dystonia pathogenesis? European Journal of Human Genetics **19**, 438–444. https://doi.org/10.1038/ejhg.2010.206

[20] Grütz, K., Seibler, P., Weissbach, A., Lohmann, K., Carlisle, F. A., Blake, D. J., Westenberger, A., Klein, C., & Grünewald, A., 2017, Faithful SGCE imprinting in iPSC-derived cortical neurons: An endogenous cellular model of myoclonus-dystonia. *Scientific Reports* **7**(1), 41156. https://doi.org/10.1038/srep41156

[21] Hewett, J., Gonzalez-Agosti, C., Slater, D., Ziefer, P., Li, S., Bergeron, D., Jacoby, D. J., Ozelius, L. J., Ramesh, V., & Breakefield, X. O., 2000, Mutant torsinA, responsible for early-onset torsion dystonia, forms membrane inclusions in cultured neural cells. *Human Molecular Genetics* **9**(9), 1403–1413. https://doi.org/10.1093/hmg/9.9.1403

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Investigating Potential New Load Patterns on Distribution Transformers from Residential Electrification

Joshua Martin[a], Jacqueline Stagner[b] ☑, Rupp Carriveau[c]

Environmental Energy Institute, Turbulence and Energy Laboratory University of Windsor (https://ror.org/01gw3d370), 401 Sunset Avenue, Windsor, Ontario, Canada

[a] ***Email:*** *martin2q@uwindsor.ca*

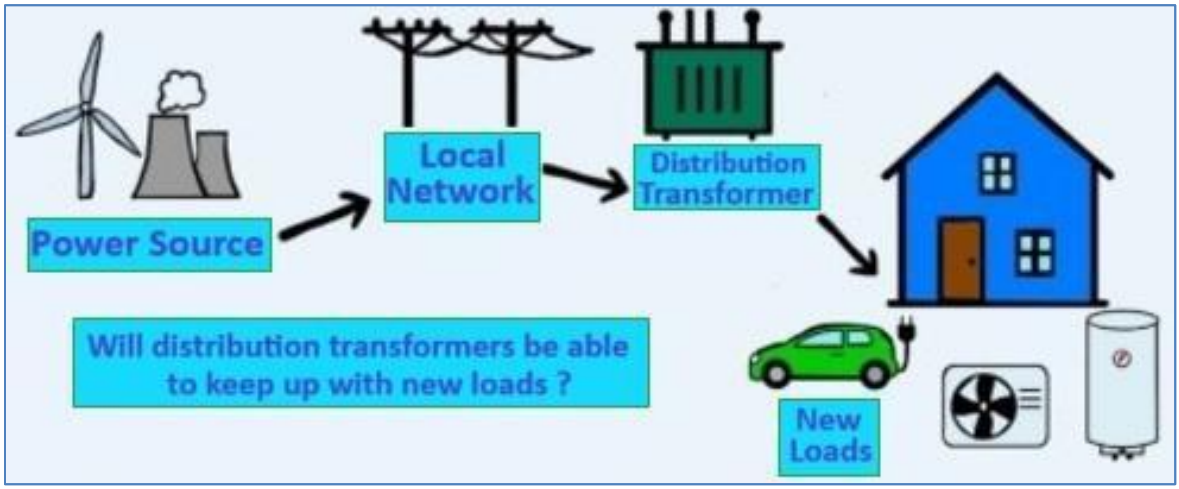
[b] ***ORCID****: 0000-0002-8039-1579;* ***Email****: stagner@uwindsor.ca*

[c] ***ORCID****: 0000-0003-3048-7991;* ***Email:*** *rupp@uwindsor.ca*

☑ **Corresponding author :** Jacqueline Stagner; ***Email adress***: stagner@uwindsor.ca

Graphical Abstract

This study examines how residential electrification—through the widespread adoption of electric vehicles (EVs), heat pumps (HPs), and electric water heaters (EWHs)—is reshaping demand on local distribution transformers. Using Ontario utility data, the analysis shows that simultaneous use of these new loads can push transformer demand beyond safe operating limits, accelerating insulation ageing and increasing the risk of failure. The findings emphasize the urgent need for utilities to anticipate emerging household load patterns and plan infrastructure upgrades to sustain a reliable and resilient neighbourhood power supply.



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Abstract: As nations set ambitious targets to phase out internal combustion engine (ICE) vehicles and electrify transport and household systems, it is anticipated that there will be a surge in demand for electric vehicles (EVs), heat pumps (HPs), and electric water heaters (EWHs). Utility providers must assess what this shift means for the existing grid. Although generation may be sufficient, attention must turn to local distribution, particularly individual street-level transformers. As EV chargers are installed and households replace gas systems with HPs and EWHs, the grid faces rising pressure. Many consumers prefer to charge vehicles at home in the evening, placing extra demand on local infrastructure. When several residents charge EVs while using water heating and cooling systems, transformer capacity may be exceeded. This study uses data from an Ontario utility to examine new loading scenarios as EVs, HPs, and EWHs are adopted in Canadian neighbourhoods. One transformer showed a maximum hourly load increase of 706.59% at 25% uptake and 1292.22% at 50%. Sustained high loads accelerate insulation ageing and raise the risk of early failure**,** with overloads possible when 11 EVs charge simultaneously at high speed.

Keywords: *Residential electrification, Distribution transformer load, Electric vehicles (EVs).*

Introduction

Governments worldwide are developing strategies to combat greenhouse gas emissions, with a significant focus on both the transportation sector and residential energy systems [1,2]. To reduce the number of internal combustion engine (ICE) vehicles, regulators are setting restrictions on their sale in future markets, thereby accelerating the adoption of electric vehicles (EVs) [1]. This transition to EVs helps to reduce air pollution emissions and supports broader efforts to mitigate climate change. The Canadian government has established a mandatory target for all new sales of light-duty cars and passenger trucks to be zero emission by 2035 [1]. Alongside phasing out ICE vehicles, the government is also pursuing a net-zero emissions target by 2050. Progress will be tracked from 2030 onwards, aiming to meet Canada's Paris Agreement target by reducing emissions from 2005 levels [2]. This means that Canadian households will also need to contribute by limiting their overall emissions. Heat pumps (HPs) and electric water heaters (EWHs) are among the household technologies that can help to lower greenhouse gas emissions. These developments are expected to increase the number of EVs on the road and the presence of HPs and EWHs in homes. This raises an important question: how will these new loads affect the electricity grid, particularly distribution transformers?

Canadian electricity providers may be able to meet total demand, but the impact on distribution transformers remains uncertain. As electrification increases and policies increasingly favour zero-emission systems, the use of EVs, HPs, and EWHs is likely to rise significantly. This study examines the consequences of electrifying these systems and their effects on the grid—focusing on distribution transformers. A load management tool was developed to incorporate these new demands into the existing loads observed on actual transformers within an Ontario utility network**.** Our review of the literature identified three main areas relevant to this study: transformer vulnerability, load forecasting, and the impact of new loads on transformers. These areas are summarized with commentary for quick reference in Table

Table 1. Summary of relevant prior work

Category	Major theme	Reference
Transformer vulnerability	Distribution transformer failures	[3-4]
	Heavy loading, overloading, and ageing of transformers	[5–8]
	Outcomes of transformer failures	[9–11]
	Modelling transformer load forecasting using grey models, neural networks, bottom-up approaches, A priori algorithm, and long short-term memory	[12–15]
Load forecasting	Incorporating EVs and HPs into load forecasting models	[16–18]
	EV charging behaviour and consumer demand patterns	[19,20]
New loads on transformers	Modelling and detecting load signatures of EVs and other household appliances	[21–26]
	Strategies to reduce strain from EVs on transformers	[27–29]
	Impacts of EV charging on residential transformers	[30,31]
	Load impact of integrating HPs into the grid: timing and energy demand	[32–36]
	Energy use patterns and demand impact of EWHs	[37–39]
	Controlled simulations of EWH behaviour	[40–42]

Distribution Transformer Vulnerabilities

Distribution transformers are the critical connection between the power grid and consumers, ensuring homes receive reliable electricity. These street-level transformers perform the final voltage step-down from medium-voltage lines [3], making them essential to daily life. In this pivotal role, distribution transformers face several threats, including overloading and insulation failure [4]. Transformer failures disrupt power supplies, leading to outages, causing costly repairs and frustrated ratepayers. Understanding the causes of transformer ageing and failure is essential for strengthening the grid, particularly as neighbourhood electrification increases. One study [4] confirmed that a distribution transformer must provide a reliable, uninterrupted electricity supply to residential homes. It examined detailed failures that occurred in 348 distribution transformers between 2010 and 2015 in Indiana. The causes and proportions of failure are presented in Table 2.

Table 2. Causes of transformer failure [4].

Cause of failure	Percentage	Cause of failure	Percentage
Insulation failure	26.44%	Oil contamination	5.75%
Line surge	20.11%	Improper maintenance	5.46%
Overloading	8.63%	Lightning	4.02%
Manufacturing defects	6.32%	Sabotage	0.57%
Moisture	6.03%	Other	16.67%

Note: Percentages are based on the analysis of 348 transformer failures recorded between 2010 and 2015 in Indiana, USA. The category *Other* includes undetermined or multiple contributing factors.

When overloading occurs for extended periods, there are thermal consequences [4]. One study recorded 98 thermal failures, of which 30 were linked to prolonged overloading. Thermal component failure reduces the strength of insulating materials, weakening them even under normal voltage conditions [4]. Heavy overloading on distribution transformers can affect supply reliability and power quality delivered to residents [5].

A study in Hubei Province, covering January 2017 to June 2018, examined the effects of heavy loading and overloading on transformer performance. It found that such conditions increased failure rates [5]. This results in over-current protection problems, including overheating, equipment damage, and transformer fires.

Overloading also accelerates transformer ageing. Several studies [6–8] explore this. Thermal stress during overloading can cause explosions or burning of insulating liquids, leading to damage across the power grid [6]. Zhang *et al*. [6] demonstrated that natural ester and aramid-reinforced cellulose materials can enhance transformer resilience under overload.

Forouhari *et al.* [7] identified key factors contributing to mechanical ageing, including temperature, moisture, acid presence, and oxygen inside the transformer [7]. As demand grows, higher internal temperatures accelerate the ageing process. Biçen *et al.* [8] estimated transformer degradation based on insulation life, showing that load conditions play a major role. Their method relied on current literature, as historical data were unavailable [8].

Casey *et al.* [9] and Rubin *et al.* [10] emphasize the downstream effects of transformer failure, particularly the disruption of essential services such as food preservation, heating and cooling, and the use of medical devices [9,10]. Frequent outages can result in financial losses for households

and businesses, making it difficult to cope with unreliable electricity supply. Prolonged power cuts may also reduce trust in utility providers, leading customers to seek alternative energy sources or demand improved reliability.

Rubin *et al.* [10] examined large-scale blackouts across the grid caused by the failure of multiple transmission lines, generators, and other high-voltage equipment under conditions of extreme overload. Yamashita *et al.* [11] noted that when multiple street-level transformers experience overload, it can trigger cascading failures in other parts of the network, potentially resulting in blackouts [11]. Utilities must monitor asset loading to ensure transformers continue to deliver stable and reliable power to consumers.

Transformer Load Forecasting

Forecasting aims to predict future energy demand and assess its impact on distribution transformers. These variables were integrated to detect periods of heavy loading and potential stress on transformers. By using weather forecasts and holiday calendars, the model could anticipate excess demand on distribution transformers. Several advanced models have been developed. Sun *et al.* [12] applied grey modelling and neural networks. Yuan *et al.* [13] and da Silva *et al.* [14] used bottom-up end-use approaches combined with stochastic and hierarchical linear models [13,14]. In a more transformer-specific study, Wang *et al.* [15] applied the A priori algorithm and long short-term memory (LSTM) networks to predict future overloads based on consumption patterns and weather data [15].

Lindberg *et al.* [16] observed that many models failed to consider growing electrification trends, particularly the impact of electric vehicles (EVs) and heat pumps (HPs) on energy demand. Boßmann *et al.* and Asare-Bediako *et al.* [17,18] incorporated EVs and HPs into load forecasting models for Germany and the Netherlands. Boßmann *et al.* [17] highlighted how these technologies shift peak demand to the evening, when there is no solar generation. As a result, evening demand may rely on fossil fuels to compensate for gaps in renewable output. Asare-Bediako *et al.* [18] noted that winter evening demand becomes a new peak, increasing transformer loading. Their study focused on distribution-level impacts and recommended that electrification trends should inform network design [18]. Both studies emphasized the need for demand-shifting strategies to reduce overload risks and better synchronize energy consumption with renewable generation.

New Loads on Transformers: EVs

Several studies have projected future growth in electric vehicle (EV) markets and how the power grid may need to adapt. Amjad *et al.* [19] examined charging behaviours that avoid overloading the grid. A rapid rise in EV adoption can lead to brownouts, blackouts, severe grid stress, and harmonics. The study considers factors such as charging duration and timing. Mobility patterns influence grid impact. For instance, some drivers may charge at work if facilities are available, but most will choose home charging. Home charging limits control over ideal load patterns, posing challenges for utilities since consumers have full autonomy over charging behaviour [19].

Moon *et al.* [20] investigated consumer preferences and projected their impact on the grid. Most users charge at public stations during the day and at home during the evening. The study identified private charging peaks between 18:00 and 06:00, with the highest demand from about 00:00 to 03:00, when electricity prices are lower. Public charging typically occurs from 06:00 to 18:00, with peaks between 09:00 and 12:00. The authors recommended adapting the grid to support EV loads, expanding infrastructure, and implementing policies that reflect real-world charging preferences.

Another way to estimate EV-related demand is through non-intrusive load monitoring (NILM). Schirmer *et al.* [21] described NILM as a method to determine the energy consumption of individual household devices. It enables better scheduling and helps manage increased demand on the grid. NILM means collecting a building's total power usage, identifying usage patterns, applying recognition algorithms, and disaggregating total consumption by device [21].

Various algorithms have been applied, such as artificial neural networks (ANN), support vector machines (SVM), k-nearest neighbours (k-NN), and hidden Markov models (HMM) [21–23]. Since these methods were not designed specifically for EV charging, they often require extensive training data and computational resources. Several studies have addressed this by developing algorithms to detect EV power signatures within household consumption data [22–26]. These approaches aim to filter out non-EV signals and isolate EV-specific load patterns.

Aravinthan *et al.* [27] proposed a method to manage EV charging in order to prevent irregular, high loads from straining system assets such as transformers. The approach analyses expected load based on previous days' consumption and uses homeowner-provided charging times. This information helps determine the maximum number of EVs the grid can support in the next hour.

Although the paper does not offer a scheduling system for individual vehicles, it focuses on optimizing total EV capacity across the grid.

Hilshey *et al.* [28] examined the impact of EVs on overhead distribution transformers using a thermal ageing model combined with travel behaviour. Charging in different climates was compared—Arizona and Vermont—and it was found that transformers in warmer conditions aged faster. Smart charging was shown to reduce transformer heating and extend asset life.

To address transformer degradation, Sarker *et al.* [29] proposed a centralized EV charging strategy. It incorporated vehicle-to-home and vehicle-to-grid modes to ease stress on transformers. The results showed that this centralized approach reduced transformer ageing compared to an equivalent distributed strategy.

The literature consistently emphasizes the need to regulate EV charging times to protect transformer health as EV use increases. Case studies by Muñoz *et al.* and Awadallah *et al.* [30,31] analysed residential-level EV penetration. Muñoz *et al.* [30] focused on charging during super off-peak hours (22:00–08:00). Awadallah *et al.* [31] examined charging at low-load (04:00–05:00), medium-load (12:00–13:00), and peak-load (20:00–21:00) periods.

Both studies considered chargers rated between 3.3 kW and 7.3 kW. Awadallah *et al.* concluded that larger chargers (10 kW or more) would likely require grid upgrades because of increased overload risk [31]**.**

Love *et al.* [32] analysed energy consumption data from 700 heat pump (HP) installations, sampled every two minutes, to assess their load profile. The study identified an after-diversity maximum demand (ADMD) of 1.7 kW per site, typically occurring in the morning. Although ADMD varies over time, 1.7 kW was the peak value. Based on this profile, four scenarios were tested, assuming HP uptake in 5%, 10%, 15%, and 20% of homes. These scenarios resulted in estimated power demand increases of 3.5%, 7.1%, 10.6%, and 14.3%, respectively. Rouwhorst *et al.* [33] studied 329 HPs in the Netherlands between January 2018 and December 2019. The HPs had rated power between 3 kW and 5.5 kW, with daily consumption ranging from 0.2 kWh to 1.1 kWh. Schlemminger *et al.* [34] examined 30 households in Germany from May 2018 to December 2020. The average annual energy use was 4,993 kWh, with a minimum of 1,431 kWh and a maximum of 14,840 kWh. Damianakis *et al.* [35] estimated HP energy demand based on seasonal variation and home insulation. In winter, insulated homes used 18 kWh daily on average, compared to 35 kWh for non-insulated ones. In summer, both types consumed approximately 8 kWh per day.

Oliyide *et al.* [36] investigated the combined impacts of EVs and HPs, forecasting energy use to 2050. Minimum daily consumption was set at 7.2 kWh, calculated using a consumption rate of 0.2 kWh/km and an average daily travel of 36 km. Maximum consumption was 16.8 kWh, based on replenishing 84 km of range in a 120 km EV.

New loads on transformers: EWHs

Nehrir *et al.* [37] simulated 1,000 electric water heaters (EWHs) to manage power consumption using voltage-controlled strategies. Two heating element power ratings were modelled: 4.5 kW and 1 kW. Voltage levels of 95%, 100%, and 105% of the base value were tested. The results showed high consumption between 07:00 and 08:00, moderate to high usage from 18:00 to 20:00, medium usage from 09:00 to 17:00, and low consumption during other periods.

Kondoh *et al.* [38] conducted a similar simulation using 10,000 EWHs and reported results consistent with those of Nehrir *et al.* [37], including similar operation durations and a 4.5 kW rating. Kondoh *et al.* [38] aimed to determine how many EWHs would be needed to provide bi-directional regulation support for 2 MW of capacity returned to the grid. They found that 33,000 EWHs would be required to meet this demand. Pourmousavi *et al.* [39] compared controlled and uncontrolled environments in a case study of 1,000 EWHs over one week. The study monitored usage during both peak and off-peak periods. Average weekly energy consumption was 280.41 GJ, with a range from 273.11 GJ to 289.70 GJ. This corresponds to an average of 11.13 kWh per household per day.

Other studies [40–42] demonstrated that controlled environments can significantly reduce peak demand fluctuations throughout the day. The aim of this study is to incorporate the load signatures identified in the literature and simulate the increased adoption of electric vehicles (EVs), heat pumps (HPs), and electric water heaters (EWHs) using existing data from an Ontario utility provider. As distribution transformers are essential for delivering power to consumers, it is important to understand how these added loads affect performance. This understanding improves lifespan prediction and informs decision-makers whether control systems are needed to avoid failures.

By addressing these challenges, utilities can reduce the risk of cascading faults and blackouts and help maintain a more reliable and resilient grid. A load management tool was developed to support utilities in analysing current demand and tracking consumption trends. This tool allows for the

application of forecasting metrics and supports planning for the electrification of transport and domestic systems. A simulation using this tool is presented to assess the potential impact of increased electrification on the distribution network**.**

Data Collection and Processing

An Ontario utility provided residential power consumption data, measured in kilowatt-hours, covering January to December 2023. Each home in the study was connected to a distribution transformer rated between 50 kVA and 167 kVA, with 9 to 19 homes per transformer. Table 3 lists the distribution transformers used in this analysis.

The data were processed to link each household with its associated transformer. This information was compiled into a structured database. Total energy consumption over time was aggregated to estimate the load on each transformer. The analysis focused on 10 distribution transformers within the utility's service area.

Table 3. Transformer ratings and maximum hourly load.

Transformer	Rating (kVA)	Number of homes	Maximum hourly load in 2023 (kWh)
T01	50	9	24.37
T02	100	19	57.06
T03	100	14	50.98
T04	100	13	29.41
T05	100	13	40.72
T06	100	14	42.38
T07	100	14	57.14
T08	100	13	61.11
T09	100	12	46.76
T10	167	14	51.71

To evaluate the impact of electrification on residential power systems, required power loads for EV chargers, heat pumps (HPs), and electric water heaters (EWHs) were sourced from the literature [20,22–26,31–42]. This study focuses on EV chargers rated at 7.7 kW, 9.6 kW, and 11.5 kW. Juda *et al.* [43] mention that Mode 2 chargers can provide charging power of up to 22 kW (AC). Tesla Wall Connector specifications [44] provide accurate information on charger sizes and

corresponding charging speeds. The charging rates are 47 km/h, 59 km/h, and 71 km/h for the 7.7 kW, 9.6 kW, and 11.5 kW chargers, respectively. Most literature reports typical charger operation between 3.3 kW and 7.3 kW. Awadallah *et al.* [31] noted that chargers rated at 10 kW or above can significantly affect the grid. In this study, higher-rated chargers were selected to reflect the trend towards faster charging, which is generally preferred by consumers and better illustrates potential impacts at the street level. Power signatures for these charger types were taken from the literature [20,22–26,31]**.**

For heat pumps, various data [33–36] are used to simulate power loads. A nominal electrical capacity of 1.9 kW or 3 kW is suggested, along with heating rods rated at 6 kW [35]. The same study proposes a combined active power consumption threshold of 4.00 kW, accounting for both the compressor and heating elements. This value is consistent with other sources [34,36], and will be used in this study.

Similarly, load demand for electric water heaters is based on various findings [38–42,45]**,** with a nominal power rating of 4.5 kW selected. Households are found to operate their electric water heaters throughout the day, with peak usage occurring between 07:00 and 08:00, and again from 18:00 to 20:00 [38-42,45]**.**

Methodology

This study will incorporate the new load patterns superposed on the historical data connected to each transformer. This process analyses current consumption patterns along with factors found in the literature representing EV charging patterns and operations of HPs and EWH to estimate future energy consumption and identify potential overloads on transformers. Many existing methods overlook the impact of electrification from EVs, HPs, and EWHs on energy consumption. This study shows the importance of examining all three systems.

Moon *et al.* [20] mention that consumers choose to charge their EVs at home between the hours of 18:00 and 06:00 hours. Awadallah *et al.* [31] states that the charging timeframes in that case study take place between 04:00 and 05:00 hours, 12:00 to 3:00 hours, and 20:00 to 21:00 hours. The present case study will start the charging at 18:00 hours. The first part of the study will examine the EVs charging at the same time, followed by a staggered start beginning at 18:00 hours. When calculating the consumption of the EV load the values needed are the Power at 240 volts, charging speed, and the distance for which the recharge is required. For this study a travel distance

of 50 km was used. To calculate the duration and power consumption by recharging the distance travelled in the day the following formula can be used:

$$TC = \frac{DT}{CS} * 60min \qquad (1)$$

Where *TC* is the total charge time, *DT* is the distance travelled, *CS* is the charging speed, and the result is multiplied by 60 to convert the time to minutes. In this study, chargers are assumed to operate at full capacity, and EVs are expected to require more than 50 km of charge. To estimate the power consumed per hour, formula (2) is applied**:**

$$PC = \frac{TC}{60min} \times P \qquad (2)$$

Where *PC* is the power consumed, *TC* is the total charge time, and *P* is the power rating of the EV charger. The result is measured in kilowatt-hours (kWh). In the example, the distance travelled is 50 km. One of the chargers used is rated at 9.6 kW, giving a charging speed of 59 km/h.

$$TC = \frac{50\ km}{59\ km/h} \times 60\ min$$

$$TC = 50.85\ min$$

$$PC = \frac{50.85\ min}{60\ min} \times 9.6\ kW$$

$$PC \approx 8.14\ kWh$$

A power consumption of 8.14 kWh is added to the target hour to reflect the increase in load. To calculate the additional loads introduced by heat pumps, certain load profiles [32–35] were consulted. These sources indicate the typical operating times and durations for residential heat pumps. As noted earlier, a power rating of 4.5 kW is applied in this study. Schlemminger *et al.* [34] reported an average annual household heat pump consumption of 4,993 kWh, equivalent to approximately 13.7 kWh per day. Damianakis [35] identified seasonal variation, with daily consumption reaching 18 kWh during winter and 8 kWh in summer, averaging 13 kWh overall. The literature suggests that heat pumps operate throughout the day, with periodic peaks in demand. In this study, heat pump load is modelled as a consistent hourly demand. Based on average daily values, hourly power consumption is set at 0.35 kWh in summer and 0.80 kWh in winter [35,36]. To define winter months, Schlemminger *et al.* [34] observed that energy use increases when

temperatures fall below 10 °C. Complementary data from Time and Date [46,47] show average monthly temperatures for Southwestern Ontario. Based on this, November through March are classified as winter months.

Finally, as noted, the electric water heater (EWH) is assumed to operate at 4.5 kW. Based on the literature [37–42], peak usage occurs in the morning between 07:00 and 08:00, and in the evening from 18:00 to 20:00. Use continues at lower levels throughout the day. Morning consumption is estimated at 1.35 kWh, which corresponds to approximately 17 minutes of operation at full capacity. This study adopts 1.35 kWh as the morning usage value. Evening usage drops to about 10 minutes per hour, equivalent to 0.8 kWh. During the early morning (01:00–06:00) and late evening (21:00–23:00), the heater is expected to run for about 3 minutes per hour, consuming 0.25 kWh. During midday hours, operation increases to about 5 minutes per hour, resulting in 0.4 kWh. Total daily consumption is estimated at 11.00 kWh, with a total run time of 2 hours and 27 minutes. This aligns closely with the average of 11.13 kWh per day reported in the simulation by Pourmousavi *et al.* [39].

Case 1: Simultaneous Charging

In this scenario, all EV chargers are assumed to begin charging simultaneously at 18:00, a time when homeowners are typically returning home and likely to recharge their vehicles. The initial implementation assumes a 25% increase in charging demand, followed by a 50% increase. In both cases, the number of homes is rounded up. For example, if a transformer serves 19 homes, 25% of 19 is 4.75, so 5 EVs would be added under the 25% scenario. Each simulation includes chargers rated at 7.7 kW, 9.6 kW, and 11.5 kW. Heat pumps (HPs) and electric water heaters (EWHs) operate as described in the methodology above. The adoption rates for HPs and EWHs also follow 25% and 50% increments, aligned with the EV charging scenarios

Case 2: Phased Start Times

In this case, EV chargers begin at staggered intervals to simulate a controlled environment. The first charger starts at 18:00, with each subsequent charger beginning one hour later. As in Case 1, this scenario considers 25% and 50% increases in the adoption of EVs, HPs, and EWHs. Heat pumps and electric water heaters operate at the same times described in Case 1. Average usage patterns for these appliances were derived from the literature [32–42, 46], which included detailed simulations of their operation. Based on this information, their operating periods remain unchanged from Case 1. The aim of this simulation is to determine how often a distribution

transformer reaches or exceeds its rated capacity. Cai *et al.* [5] define a heavy load as operating at 80% to 100% of rated capacity. This scenario assesses the frequency of both heavy load and overload conditions. Because the dataset records hourly energy consumption (in kWh), it does not capture short-duration power spikes. Therefore, the analysis focuses on hours where total consumption exceeds 80% or 100% of transformer capacity**,** even if the transformer's instantaneous power demand stays within its technical limits. For example, transformers rated between 50 kVA and 167 kVA may not always experience overload in real-time operation. But, if hourly consumption exceeds 50 or 167 kWh respectively, this indicates sustained demand that may accelerate ageing and increase thermal stress**.**

Results and Discussion

Among the three added devices—EVs, HPs, and EWHs—electric vehicles introduce the most significant load**,** given their higher power demands. The results indicate the number of hours per week during which total hourly energy consumption (in kWh) exceeds the transformer's rated capacity (in kVA). Although this measurement does not represent instantaneous power, it highlights periods of sustained high loads. These periods often coincide with potential overloads, particularly when several devices operate simultaneously, placing stress on the transformer.

Additional metrics in the tables include the frequency with which energy consumption surpasses the transformer's peak hourly values. The yearly peak refers to the number of times per week a transformer exceeds its highest hourly consumption recorded across the entire year. The monthly peak refers to how often it exceeds the highest hourly consumption within a given month. These indicators provide insight into how frequent increases in load contribute to a rise in the transformer's operating temperature. Over time, this thermal stress degrades insulation and accelerates ageing—even without technical overload.

The average and maximum hourly increase values show the percentage growth in power consumption. These figures offer a clearer picture of the consequences of integrating new electrical loads. Although EVs dominate in terms of demand, heat pumps and electric water heaters also contribute significantly to overall consumption. Tables 4 and 5 present the outcomes for 25% and 50% adoption rates of HPs and EWHs**,** respectively.

Table 4. HPs and EWHs – Weekly impact of 25% adoption on transformer load.

Statistic	Hours Exceeding 100% Rating (kWh, Weekly)	Hours Exceeding 80% Rating (kWh, Weekly)	Times Exceeding Yearly Peak (Hourly Usage)	Times Exceeding Monthly Peak (Hourly Usage)	Average Hourly Increase (%)	Highest Hourly Increase (%)
Average	0.00	0.00	2.46	5.69	34.48	97.69
Median	0.00	0.00	0.10	2.34	31.53	88.95
Maximum	0.00	0.00	39.57	47.87	78.87	202.97
Minimum	0.00	0.00	0.00	0.23	13.42	44.29

In Table 4**,** there are no instances in which the distribution transformer experiences a heavy load or overload. Yet, transformers are frequently operating beyond the maximum values currently recorded. One of the ten transformers averages 39.57 and 47.87 hours per week in which power consumption exceeds the current monthly and yearly peaks. This same transformer registers an average hourly increase of 34.48%, with a maximum increase of 202.97% recorded during a single hour. Table 5 illustrates the effect of adding 50% adoption of only HPs and EWHs to the existing transformer loads. Although no transformer reaches the heavy load or overload thresholds, the rise in load is considerable. On average, transformers experience a 62.26% increase in power consumption per hour**,** and one transformer shows a maximum increase of 355.20% during a single hour. Figure 1 presents the results for Transformer T02 in June, under the 50% adoption scenario.

Table 5. Weekly Impact of a 50% Adoption of Heat Pumps (HPs) and Electric Water Heaters (EWHs) on Transformer Load

50% Increase	Hours Exceeding 100% Rating (kWh, Weekly)	Hours Exceeding 80% Rating (kWh, Weekly)	Times Exceeding Yearly Peak (Hourly Usage)	Times Exceeding Monthly Peak (Hourly Usage)	Average Hourly Increase (%)	Highest Hourly Increase (%)
Average	0.00	0.00	12.84	24.25	62.26%	176.07%
Median	0.00	0.00	0.91	13.21	60.73%	160.97%
Maximum	0.00	0.00	119.16	119.16	138.02%	355.20%
Minimum	0.00	0.00	0.00	0.45	23.48%	77.51%

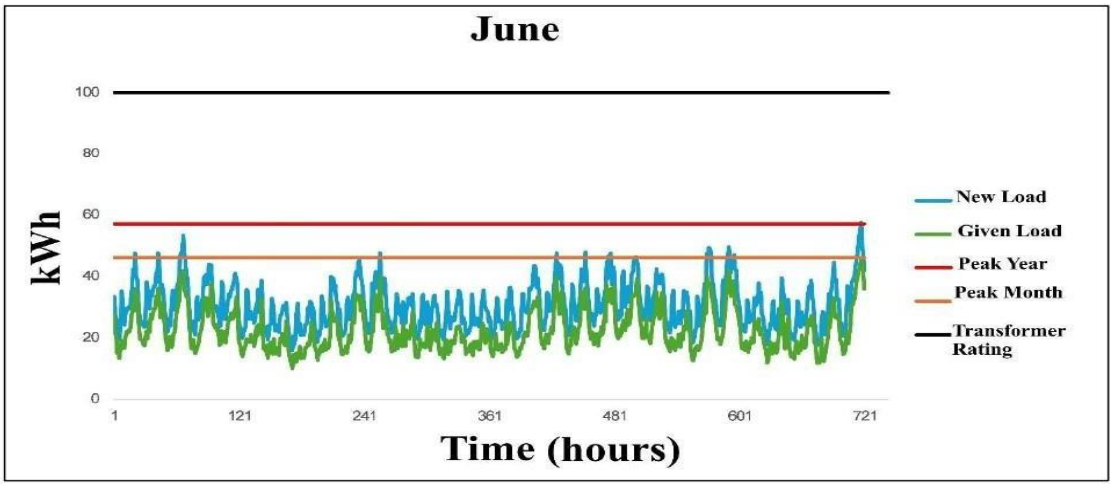

Figure 1. T02: 50% increase of HPs and EWHs for the month of June 2023

Case 1: Simultaneous Charging

For each transformer, the study added EVs, HPs, and EWHs to either 25% or 50% of homes. The scenarios assumed that all homeowners charged their EVs simultaneously at 18:00 hours. The HPs and EWHs operated consistently**,** following the methodology and aligned with the usage patterns and load profiles found in the literature. Tables 6 and 7 present the results obtained using an 11.5 kW charger.

Table 6. Simultaneous Charging – 25% Adoption (11.5 kW Charger).

25% Increase	Hours Exceeding 100% Rating (kWh, Weekly)	Hours Exceeding 80% Rating (kWh, Weekly)	Times Exceeding Yearly Peak (Hourly Usage)	Times Exceeding Monthly Peak (Hourly Usage)	Average Hourly Increase (%)	Highest Hourly Increase (%)
Average	0.01	0.38	7.55	11.37	43.41%	366.96%
Median	0.00	0.00	7.00	8.82	40.00%	351.77%
Maximum	0.23	4.97	40.02	48.77	95.29%	738.41%
Minimum	0.00	0.00	0.00	2.33	16.77%	140.06%

These first three cases represent a 25% adoption of these devices across the transformers but differ in the size of the charger employed. As the charger size increases, so does the likelihood of the transformer reaching overload conditions and experiencing more frequent heavy loads.

Table 7. Simultaneous charging 50% : 11.5 Kw.

50% Increase	Hours Exceeding 100% Rating (kWh, Weekly)	Hours Exceeding 80% Rating (kWh, Weekly)	Times Exceeding Yearly Peak (Hourly Usage)	Times Exceeding Monthly Peak (Hourly Usage)	Average Hourly Increase (%)	Highest Hourly Increase (%)
Average	2.35	4.19	19.48	30.39	80.59%	682.48%
Median	0.06	5.74	8.23	20.49	79.59%	651.70%
Maximum	7.01	7.01	119.16	119.16	166.76%	1,292.22%
Minimum	0.00	0.00	7.00	7.00	29.93%	260.73%

The last three cases in this scenario show an adoption of 50% of EVs, HPs, and EWHs. The difference lies in the charging capacity**.** There is a significant increase in the number of times the transformer reaches 100% of its capacity during the week compared to the 25% scenario. The maximum weekly overload occurs daily on one of the transformers, showing an increase of 1,292.22% during one of the hours. Figure 2 presents the results for transformer T04, which recorded the highest monthly value in August.

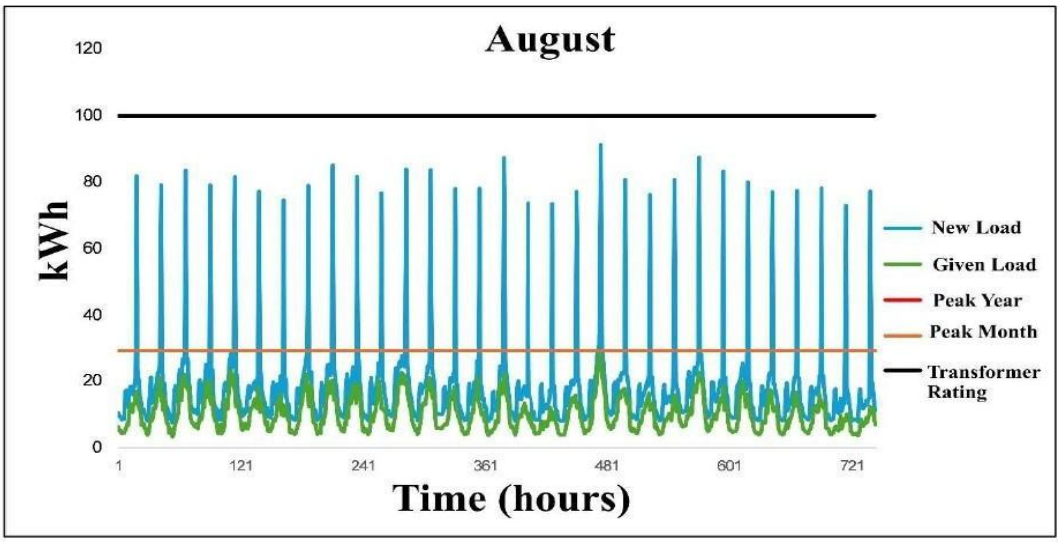

Figure 2. T04: 50% penetration for the month of August 2023, 9.6 kW charger.

Case 2: Phased Start Times

For each transformer, the study added EVs, HPs, and EWHs to 25% and 50% of homes. The scenarios assumed that all homeowners charged their EVs at different start times, with the first EV beginning at 18:00 hours. The HPs and EWHs, as in the first case**,** operate at the same times outlined in the methodology. They run concurrently based on the findings in the literature and the averaged operational patterns of these devices**.** The results for the 11.5 kW charger are presented in Tables 8 and 9.

Table 8. Phased start times – 25% adoption with 11.5 kw chargers

25% Increase	Hours Exceeding 100% Rating (kWh, Weekly)	Hours Exceeding 80% Rating (kWh, Weekly)	Times Exceeding Yearly Peak (Hourly Usage)	Times Exceeding Monthly Peak (Hourly Usage)	Average Hourly Increase (%)	Highest Hourly Increase (%)
Average	0.00	0.00	8.57	17.37	43.24%	143.14%
Median	0.00	0.00	2.18	16.55	39.61%	142.49%
Maximum	0.00	0.00	47.94	56.23	94.72%	253.92%
Minimum	0.00	0.00	0.00	0.90	17.00%	51.14%

In this scenario, a 25% increase with staggered start times and varying charger capacities results in a notable reduction in the hourly consumption rate. It is important to highlight that the transformers still experience elevated consumption levels compared to operations excluding EVs, HPs, and EWHs. The average number of weekly instances exceeding the yearly peak consumption ranges from 8.57 to 8.62**,** and one transformer registers 47.94 to 48.39 instances per week where consumption surpasses the typical peak recorded for the year.

Table 9. Phased Start Times – 50% Adoption Scenario (11.5 kW).

50% Increase	Hours Exceeding 100% Rating (kWh, Weekly)	Hours Exceeding 80% Rating (kWh, Weekly)	Times Exceeding Yearly Peak (Hourly Usage)	Times Exceeding Monthly Peak (Hourly Usage)	Average Hourly Increase (%)	Highest Hourly Increase (%)
Average	0.00	0.00	20.57	39.85	80.12	207.56
Median	0.00	0.00	4.89	33.66	80.04	197.70
Maximum	0.00	0.00	126.40	128.71	170.03	427.42
Minimum	0.00	0.00	0.00	0.90	30.71	77.51

Even with staggered EV charging, transformers record notable increases in hourly consumption. Slower EV chargers, which take more time to charge vehicles, extend charging periods into later hours**,** thereby increasing transformer load throughout the day. In contrast**,** faster chargers impose higher loads during shorter periods, which amplifies peak stress. The energy drawn by each charger within an hour may reach 7.7 kWh, 9.6 kWh, or 11.5 kWh**.** When these chargers operate to replenish distances greater than 50 km, they impose greater demands on the transformer. As the number of EVs, HPs, and EWHs increases**,** the likelihood of heavy loading and overload conditions becomes higher. Figure 3 presents the results for transformer T06 during the month of August, with a 50% increase in charging at staggered start times.

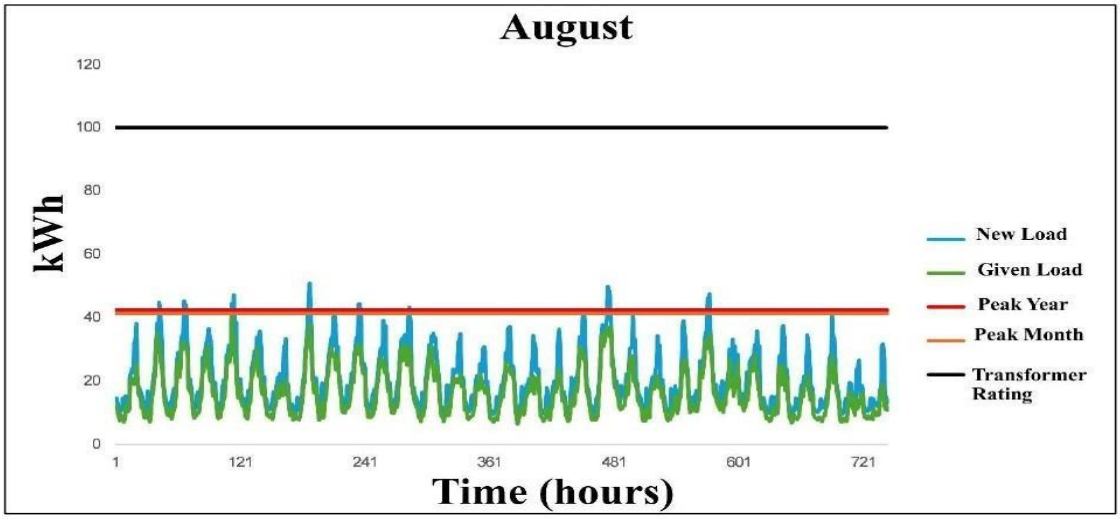

Figure 3. T06: 50% penetration for the month of August 2023, 11.5 kW charger.

An analysis of the increased total power consumption from EVs, HPs, and EWHs reveals that a 50% rise in HPs and EWHs leads **to** greater energy usage than a scenario with a 25% increase in EVs, HPs, and EWHs. These findings emphasize the need for utilities to assess the impact of integrating HPs and EWHs into the grid. EVs often attract attention as the main source of concern because of their high demand, yet the frequent operation of HPs and EWHs highlights their capacity to raise energy consumption significantly.

Utilities must consider several concerns indicated by the tables. Transformer T04 has experienced load increases of 71% and 124%**,** which are significantly higher than values observed in previous years. Loads of this magnitude could accelerate the transformer's deterioration. If it is already approaching the end of its life cycle, this stress may result in failure. By contrast**,** transformer T03 shows a smaller percentage increase. Yet**,** it is already operating near full capacity. Any additional load may cause overloads, leading to faster deterioration than expected.

The importance of this study lies in evaluating the rate of change in load consumption as the penetration of EVs, HPs, and EWHs increases. At 25% penetration, simultaneous EV charging at 7.7 kW results in a 43.50% rise in the average hourly load, which climbs to 80.59% at 11.5 kW with 50% penetration. One transformer recorded a maximum hourly increase of 706.59% at 25%

penetration and 1,292.22% at 50% penetration. These high loads may not always lead to overload conditions. Yet**,** they accelerate transformer ageing by raising operational temperatures, which compromise insulation over time. This premature ageing will require more frequent transformer replacements than utilities may have anticipated.

Recommendations

To help prevent the growing strain on distribution transformers caused by the increasing penetration of EVs, HPs and EWHs, it is recommended that utilities implement controlled environments. This could mean introducing regulations or incentives to encourage staggered charging times for EVs. The likelihood of transformers experiencing heavy load or overload conditions can be reduced by distributing the load throughout the day. As EV charging technology advances, faster chargers, although reducing charging times, will demand more power. In this study, it was found that a transformer with a 100 kVA rating would reach overload condition if approximately 11 EVs were charging simultaneously at fast charger rates. Since transformers typically serve an average of 14 homes, it is not feasible for every household to charge an EV simultaneously without increasing the risk of transformer failure. This represents a future risk, as higher power demands from these devices will place greater thermal and electrical stress on transformers. At the same time, the electrification of household systems, such as HPs and EWHs, accentuates this problem, as these devices operate continuously. As a result, utilities should also prioritize planning for infrastructure upgrades to accommodate these emerging loads. A second recommendation is for utilities to assess the current lifespan of their distribution transformers and use this study as a tool to model simulations that evaluate the effects of increased load scenarios on their assets. Transformers will still experience higher overall consumption levels, even with managed load strategies. The primary concern is the long-term impact of rising temperatures on the transformer's insulation, which is a critical factor in determining transformer life. As transformers operate under greater load conditions, their core and windings generate more heat, which leads to degradation of the insulation. The insulation's ability to withstand electrical stress will diminish over time, especially when operating at elevated temperatures for prolonged periods. This thermal ageing process can cause the insulation to become brittle and lose its dielectric strength, thereby reducing its operational efficiency and causing premature transformer failure. Therefore, even if transformers are not operating under heavy load or overload conditions, the

continuous rise in power consumption will accelerate transformer ageing. Utilities are recommended to monitor thermal levels and conduct increased load simulations to help prevent transformer failures.

Conclusion

This study has explored the effects of increased power consumption on ten distribution transformers, with a focus on the electrification of transport and residential systems, including EVs, HPs, and EWHs. The results show that even without reaching transformer limits, higher overall energy consumption during peak hours can contribute to accelerated ageing and increased thermal stress on transformers. The study emphasizes the need for utilities to adopt load management strategies that prevent overload and limit long-term deterioration**.** By strategically planning and promoting off-peak charging times, the stress placed on transformers can be reduced**.** Load management alone will not eliminate deterioration**,** as transformers operating under elevated temperatures for extended periods will continue to age. This study underscores the importance of proactive infrastructure planning, including upgrading distribution transformers and closely monitoring their thermal conditions. Neglecting the electrification of transport and residential systems leaves utilities unprepared for necessary repairs or replacements. As transformers in a neighbourhood experience increased stress, cascading failures may occur, affecting other parts of the network and placing consumers at risk. Maintaining the integrity and performance of distribution transformers is essential for reliable power delivery and for supporting the shift towards widespread electrification of vehicles and heating systems.

References

[1] Axsen, J., Bhardwaj, C., & Crawford, C., 2022, Comparing policy pathways to achieve 100% zero-emissions vehicle sales by 2035. *Transportation Research Part D: Transport and Environment* **112**, 103488. https://doi.org/10.1016/j.trd.2022.103488

[2] Raihan, A., & Tuspekova, A., 2023, Towards net zero emissions by 2050: the role of renewable energy, technological innovations, and forests in New Zealand. *Journal of Environmental Science and Economics* **2**(1), 1-16. https://doi.org/10.56556/jescae.v2i1.422

[3] Lee, H. J., Yoon, S. W., & Yoon, Y. D., 2022, *Hybrid distribution transformer based on an existing distribution transformer and a series-connected power converter. IEEE Transactions on Power Delivery* **37**(5), 4202-4211. https://doi.org/10.1109/TPWRD.2022.3147820

[4] Singh, J., Singh, S., & Singh, A., 2019, Distribution transformer failure modes, effects and criticality analysis (FMECA). *Engineering Failure Analysis* **99**, 180-191. https://doi.org/10.1016/j.engfailanal.2019.02.014

[5] Cai, D., Wang, W., Ma, X., Xu, M., He, Z., Tang, Z., Zhou, C., Han, N., & Wang, Y., 2018, Analysis

of heavy load and overload distribution transformer in regional power grid. In 2018 2nd IEEE Conference on Energy Internet and Energy System Integration (EI2) (pp. 1-5). IEEE, 20-22 October. https://doi.org/10.1109/EI2.2018.8581984

[6] Zhang, X., Qian, S., Xu, Y., Marek, R., & Lei, Q., 2020, Overload distribution transformer with natural ester and aramid-enhanced cellulose. *IEEE Transactions on Power Delivery* **36**(3), 1829-1836. https://doi.org/10.1109/TPWRD.2020.3015797

[7] Forouhari, S., & Abu-Siada, A., 2018, Application of adaptive neuro fuzzy inference system to support power transformer life estimation and asset management decision. *IEEE Transactions on Dielectrics and Electrical Insulation* **25**(3), 845-852. https://doi.org/10.1109/10.1109/TDEI.2018.006392

[8] Biçen, Y., Aras, F., & Kirkici, H., 2014, Lifetime estimation and monitoring of power transformer considering annual load factors. *IEEE Transactions on Dielectrics and Electrical Insulation* **21**(3), 1360-1367. https://doi.org/10.1109/TDEI.2014.6832284

[9] Casey, J. A., Fukurai, M., Hernández, D., Balsari, S., & Kiang, M. V., 2020, Power outages and community health: a narrative review. *Current environmental health reports* **7**, 371-383. https://doi.org/10.1007/s40572-020-00295-0

[10] Rubin, G. J., & Rogers, M. B., 2019, Behavioural and psychological responses of the public during a major power outage: A literature review. *International Journal of Disaster Risk Reduction* **38**, 101226. https://doi.org/10.1016/j.ijdrr.2019.101226

[11] Yamashita, K., Joo, S. K., Li, J., Zhang, P., & Liu, C. C., 2008, Analysis, control, and economic impact assessment of major blackout events. *European Transactions on Electrical Power* **18**(8), 854-871. https://doi.org/10.1002/etep.304

[12] Sun, M., Jiang, H., Lu, Y., Liu, Q., Yang, Y., & Yu, B., 2020, A prediction method of residential load transformer demand factor based on time series. In *Journal of Physics: Conference Series* (Vol. 1633, No. 1, p. 012161). IOP Publishing. https://doi.org/10.1088/1742-6596/1633/1/012161

[13] Yuan, P., Duanmu, L., Wang, Z., Gao, K., Zhao, X., Liu, X., & Kong, W., 2023, Electricity consumption and load prediction method for Chinese rural residences based on the randomness and seasonality in electricity usage behavior. *Energy and Buildings* **279**, 112647. https://doi.org/10.1016/j.enbuild.2022.112647

[14] da Silva, F. L., Oliveira, F. L. C., & Souza, R. C., 2019, A bottom-up bayesian extension for long term electricity consumption forecasting. *Energy* **167**, 198-210. https://doi.org/10.1016/j.energy.2018.10.201

[15] Wang, X., Wang, J., Deng, Y., Hou, Z., Liu, H., & Huang, Y., 2021, Overload analysis of distribution transformers based on relevance analyse and machine learning. In *2021 IEEE 5th Advanced Information Technology, Electronic and Automation Control Conference (IAEAC)* (pp. 2505-2509). IEEE. https://doi.org/10.1088/10.1109/IAEAC50856.2021.9390992

[16] Lindberg, K. B., Seljom, P., Madsen, H., Fischer, D., & Korpås, M., 2019, Long-term electricity load forecasting: Current and future trends. *Utilities Policy* **58**, 102-119. https://doi.org/10.1016/j.jup.2019.04.001

[17] Boßmann, T., Elsland, R., Lickert, F., & Wietschel, M., 2013, Boßmann, T., Elsland, R., Lickert, F., & Wietschel, M. (2013). The German electricity demand in the year 2050: Structural changes in the load curve and their impact on the supply side. In *Internationale Energiewirtschaftstagung (IEWT) 2013*. https://doi.org/10.24406/publica-fhg-379827

[18] Asare-Bediako, B., Kling, W. L., & Ribeiro, P. F., 2014, Future residential load profiles: Scenario-based analysis of high penetration of heavy loads and distributed generation. *Energy and Buildings* **75**, 228-238. https://doi.org/10.1016/j.enbuild.2014.02.025

[19] Amjad, M., Ahmad, A., Rehmani, M. H., & Umer, T., 2018, A review of EVs charging: From the perspective of energy optimization, optimization approaches, and charging techniques. *Transportation Research Part D: Transport and Environment* **62**, 386-417. https://doi.org/10.1016/j.trd.2018.03.006

[20] Moon, H., Park, S. Y., Jeong, C., & Lee, J., 2018, Forecasting electricity demand of electric vehicles by analyzing consumers' charging patterns. *Transportation Research Part D: Transport and Environment* **62**, 64-79. https://doi.org/10.1016/j.trd.2018.02.009

[21] Schirmer, P. A., & Mporas, I., 2022, Non-intrusive load monitoring: A review. *IEEE Transactions on Smart Grid* **14**(1), 769-784. https://doi.org/10.1109/TSG.2022.3189598

[22] Munshi, A. A., & Mohamed, Y. A. R. I., 2018, Unsupervised nonintrusive extraction of electrical vehicle charging load patterns. *IEEE Transactions on Industrial Informatics* **15**(1), 266-279. https://doi.org/10.1109/TII.2018.2806936

[23] Wang, Y., Ma, C., Zhao, B., & Luan, W., 2021, Non-intrusive electric vehicle charging load disaggregation based on independent component analysis with reference. In 2021 IEEE 5th Conference on Energy Internet and Energy System Integration (EI2) (pp. 490-495). IEEE, 22-24 October. https://doi.org/10.1109/EI252483.2021.9713260.

[24] Shaw, A., & Nayak, B. P., 2017, Electric vehicle charging load filtering by power signature analysis. In *2017 International Conference on Data Management, Analytics and Innovation (ICDMAI)* (pp. 71-75). IEEE. https://doi.org/10.1109/ICDMAI.2017.8073488

[25] Zhang, Z., Son, J. H., Li, Y., Trayer, M., Pi, Z., Hwang, D. Y., & Moon, J. K., 2014, Training-free non-intrusive load monitoring of electric vehicle charging with low sampling rate. In IECON 2014-40th annual conference of the IEEE industrial electronics society (pp. 5419-5425). IEEE, 29 October – 01 November. https://doi.org/10.1109/IECON.2014.7049328

[26] Zhao, H., Yan, X., & Ma, L., 2019, Training-free non-intrusive load extracting of residential electric vehicle charging loads. *IEEE Access* **7**, 117044-117053. https://doi.org/10.1109/ACCESS.2019.2936589

[27] Aravinthan, V., & Jewell, W., 2015, Controlled electric vehicle charging for mitigating impacts on distribution assets. *IEEE Transactions on Smart Grid* **6**(2), 999-1009. https://doi.org/10.1109/TSG.2015.2389875

[28] Hilshey, A. D., Hines, P. D., Rezaei, P., & Dowds, J. R., 2012, Estimating the impact of electric vehicle smart charging on distribution transformer aging. *IEEE Transactions on Smart Grid* **4**(2),

905-913. https://doi.org/10.1109/TSG.2012.2217385

[29] Sarker, M. R., Olsen, D. J., & Ortega-Vazquez, M. A., 2016, Co-optimization of distribution transformer aging and energy arbitrage using electric vehicles. *IEEE Transactions on Smart Grid* **8**(6), 2712-2722. https://doi.org/10.1109/TSG.2016.2535354

[30] Muñoz, E. R., Razeghi, G., Zhang, L., & Jabbari, F., 2016, Electric vehicle charging algorithms for coordination of the grid and distribution transformer levels. *Energy* **113**, 930-942. https://doi.org/10.1016/j.energy.2016.07.122

[31] Awadallah, M. A., Singh, B. N., & Venkatesh, B., 2016, Impact of EV charger load on distribution network capacity: A case study in Toronto. *Canadian Journal of Electrical and Computer Engineering* **39**(4), 268-273. https://doi.org/10.1109/CJECE.2016.2545925

[32] Love, J., Smith, A.Z.P., Watson, S., Oikonomou, E., Summerfield, A., Gleeson, C., Biddulph, P., Chiu, L.F., Wingfield, J., Martin, C., Stone, A., Lowe, R, 2017, The addition of heat pump electricity load profiles to GB electricity demand: Evidence from a heat pump field trial. *Applied Energy* **204**, 332-342. https://doi.org/10.1016/j.apenergy.2017.07.026

[33] Rouwhorst, G., Pondes, A., Nguyen, P. H., & Slootweg, H., 2024, Medium-term forecasting of daily aggregated peak loads from heat pumps using clustering-based load duration curves to calculate the annual impact on medium to low voltage transformers. *IET Smart Grid* **7**(2), 157-171. https://doi.org/10.1049/stg2.12134

[34] Schlemminger, M., Ohrdes, T., Schneider, E., & Knoop, M., 2022, Dataset on electrical single-family house and heat pump load profiles in Germany. *Scientific Data* **9**(1), 56. https://doi.org/10.1038/s41597-022-01156-1

[35] Damianakis, N., Mouli, G. C. R., & Bauer, P., 2023, June, Risk-averse estimation of electric heat pump power consumption. In 2023 IEEE 17th international conference on compatibility, power electronics and power engineering (CPE-POWEREnG) (pp. 1-6). IEEE, 14-15 June. https://doi.org/10.1109/CPE-POWERENG58103.2023.10227424

[36] Oliyide, R. O., & Cipcigan, L. M., 2021, The impacts of electric vehicles and heat pumps load profiles on low voltage distribution networks in Great Britain by 2050. *International Multidisciplinary Research Journal* **11**, 30-45. http://dx.doi.org/10.25081/imrj. 2021.v11.7308

[37] Nehrir, M. H., Jia, R., Pierre, D. A., & Hammerstrom, D. J., 2007, Power management of aggregate electric water heater loads by voltage control. In 2007 IEEE Power Engineering Society General Meeting (pp. 1-6). IEEE, 24-28 June. https://doi.org/10.1109/PES.2007.386024.

[38] Kondoh, J., Lu, N., & Hammerstrom, D. J., 2011, July, An evaluation of the water heater load potential for providing regulation service. In 2011 IEEE Power and Energy Society General Meeting (pp. 1-8). IEEE, 24-28 July. https://doi.org/10.1109/PES.2011.6039149

[39] Pourmousavi, S. A., Patrick, S. N., & Nehrir, M. H., 2014, Real-time demand response through aggregate electric water heaters for load shifting and balancing wind generation. *IEEE Transactions on Smart Grid* **5**(2), 769-778. https://doi.org/10.1109/TSG.2013.2290084

[40] Diao, R., Lu, S., Elizondo, M., Mayhorn, E., Zhang, Y., & Samaan, N., 2012, Electric water heater

modeling and control strategies for demand response. In 2012 IEEE power and energy society general meeting (pp. 1-8). IEEE, 22-26 July. https://doi.org/10.1109/PESGM.2012.6345632

[41] Gong, H., Akeyo, O. M., Rooney, T., Branecky, B., & Ionel, D. M., 2021, Aggregated generic load curve for residential electric water heaters. In 2021 IEEE Power & Energy Society General Meeting (PESGM) (pp. 1-5). IEEE, 26-29 July. https://doi.org/10.1109/PESGM46819.2021.9638032

[42] Reed, J. H., Broadwater, R. P., Chandrasekaran, A., & Thompson, J., 1988, Patterns of electric water heater use and the effects of water heater load control on customers. In Proceedings of the 1988 ACEEE Summer Study on Energy Efficiency in Buildings (Vol. 11). Available online at: https://www.aceee.org/files/proceedings/1988/data/papers/1988_V11_011.pdf

[43] Juda, Z., 2016, Technical and legal considerations and solutions in the area of battery charging for electric vehicles. In *IOP Conference Series: Materials Science and Engineering* (Vol. 148, No. 1, p. 012043). IOP Publishing. https://doi.org/10.1088/1757- 899X/148/1/012043

[44] Tesla. (2024, September 9). *Wall Connector: Charging speeds and technical specifications*. https://www.tesla.com/en_ca/support/charging/wall-connector

[45] Javadnejad, F., Jahanbakh, M., Pinto, C. A., & Saeidi, A., 2024, Analyzing incentives and barriers to electric vehicle adoption in the United States. *Environment Systems and Decisions* **44**(3), 575-606. https://doi.org/10.1007/s10669-023-09958-3

[46] Pitropov, M., Garcia, D. E., Rebello, J., Smart, M., Wang, C., Czarnecki, K., & Waslander, S., 2021, Canadian adverse driving conditions dataset. *The International Journal of Robotics Research* **40**(4-5), 681-690. https://doi.org/10.1177/0278364920979368

[47] Wazneh, H., Arain, M. A., & Coulibaly, P., 2017, Historical spatial and temporal climate trends in southern Ontario, Canada. *Journal of Applied Meteorology and Climatology* **56**(10), 2767-2787. https://doi.org/10.1175/JAMC-D-16-0290.1

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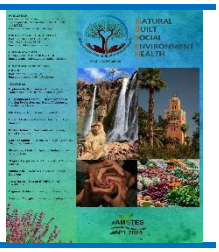


VIEWPOINT

Floating Wetlands in Nepal: A Sustainable Solution to Water Pollution

Bipin Silwal [1,a], Ujjwal Koirala [1,b], Nadia Machkour [2,c], Shukra Raj Paudel [1,d,☑]

[1] *Environmental Engineering Program, Department of Civil Engineering, Pulchowk Campus, Institute of Engineering, Tribhuvan University (ROR: https://ror.org/02rg1r889), Lalitpur, Nepal*

[2] *DELTA LAB (Digital Engineering for Leading Technology and Automation), Hassan II University of Casablanca (https://ror.org/001q4kn48), Morocco*

[a] ***ORCID**: 0009-0000-1708-2936, **Email**: silwal.bipin@gmail.com*

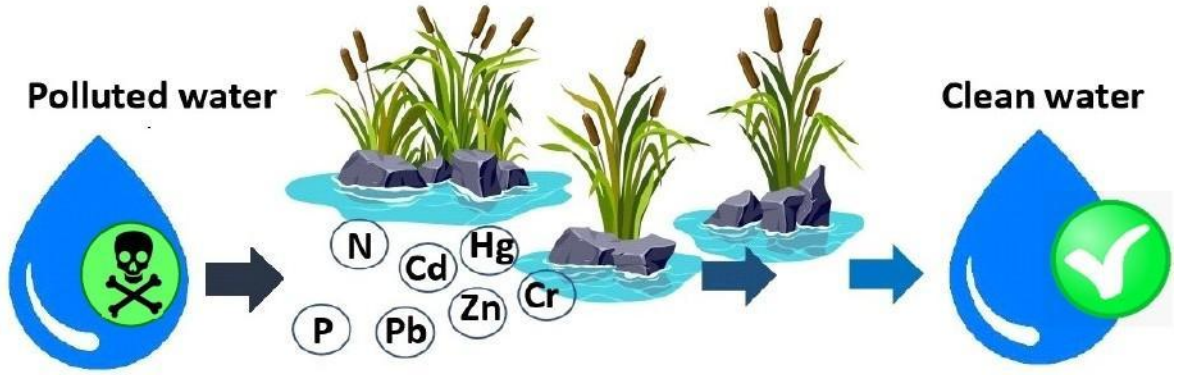
[b] ***ORCID**: 0009-0004-7914-1099, **Email**: ujjwalkoirala2058@gmail.com*

[c] ***ORCID**: 0000-0002-7678-2542, **Email**: nadia.machkour@univh2c.ma*

[d] ***ORCID**: 0000-0002-5764-2990, **Email**: srpaudel@ioe.edu.np*

☑ **Corresponding author:** Shukra Raj Paudel, **Email:** srpaudel@ioe.edu.np, **Phone:** +977-9851220184.

Floating wetlands as a nature-based solution can improve water quality in Nepal. Native plants on rafts absorb nutrients and heavy metals, while microbes on their roots break down pollutants. Polluted water passes through successive rafts, generating cleaner water. These systems can restore ecosystems, build climate resilience, and support Sustainable Development Goals: 3 (Good Health and Well-being), 6 (Clean Water and Sanitation), and 13 (Climate Action). Adoption in Nepal's lakes and rivers can boost biodiversity, protect livelihoods, and promote community-led water management.



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Abstract: Water is crucial to maintain a healthy and balanced ecosystem. Yet water bodies are rapidly deteriorating across the globe, and Nepal is not immune to this growing concern. This viewpoint article highlights the urgent need for sustainable solutions. Floating wetlands have emerged as a widely accepted and promising option. In Nepal, this approach could be particularly effective by using native plants capable of absorbing organic pollutants, nutrients, and heavy metals from polluted water, along with promoting biodegradation through biofilms on their root systems. We emphasize the need for effective policy to ensure implementation of floating wetlands in water bodies — an effort that can significantly contribute to achieving the Sustainable Development Goals (SDGs 3, 6, and 13).

Keywords: Floating Wetland, Pollution, Sustainable Development Goals.

Background

Around the globe, the quality of natural water bodies such as rivers, lakes, and ponds is rapidly degrading because of the accumulation of organic pollutants, pathogens, nutrients, pesticides, pharmaceutical waste, and heavy metals arising from unchecked urbanization, population growth, and poor wastewater management practices [1,2]. This situation is even worse in urban cities of developing countries like Nepal, where only 12% of wastewater is treated, and the remaining untreated domestic wastewater, industrial discharges, and agricultural effluents are released directly into water resources [3]. In Nepal, climate change further threatens the degradation of water systems, as the Hindu Kush–Himalayan region, where Nepal is situated, is experiencing accelerated warming nearly triple the global average [4]. This causes more frequent flooding and intense rainfall events that increase runoff, carrying pollutants into water bodies. These impacts degrade water quality, result in environmental damage, pose a serious risk to human health, lead to a decline in biodiversity, and disturb aquatic ecosystems [5]. Furthermore, the achievement of Sustainable Development Goals (SDGs) 3 (Good Health and Well-Being, which aims to reduce health risks), 6 (Clean Water and Sanitation, which focuses on ensuring access to clean water and sustainable water management), and 13 (Climate Action, resilience to climate change and its impact) is also challenged. There is an urgent need for innovative, cost-effective, and environmentally sustainable solutions to restore water bodies, ensure timely achievement of Sustainable Development Goals, and enhance resilience against climate-induced stresses.

Over the years, Nepal has undertaken multiple efforts to restore its increasingly degrading water bodies using conventional physical, chemical, and biological Centralized Treatment Plants (CTPs) and Constructed Wetlands (CWs), mostly supported by external donor funding. CTPs have failed to achieve long-term effectiveness because of high operational costs, dependence on energy, inadequate maintenance, and lack of local ownership [6]. CWs, although a nature-based solution, require a large area of land, which presents a major challenge in densely populated cities. Floating Wetland Treatment (FWT), a widely recognized emerging alternative that offers simple construction, low cost, and environmentally sustainable nature-based treatment for polluted water, shows significant potential in the Nepalese context. This approach is particularly well-suited for resource-constrained, densely populated, and land-scarce regions [7].

In this study, a literature survey was conducted using search engines such as Google Scholar and Scopus with key words including “Floating Wetland”, “Water Pollution”, “Macrophytes Native to Nepal”, and “SDGs”. Relevant documents were identified, reviewed, and discussed in this article.

Discussion

Floating Wetlands (FWs) function by supporting the hydroponic growth of macrophytes on floating platforms, with their roots suspended in the water column. The roots provide a surface for microorganisms to form biofilms. As shown in Figure 1, pollutants are removed through plant uptake, microbial degradation, filtration, sedimentation, and adsorption. These combined mechanisms are highly efficient in removing pollutants such as nitrogen, phosphorus, and organic matter present in water [1,7]. They are also capable of effectively reducing heavy metals such as zinc, manganese, and iron, as well as aiding nutrient cycling and reducing toxicity from contaminated water [8,9].

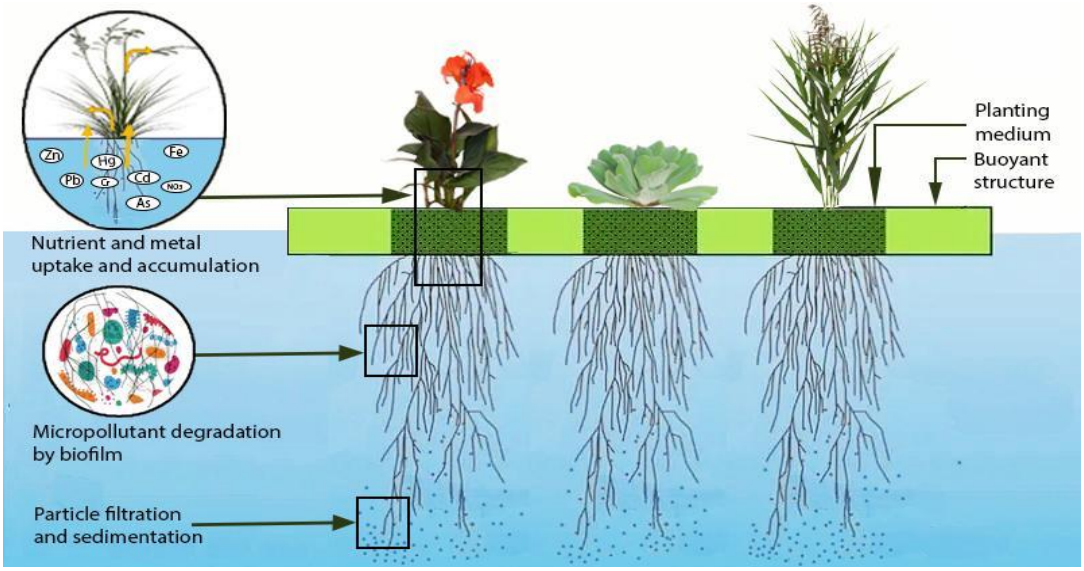

Figure 1. Schematic of pollutant removal mechanisms in a Floating Wetland system

Structurally, the FW system consists of floating mats or platforms made of durable and lightweight materials such as sealed plastic pipes and drums of polyvinyl chloride (PVC), polyethylene (PE), synthetic foams, and natural alternatives such as bamboo, providing a stable supporting framework. To anchor the plants and growth media, porous plastic cups or baskets are commonly used, resting on the mat. Growth media often employed to improve plant stability and enhance microbial colonisation include palm sugar fibre, coconut husk, mulch, straw, gravel, and light expanded clay aggregates. The selection of the macrophyte species is critical because pollutant removal efficiency is highly dependent on it. The plants must also be locally adaptable to ensure survival and compatibility with the surrounding ecosystem [1]. Table 1 lists different types of plants commonly used in FWT systems that are available in Nepal, including species such as

mosquito fern (*Azolla filiculoides*) and umbrella palm (*Cyperus alternifolius*), which achieve high removal rates of up to 87.50% for nitrates, 90.91% for phosphates, and 89.50% for ammonia. A study proposed six FW installation sites at the junctions between the Bagmati River and its tributaries within the Kathmandu Valley, though this is yet to be implemented [10]. Pilot research at the Hanumante River and Naghdaha Pond confirmed the effectiveness of these macrophytes in removing pollutants, demonstrating their widespread potential for the treatment of Nepalese water bodies [11].

Table 1. Pollutant Removal Efficiencies of Macrophytes Native to Nepal used in FWT Systems [11,12,13].

S.N.	Scientific name	Common name/ Local name	Percentage of primary pollutants removed					
			BOD	COD	Nitrate	Ammonia	Phosphate	TDS
1	*Chrysopogon zizanioides*	Vetiver grass/ Beti ghaans	77.60	78.60	81.94	38.46	86.36	59.17
2	*Azolla filiculoides*	Mosquito fern/ Ajulla	75.70	77.50	87.50	34.62	90.91	31.91
3	*Canna generalis*	Canna lily/ Kalo kana	33.20	58.20	76.30	83.80	81.40	_
4	*Pistia stratiotes*	Water lettuce/ Kumbhika	82.30	82.10	87.50	46.15	86.36	57.08
5	*Phragmites australis*	Common reed/ Narkat/ Naal	53.00	50.00	33.00	-	14.00	24.00
6	*Zephyranthes grandiflora*	Pink rain lily/ Pani phool	77.40	83.30	83.33	50.00	86.36	50.00
7	*Cyperus alternifolius*	Umbrella palm/ Chhata mothe	23.10	40.50	72.70	89.50	82.30	_
8	*Alternanthera philoxeroides*	Alligator weed/ Pani besar	39.70	69.70	86.00	89.50	82.30	_

BOD: Biochemical Oxygen Demand; COD: Chemical Oxygen Demand; TDS: Total Dissolved Solids.

Beyond removing pollutants, FWs provide various secondary ecological, aesthetic, and economic benefits that make them an attractive sustainable water treatment solution. They promote ecosystem health by supporting biodiversity, attracting aquatic organisms, birds, and insects, and

offering breeding habitats for them. Plants and flowers used also enhance the appearance of water bodies. Additionally, valuable products from harvested plant biomass are produced, which can be used for soil improvement, biogas and bioenergy generation, thereby promoting a circular economy. It is important to harvest plants and replace them in a timely manner, as decaying biomass can re-release previously absorbed pollutants back into the water [9,14].

Floating Wetland Treatments (FWTs) have been widely adopted across countries such as Pakistan, Vietnam, India, and China in various water bodies including rivers, lakes, canals, and drainage systems [9,14]. Their capacity to filter pollutants and facilitate biodegradation makes them a valuable tool for robust water quality management and for reducing environmental health risks.

Conclusions

Water pollution has significant and far-reaching impacts on the environment, and addressing these challenges requires the implementation of sustainable solutions. Floating Wetlands provide an effective nature-based solution for removing excess pollutants from water, improving water quality, supporting ecosystem health, and combating climate stresses, which are vital for achieving SDG targets. For effective adoption of FWTs in Nepal, the participation of the government, stakeholders, and local communities is essential. The government should initiate pilot projects at multiple sites and integrate FWTs into national policies on water management and urban development. Engaging local communities in monitoring and maintenance will ensure long-term success and public acceptance. Future research should emphasize long-term performance under seasonal variations, explore safe reuse pathways for harvested biomass, and focus on the integration of data-driven methods to enhance the performance, monitoring, and management of FWTs.

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Authors' Contribution

Bipin Silwal: Conceptualization, Writing original draft, Visualization, Literature review, Data collection. **Ujjwal Koirala**: Conceptualization, Writing original draft, Visualization, Literature review, Data collection. **Nadia Machkour**: Writing-review and Editing, Critical comments. **Shukra Raj Paudel:** Conceptualization, Supervision, Writing-Review and Editing, Critical comments.

Ethics approvals: Not applicable

Data availability: Not applicable

Code availability: Not applicable

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References

[1] Vo, T.K.Q., Vo, T.D.H., Ntagia, E., Amulya, K., Nguyen, N.K.Q., Tran, P.Y.N., Ninh, N.T.T., Le, S.L., Le, L.T., Tran, C.S., Ha, T.L., Pham, M.D.T., Bui, X.T., & Lens, P.N.L., 2023, Pilot and full scale applications of floating treatment wetlands for treating diffuse pollution. *Science of the Total Environment* **899,** 165595. https://doi.org/10.1016/j.scitotenv.2023.165595

[2] Strokal, M., Bai, Z., Franssen, W., Hofstra, Nynke., Koelmans, A.A., Ludwig, F., Ma, L., Puijenbroek, P.V., Spanier, J.E., Vermeulen, L.C., Vliet, M.T.H.V., Wijnen, J.V., & Kroeze, C., 2021, Urbanization: an increasing source of multiple pollutants to rivers in the 21st century. *npj Urban Sustainability* **1** (1), 24. https://doi.org/10.1038/s42949-021-00026-w

[3] United Nations World Water Assessment Programme (WWAP), 2017, The United Nations World Water Development Report 2017. Wastewater: The Untapped Resource, (Paris, UNESCO). Available online at: https://www.unep.org/resources/publication/2017-un-world-water-development-report-wastewater-untapped-resource (accessed 14 July 2025)

[4] Acharya, G., Shrestha, S., Poudel, S. and Paudel, S.R., 2024. Climate change challenges to meeting the sustainable development goals in the Hindu Kush Himalayan region. *International Journal of Environmental Studies* **81**(2),531-536, https://doi.org/10.1080/00207233.2024.2322883

[5] Kharel, A.B., 2025, Drowning in Contamination: The Hidden Perils and Solutions to Water Pollution in Nepal. *HPE Forum* **17**(1), 9-16. https://doi.org/10.3126/hpef.v17i1.76511

[6] Initial Environmental Examination (IEE), 2018, NEP: Kathmandu Valley Wastewater Management Project –Interceptor Sewer, (Kathmandu, KUKL). Available online at: https://www.adb.org/projects/43524-014/main (accessed 15 July 2025).

[7] Khadeeja, R., Amna, I., Muhammad, A., & Muhammad, A., 2019, Floating treatment wetlands as biological buoyant filters for wastewater reclamation. *International Journal of Phytoremediation* **21**(13), 1273-1289. https://doi.org/10.1080/15226514.2019.1633253

[8] Timalsina, H., Gyawali, T., Ghimire, S., & Paudel, S.R., 2022, Potential application of enhanced phytoremediation for heavy metals treatment in Nepal, *Chemosphere* **306,** 135581. https://doi.org/10.1016/j.chemosphere.2022.135581

[9] Vo, T.D.H., Vo, T.K.Q., Tran, P.Y.N., Dao, T.V.H., Hoang, Q.H., Le, L.T., Phan, N.N., Ngo, T.D.T., Lens, P.L., & Bui, X.T., 2024, Floating treatment wetlands to improve the water quality of the Hang Bang canal, Ho Chi Minh City, Vietnam: Effect of plant species. *Chemosphere* **362,** 142786. http://dx.doi.org/10.1016/j.chemosphere.2024.142786

[10] Ghimire, S., Pokhrel, N., Pant, S., Gyawali, T., Koirala, A., Mainali, B., Angove, M.J., & Paudel, S.R., 2022, Assessment of technologies for water quality control of the Bagmati River in Kathmandu valley, Nepal, *Groundwater for Sustainable Development* **18,** 100770. https://doi.org/10.1016/j.gsd.2022.100770

[11] Prajapati, M., Sayaju, N., Gosai, S., Gwachha, S., Kayastha, S.P., & Ghimire, M., 2025, Nutrient and Heavy Metal Removal Efficiencies Using Floating Wetland Treatment Techniques Of Polluted Hanumante River Water, Nepal, *Water Air Soil Pollution*, **236**(7), 430. https://doi.org/10.1007/s11270-025-08013-y

[12] Yadav, S., Kumar, J., Malyan, S.K., Goyal, V.C., Singh, J., & Negi, R., 2023, Evaluating pilot-scale floating wetland for municipal wastewater treatment using *canna indica* and *phragmites australis* as plant species. *Sustainability (Switzerland)* **15**(18), 13601. www.doi.org/10.3390/su151813601

[13] Zhang, C.B., Liu, W.L., Pan, X.C., Gaun, M., Liu, S.Y., Ge, Y., & Chang, J., 2014, Comparison of effects of plant and biofilm bacterial community parameters on removal performances of pollutants in floating island systems, *Ecological Engineering* **73**, 58-63. https://doi.org/10.1016/j.ecoleng.2014.09.023

[14] Shen, S., Li, X., & Lu, X., 2021, Recent developments and applications of floating treatment wetlands for treating different source waters: a review. *Environmental Science and Pollution Research* **28,** 62061-62084. https://doi.org/10.1007/s11356-021-16663-8

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VIEWPOINT

Guardians of the Irbis, Our Beloved Snow Leopard

Oleg Loginov ✉

Snow Leopard Fund, Licharev str. 9-24, Ust'-Kamenogorsk, Shyghys Qazaqstan, Kazakhstan

✉ **Corresponding Author:** Oleg Loginov; ***Email address***: irbisslc@yandex.kz or snow.leopard.fund@gmail.com

This *Viewpoint* reflects on the lifelong commitment of Oleg and Irina Loginov to the protection of the snow leopard (*Panthera uncia*), a symbol of Kazakhstan's mountain ecosystems. Their work combines scientific observation, artistic expression, and cultural heritage to inspire public awareness of nature conservation. Through their books, exhibitions, and the *Snow Leopard Fund*, the Loginovs try to integrate research and creativity — transforming knowledge into empathy, and conservation into an act of cultural preservation.

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Abstract: This *Viewpoint* traces the scientific and cultural contribution of Oleg and Irina Loginov to the protection of the snow leopard (*Panthera uncia*), a rare species showing the fragile balance of Kazakhstan's mountain ecosystems. Their lifelong work demonstrates how conservation can be both a scientific and artistic mission, expressed through education, photography, and literature. By integrating field observation, creative expression, and community awareness, the Loginovs have brought together ecological research and public understanding. Conservation of a rare cat species means safeguarding a shared heritage of biodiversity, memory, and national identity.

Keywords: Snow leopard, Kazakhstan, conservation, cultural heritage.

Irina and Oleg Loginov have been studying leopards for more than thirty years. The Snow Leopard Fund, established by them in 2009, implements long-term projects for the study and preservation of this species [1–4]. For example, they presented the national park with camera traps that recorded not only the first snow leopard, but also a rare species of cat, the Pallas's cat (*Manul*)**,** which climbed to great heights and had not been recorded there before; this became a scientific discovery.

The Loginovs fell in love with snow leopards for life when they began working at the Almaty Zoo on the recommendation of one of its founders, the world-famous zoologist and folk writer Maxim Zverev. He, like the Loginov biologists, was a graduate of the historic Tomsk University, in Siberia. Oleg and Irina Loginov have written several books about the snow leopard: *Lord of the Heavenly Mountains*, *Snow Leopard – Snow Leopard*, and *Wildlife of the Mountains of Kazakhstan***.** The series *Myths and Legends of the Snow Leopard* brings together folk tales and works by modern authors dedicated to the snow leopard, also known as the irbis (Figure 1).

Biologists and naturalist writers, the Loginovs were among the first in Kazakhstan to protect this rare animal, listed in the International Red Book. Maxim Zverev, a naturalist writer, warmly supported the Loginovs' publication of a journal about animals and nature in Kazakhstan titled ***Irbis***, and he became one of its first contributors

The Loginovs are also the organizers of the first NGO in Kazakhstan, whose main purpose is the protection of the snow leopard. According to their recollections, the renowned Kazakh archaeologist Professor Kemal Akishev, together with his friend Beken Nurmaganbetov, the founder of the Museum of the Golden Man in the city of Yesik, assisted them in its establishment. It is remarkable that Academician Akishev was a student of the distinguished professor from Leningrad, S. S. Chernikov. In 1956, under his supervision, he defended the first dissertation in archaeology in Kazakhstan.

S. S. Chernikov discovered petroglyphs depicting wild animals near Katon-Karagai and later donated the engraved stone to the Hermitage Museum, in St Petersburg.

Figure 1. (a) Artistic realization of the snow leopard wearing a traditional Kazakh *chapan* (robe), symbolizing the union of wildlife and national identity — a creative reflection of the "Irbis" spirit expressed in Kazakh folklore and contemporary art; (b) Digital drawing by Katya Savchenko, granddaughter of Oleg and Irina Loginov, portraying the intergenerational bond of empathy and guardianship towards the snow leopard.

The Loginovs learned of this event from teacher N. V. Zenkova, who, when still a schoolgirl**,** took part in an archaeological expedition in 1965 and assisted Professor Chernikov. Later, in 1969, during an excursion to the Hermitage, she saw the petroglyphs stone on display there.

In addition to his degree in biology, which he teaches, Oleg Loginov is passionate about wildlife photography, videography, and painting. He regularly organises photo and solo art exhibitions. His work is in many private collections. For instance, his paintings are held in the house-museum of Chingiz Aitmatov, in the Museum of Almaty, and in the collections of Olzhas Suleimenov, Professor Kathleen Braden, and in private galleries across America and Europe (Figure 2)**.**

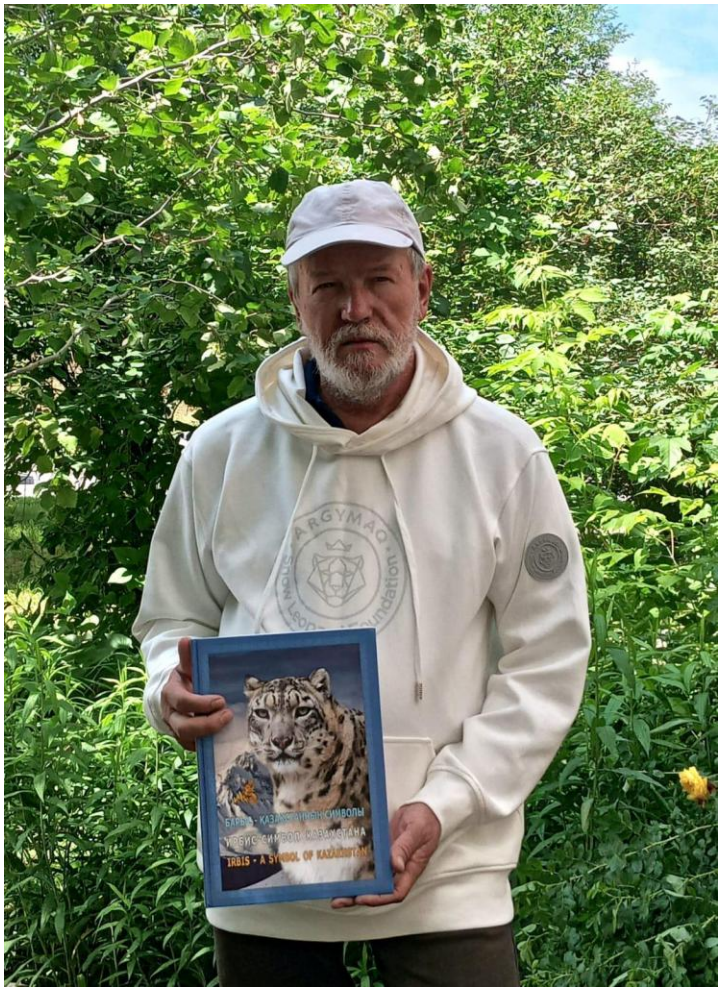

Figure 2. Oleg Loginov, biologist and wildlife artist, holding one of his published works dedicated to the snow leopard (*Irbis – A Symbol of Kazakhstan*), symbolizing his lifelong dedication to wildlife conservation and environmental education.

Oleg Loginov frequently is in touch with renowned domestic and international wildlife artists. Scientists continue to study the animal style represented in the imagery of ancient creators. Today, contemporary artists preserve this tradition, portraying snow leopards and natural landscapes not on rocks but upon the walls of buildings (Figure 3). Murals featuring the snow leopard and the celebrated Belukha Mountain have now appeared in Ust-Kamenogorsk**.**

Figure 3. Mural depicting a snow leopard on a residential building in Ust-Kamenogorsk, Kazakhstan — symbolizing the harmony between human beings and nature and expressing the cultural appreciation for wildlife conservation fostered by the Loginovs.

When tourists visit Katon-Karagai and the recreation centre at Yasnaya Polyana to experience wildlife, guides welcome them with Loginov's books on the snow leopard and excursions to the surrounding mountains where the animals dwell. Oleg Loginov often travels by car with his grandson Yaroslav, who shares his enthusiasm for photographing wildlife. Together, they organized a joint exhibition of their photographs (Figure 4).

Figure 4. (a) Oleg Loginov and his grandson Yaroslav presenting their published works on the snow leopard and the wildlife of Kazakhstan. (b) Oleg Loginov showcasing his own books dedicated to the snow leopard and biodiversity education in Kazakhstan.

Loginov's stories and articles have also appeared in international scientific and popular publications. Grandfather and grandson remain regular contributors to the distinguished journal *Young Naturalist* (Figure 5).

Figure 5. The "Guardians of the Irbis" collection — works by Oleg and Irina Loginov uniting scientific insight and cultural identity in the protection of Kazakhstan's mountain wildlife

The Loginovs are currently preparing new books on the snow leopard and the natural heritage of Kazakhstan, and are working on the realization of a new issue of the *Irbis* magazine (Figure 6).

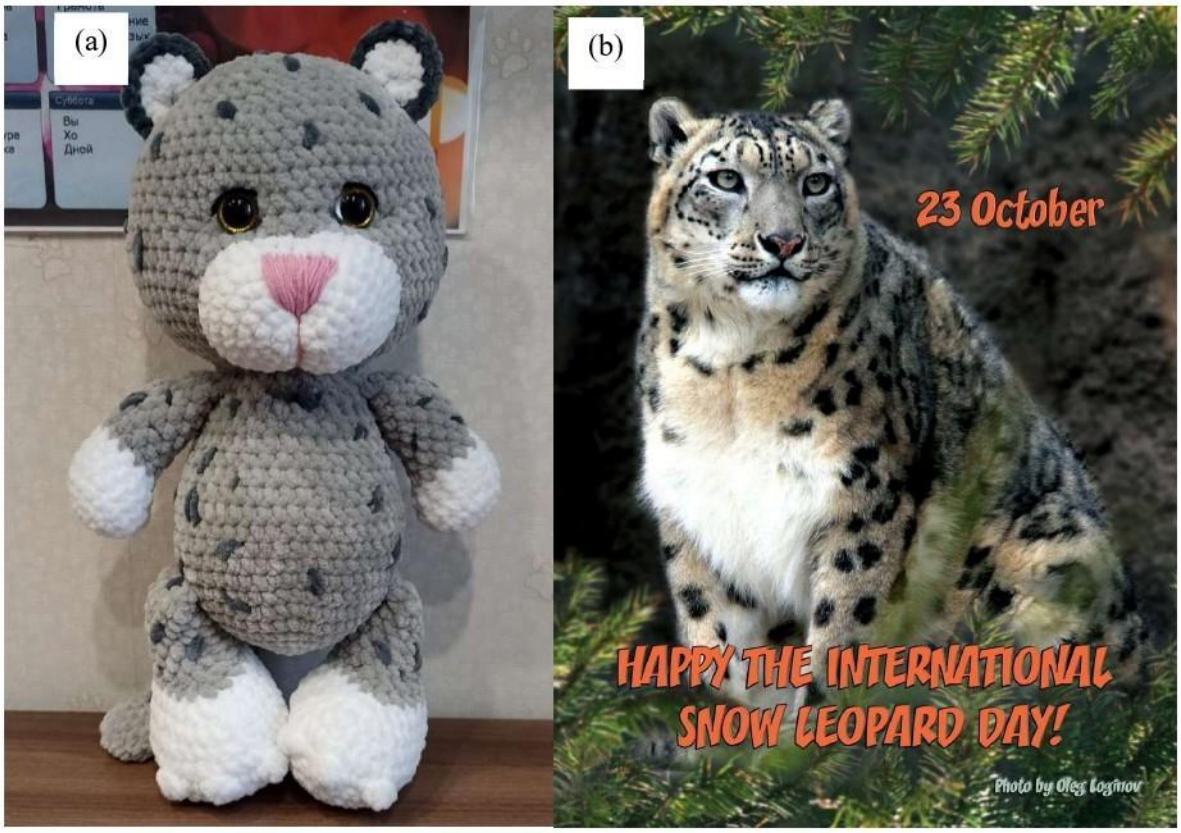

Figure 6. (a) Educational soft toy of a snow leopard used in awareness activities for children, symbolizing empathy and the intergenerational transmission of conservation values. (b) Photograph of a snow leopard by Oleg Loginov, created for *International Snow Leopard Day* (23 October) [5], illustrating the global commitment to the protection of this endangered species.

References

[1] Loginov, O., & Loginova, I. (2017). Reverse side of Chinese medicine. *International Journal of Environmental Studies* **74**(5), 915–919. https://doi.org/10.1080/00207233.2017.1341720

[2] Loginov, O., & Loginova, I. (2017). The snow leopard: the elusive ghost, but not yet lost, cat. A review of its conservation status in Siberia and Central Asia. *International Journal of Environmental Studies* **74**(5), 903–914. https://doi.org/10.1080/00207233.2017.1341721

[3] Loginov, O., 2016, *Chapter 32 – Central Asia: Kazakhstan.* In T. McCarthy & D. Mallon (Eds.), *Snow Leopards* (pp. 427–432). (London: Academic Press). https://doi.org/10.1016/B978-0-12-802213-9.00032-8

[4] Loginov, O., & Loginova, I., 2011, *Irbis — the snow leopard.* (Ust-Kamenogorsk, Kazakhstan: Satura Publishing).

[5] Sharma, K., Alexander, J. S., Zakharenka, A., Kochorov, C., Rutherford, B., Varma, K., Seth, A., Kushlin, A., Lumpkin, S., Seidensticker, J., Laporte, B., Tichomirow, B., Jackson, R. M., Mishra, C., Abdiev, B., Modaqiq, A. W., Wangchuk, S., Zhongtian, Z., Khanduri, S. K., Duisekeyev, B., Dorjgurkhem, B., Pandey, M. B., Nasir, S. M., Nawaz, M. A., Fominykh, I., Saidov, N., Yunusov, N., & Murali, R., 2024, *Chapter 49 – The Global Snow Leopard and Ecosystem Protection Program.* In D. Mallon & T. McCarthy (Eds.), *Snow Leopards* (2nd ed., pp. 633–646). (London: Academic Press). https://doi.org/10.1016/B978-0-323-85775-8.00009-1

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LETTER TO THE EDITOR

Sustainable EV Battery Waste Management: Global Lessons for Nepal

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Sir,

By the end of 2024, the global number of electric vehicles (EVs) reached 58 million, with 17 million units added in that year alone—highlighting the rapidly increasing demand, production, and adoption of EVs worldwide [1]. As a result, both the annual battery production capacity and the demand for lithium-ion battery (LIB) materials are rising sharply. The relatively short lifespan of these batteries raises the questions of recycling technologies, second-life battery (SLB) applications, and policy frameworks for sustainable management. It is crucial to evaluate their relevance in Nepal's context, where EV adoption is accelerating but supporting systems remain underdeveloped. For instance, based on Nepal's current EV market and import trends (as shown in Table 1), battery packs totalling 2,966,846 kWh are projected to reach end-of-life (EOL) within the next 20 years [2]. Managing this emerging stream of hazardous waste presents significant challenges, especially for low-income countries like Nepal.

LIBs are classified as hazardous waste because they contain toxic components such as heavy metals and organic electrolytes. These substances can release harmful gases, leach toxic chemicals, and pose fire risks, leading to environmental issues like acidification and reduced bacterial activity, which negatively affect both ecosystems and public health [4]. The specific health hazards depend on the types of electrolytes and electrode materials used in LIBs, and may include allergic skin reactions, eye irritation, skin burns, carcinogenic effects, and toxicity to specific organs. Moreover, prolonged exposure to high levels of cobalt, nickel, and manganese can cause respiratory problems and increase the risk of cancer [4]. Therefore, effective collection systems, advanced recycling

technologies, and robust regulatory frameworks are essential to ensure the safe and sustainable disposal of LIBs containing complex chemical compositions.

Table 1 Units of EVs imported into Nepal by category during the past four fiscal years [3]

EV category	2021/2022	2022/2023	2023/2024	2024/2025
Electric motorcycle & scooter	3225	7155	7747	11318
Electric microbuses (11–14-seater)	84	241	537	1830
Electric minibuses (15–25-seater)	1	3	336	1260
Electric car, jeep & van ≤ 200KW	1801	4046	11673	13525
Assembled electric three wheelers*	917	549	3114	6777
Electric three wheelers	6405	6914	9057	9728

*indicates that only parts imported, then assembled in Nepal

Since inconvenient collection facilities result in a poor recycling rate, prioritizing an adequate collection system is crucial for proper disposal and recovery. Collection of LIBs is a major challenge because there is a lack of safe handling, efficient dismantling, and transporting facilities. Establishing comprehensive collaboration between EV manufacturers, retailers, collectors, and recyclers is necessary. Various strategies like tracing LIBs, providing incentives to customers, and establishing drop-off sites can be implemented to encourage the 3 Rs principle. In the EU and China, EV manufacturers are made accountable for taking back end-of-life (EOL) batteries [5]. During collection, grading parameters like State of Health (SOH) should be checked to plan whether the battery can be repurposed for Second Life Battery (SLB) application or recycled.

SLB application refers to repurposing those LIBs for another use which fails to meet the usable performance of the first application. Major areas of application include Stationary Energy Storage Systems (SESS), Backup Power, Low-Power Mobility, and off-grid applications [6]. This not only provides economic benefits but also helps in extending the lifespan of batteries. Recycling retired batteries offers scalability in management, economic advantages, and resource recovery which reduces the mining of metal ores to some extent [5]. Currently, more adopted commercial methods of recycling include hydrometallurgy and pyrometallurgy. Pyrometallurgy is a low-cost smelting and roasting process that requires minimum pre-treatment, but it is highly energy

intensive and associated with poor recovery, release of toxic gases, and slag formation. Hydrometallurgy uses organic and inorganic solvents to dissolve selective metals resulting in good recovery, but it results in high chemical cost and wastewater generation [7]. Studies and research on new emerging green technologies like direct recycling, bio metallurgy, electrometallurgy, green solvent, etc. are going on to reduce the operation emissions and energy cost [5].

Since there are advances worldwide in battery recycling, it is crucial to evaluate Nepal's current infrastructure and policy. Despite productions of LIBs from both e-waste and EVs, the Nepalese market lacks dominant recycling companies. Even though start-ups and partnerships with foreign recycling companies have emerged in recent years proper implementation and visible results are yet to be seen. In 2023, LOHUM (India) aimed to recycle 200,000 batteries over a five-year period through Extended Producer's Responsibility (EPR) services. In 2024, the Chinese EV brand BYD expressed a similar intention to recycle and reuse LIBs through service providers IT Partners Inc. (USA) and Anhui Lecheng Lithium-ion Technology (China) [8]. But there is no real development from these commitments yet. Generally, EV distributors provide warranty services to repair dead battery packs of LIBs having SOH below 70-80%. This is practised in Nepal. Although large recycling facilities may not be economically feasible because of unit economics, SLB application presents a promising opportunity for companies in a low volume market [2,9].

Battery recycling regulations formed around the world are inconsistent, some countries adopting strict measures whereas others are more relaxed. For instance, China has introduced "Comprehensive Utilization Standards for New Energy Vehicles Retired Power Batteries (2024)" transitioning from fragmented policies to a system that emphasizes EPR, traceability via battery coding, and lifecycle management. Similarly, the recent "New Battery Regulation (EU) 2023/1542" governs all the member states of the EU setting targets for collection and recovery rate [10]. The US lacks a unified national regulatory framework but there are federal and state policies focused on achieving circular economy goals and recycling valuable minerals [2]. Nepal has a Solid Waste Management National Policy (2022) which explicitly promotes the 3Rs approach, waste classification and source segregation. In 2024, the Ministry of Physical Infrastructure and Transport (MOPIT) and the National Road Safety Council (NRSC) developed an action plan to address the management problem of expired batteries in Nepal. It appears that Nepal lacks national policies that entail EPR, tracing hazardous waste and adequate management of EOL batteries [2].

Nepal's transition to electric mobility has introduced new challenges in waste management, particularly concerning lithium-ion batteries (LIBs). Accordingly, Nepal should adopt and adapt global best practices in battery repurposing, recycling, and regulatory framework development. Promoting SOH grading of spent LIBs for second-life applications—such as energy storage in solar or hydropower projects, institutional backup systems, and other alternatives—can significantly extend their useful life. The integration of data-driven approaches, such as Artificial Intelligence (AI) and Machine Learning (ML), should be prioritized to enhance the optimization of State of Health (SOH) diagnostics, thermal runaway detection, lifecycle assessment, and end-of-life (EOL) decision-making strategies [11]. Early implementation of these measures will not only provide a critical buffer period before fully operational recycling facilities are established but also support the development of a circular economy [2].

More importantly, since Nepal's market is small, with no direct role in the battery materials or construction supply chain and limited technological capacity, the country should first focus on developing an efficient waste collection system. In the early phase, exporting the collected waste to neighbouring countries like China and India—where several leading battery recycling companies have already established [12,13]—would be a practical and strategic approach. We consider that there is an urgent need for national policies to manage battery waste, mitigate environmental impacts, enforce compliance, and stimulate investment.

References

[1] IEA, 2025, Trends in electric car markets – Global EV Outlook 2025, *International Energy Agency*, Paris. Available online at : https://www.iea.org/reports/global-ev-outlook-2025/trends-in-electric-car-markets-2

[2] NRSC, 2024, The comprehensive Management of After-Life Battery Pack Management, Ministry of Physical Infrastructure and Transport National Road Safety Council, Kathmandu. Available online at: https://www.mopit.gov.np/downloadfiles/The-comprehensive-Management-of-After-Life-Battery-Pack-Management-(1)-1750580464.pdf

[3] Department of Customs Accessed: Jul. 15, 2025. Available online at: https://customs.gov.np/

[4] Sankar, T.K., Meshram, A., & Meshram, p., 2024, Environmental Impact Assessment in the Entire Life Cycle of Lithium-Ion Batteries. *Reviews of Environmental Contamination and Toxicology* **262**(1), 5. https://doi.org/10.1007/s44169-023-00054-w

[5] Amusa, H. K., Sadiq, M., Alam, G., Alam, R., Siefan, A., Ibrahim, H., Raza, A., & Yildiz, B., 2024, Electric vehicle batteries waste management and recycling challenges: a comprehensive review of green technologies and future prospects. *Journal of Material Cycles and Waste Management* **26**(2), 1959-1978. https://doi.org/10.1007/s10163-024-01982-y

[6] Hossain, E., Murtaugh, D., Mody, J., Faruque, H.M.R., Sunny, S.H., & Mohammad, N., 2019, A Comprehensive Review on Second-Life Batteries: Current State, Manufacturing Considerations, Applications, Impacts, Barriers Potential Solutions, Business Strategies, and Policies. *Institute of Electrical and Electronics Engineers* **7**, 73215-73252. https://doi.org/10.1109/ACCESS.2019.2917859

[7] Srinivasan, S., Shanthakumar, S., & Ashok, N., 2025, Sustainable lithium-ion battery recycling: A review on technologies, regulatory approaches and future trends. *Energy reports* **13**, 789-812. https://doi.org/10.1016/j.egyr.2024.12.043

[8] Baral, A., 2025, EV Battery Recycling in Nepal: The Time Bomb No One Talks About, *Motar*. Available online at: https://motar-company.com.np/ev-battery-recycling-in-nepal-the-time-bomb-no-one-talks-about/

[9] Ryan, A., 2022, EV batteries: talking about degradation, *Fleet news*, 8 Nov. Available online at: https://www.fleetnews.co.uk/news/fleet-industry-news/2022/11/08/ev-batteries-talking-about-degradation

[10] Su, D., Mei, Y., & Amine, K., 2025, Global Regulations for Sustainable Battery Recycling: Challenges and Opportunities. *Sustainability* **17**(7), 3045. https://doi.org/10.3390/su17073045

[11] Schuett, L.R., 2025, Energizing Electrification - A Future of Batteries, AI, and Hydrogen, Available online at: https://www.offgridenergyindependence.com/articles/33585/energizing-electrification-a-future-of-batteries-ai-and-hydrogen

[12] TYCORUN. Top 10 power battery recycling companies in China in 2022. 2022 Jul 1. Available online at: https://www.tycorun.com/blogs/news/top-10-power-battery-recycling-companies-in-china-in-2022

[13] Garg Trading Company, 2025, Top 10 battery recycling companies in India 2025, Available from: https://www.onlinebattery.co.in/blogs/details/top-10-battery-recycling-companies-in-india-2025

Yours sincerely,

Aadarsha Timilsina [a], Ujjwal Koirala [a], Shukra Raj Paudel [a,✉]

[a] Environmental Engineering Program, Department of Civil Engineering, Pulchowk Campus, Institute of Engineering, Tribhuvan University (ROR: https://ror.org/02rg1r889), Lalitpur, Nepal

✉ **Corresponding Author:**
Shukra Raj Paudel
Email: mailto:srpaudel@ioe.edu.np| +977-9851220184 | ORCID: 0000-0002-5764-2990

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BOOK REVIEW

Planta Sapiens: Unmasking Plant Intelligence, by Paco Calvo with Natalie Lawrence, London, The Bridge Street Press, 2022, 304 pp., £22 (hbk), ISBN: 978-0-34912-845-0.

According to Paco Calvo, professor of philosophy of science, plants are intelligent or rather sentient beings making choices just as animals (even the most primitive and unicellular). Plants of the genus *Lavatera* (Cornish mallow) turn after the sun, and they can hold information about what direction the sun will appear from for several days, even in the absence of sunlight. Mimosas seem to have long-term memory, their defensive folding up of the leaves being a variable habituation that could last for up to 28 days. Cognitive behaviour is by definition adaptive, anticipatory, goal-directed and flexible, and Calvo finds it hard to deny these capabilities in plants.

Plants have "many, nuanced ways of selecting information and using it to guide what they do." They demonstrate self-recognition and territory-guarding, and they can make internal maps of their surroundings to guide root growth. Like animals, they have "proprioception" or sense where all their body parts are in space. And after "judicious cost-benefit analyses, plants decide where to invest their precious metabolic resources." There are "IQ" differences between wild and domesticated varieties of plants, some vines are the lapdogs of the plant world, trained to survive only in sanitized environments, whereas the wild varieties are much better in finding climbing supports, protecting their leaves from being eaten etc. There is even variation in individual capabilities of plants which indicates that they have individual personalities.

And like Pavlov's dogs which salivate by the sound of a bell when they have been trained to hear a bell each time they get food, a plant will turn towards the wind from a fan when trained to associate the wind with light. The *Arabidopsis* plant seems to use the unique wavelength profiles of the light reflected by its neighbours to tell whether they are relatives or not. Grown together with kin these plants will produce more seed than when growing with strangers. Individual strawberry plants can learn during their lifetime, improving their ability to choose between suitable conditions for their roots. The parasitic dodder can discover when it grows towards an unsuitable host plant and then change direction and choose another one, and another species of climbing plant can choose between climbing differently coloured poles. Just a few examples of the abilities of plants.

Calvo points out that though plants do not have a nervous system, many of the chemicals active in the transmission of signals in the body are the same in animals and in plants. But of course a question is whether an organism really needs a nervous system as known from animals to have cognitive abilities. It has just been a common assumption. As Calvo says in his plea for thinking outside the box, blindly subscribing to the dominant ideas of the past is dangerous. He has been aggressively criticized by reputable plant scientists, but on the other hand he can refer to Darwin himself.

Some would perhaps downplay the disagreements as being mostly a war of words. According to Calvo we need to view plants "as information processors with complex algorithms that turn sensory data into representations of the outside world" (like animals). Evidently he stretches many definitions as far as possible to make his point. Taken literally it would certainly be an inconvenient truth, not the least for vegetarians who will see the moral reasons for distinguishing between plant and animal food undermined. And many tasks would be complicated when taking due regard to the feelings of plants.

Calvo gives the example of Sir J. C. Bose who in the early twentieth century would minimize the stress endured by trees about to be transplanted. He performed anaesthesia on them, even very large individuals, by creating a tent to cover the whole tree and filled it with chloroform to put the tree to sleep (remarkable in itself that the same anaesthesia works on animals and plants). Calvo envisages the practical problems in treating plants as sentient beings. He is in fact also more realistic than this account may suggest. He just hopes that his view will contribute to a more respectful treatment of all of nature's creatures.

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pnbuhl@hotmail.com

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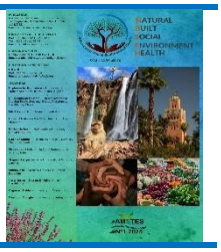

BOOK REVIEW

The Case for Nature: Pioneering Solutions for the Other Planetary Crisis, by Siddarth Shrikanth, Richmond, Duckworth, 2023, 293 pp., £20 (hbk), ISBN: 978-0-71565-473-6.

The combination of Siddarth Shrikanth's fields of expertise, conservation biology and business, is too rare in an era where the credo of conservationists has become that nature has no money value but should be saved solely for its own sake. This sounds nice in the ears of true believers, but politicians and perhaps most people struggling to make ends meet could perhaps better be persuaded to protect nature when convinced that this adds "real value" to society. Many years ago the concept "ecolonomics" was coined but sadly never really caught on. Shrikanth is himself a lover of nature for its own sake and knows that it is priceless. That does not alter the fact that a price would often help, as the value of nature for human capital is high. As Shrikanth says, for better or worse we live in a capitalist system, and nature will suffer if we only want to plan for perceived ideal solutions.

In the subtitle of the book is mentioned "the *other*" planetary crisis. The first which gets most of the spotlight is of course the climate crisis. The crisis for wild nature and biodiversity seems almost forgotten relative to that. But whereas the real climate disasters are still predictions, Shrikanth describes disasters already happening, such as nearly 90 percent of global fish stocks being overexploited or depleted, and 96 percent of the global mammal biomass accounted for by human beings and our livestock (only 2 percent before modern civilization). International climate conferences are at the centre of global attention, but biodiversity conferences hardly get mentioned in the media. In 2022, 83 percent of Fortune Global 500 Companies had set a specific climate target, compared to just 5 percent for biodiversity loss. Shrikanth notes that the challenge of climate change has been framed in economic terms. Biodiversity has not been seen to exist - and climate change is not seen very clearly by society as a reality.

Yet, perhaps this is already well understood as a problem in Europe. The Senckenberg – Leibniz Institution for Biodiversity and Earth System Research // Senckenberg Gesellschaft für Naturforschung has been working on such matters for a long time.

Of course, protecting wild nature is also a part of the climate solution, natural ecosystems being the best absorbers of human emissions (with successful conservation they could absorb one-third of the carbon by 2050). One way of making nature conservation lucrative is by promoting ecotourism, the great potentials of which Shrikanth discusses at length. He stresses that the profits of ecotourism should go mostly to the local residents and to prevent degradation of nature. And travelling should be planned in ways so that the benefits for nature will greatly outweigh the unavoidable imprint. Most important here is to limit the absolute numbers of tourists (a risk being that this will become an expensive pleasure for the few).

Shrikanth also explains the direct economic gains in the "greening" of cities, the six million trees in Sacramento, for example, saving about $20 million annually in air conditioning. Generally, in the design of modern cities it would benefit resilience if just steel and concrete were left behind to be replaced by a "rethinking what the aesthetic of modern development looks like." Shrikanth gives good examples from Singapore and Mumbai. Likewise, regeneration of mangroves at vulnerable coastal cities could save many billions of dollars. But most elaborate in the book is the rather technical discussion of financial schemes to promote regeneration of nature, especially from trading carbon credits. Generally, the problem is that the financial system was created when resources were plentiful, capital and labour scarce. Today we have the opposite situation, but the financial system is "still one of the most powerful tools that humans have ever created". But still many environmentalists are against using it for their own cause.

Shrikanth describes the many exciting emerging technological possibilities to support nature conservation, the growth of every tree involved in carbon trade and other nature businesses could be monitored, and he imagines a "technology dashboard for the planet" for surveillance of all ecosystems on the globe. Another open field for business is alternative food production. Shrikanth states that we already are able to produce enough healthy food for nine billion people (and 17 percent of all food is being discarded). And of the more than $500 billion with which governments globally are subsidizing farmers, more than 90 percent go to production which is "harmful" for nature. In contrast, the world currently spends at most $143 billion per year on conservation of all sorts. This is recommended to be at least $600 billion in 2030. But this should be regarded as a business investment.

Shrikanth rejects the popular current Western view among activists that all human use of nature is "environmentally damaging or problematic". He prefers the view of indigenous peoples who regard nature and wildlife as a resource, but to be used with respect. In fact Shrikanth stresses the importance of empowering the indigenous peoples as custodians of nature. The territories of indigenous peoples house 20 to 30 percent of the above ground carbon on Earth, half of the tropical

forests, 80 percent of biodiversity, and 40 percent of intact ecosystems. The indigenous peoples should be part of the lucrative green business solutions for the future which Shrikanth so refreshingly discusses from many angles, more constructively and without the ideological prejudices of so many vocal nature lovers.

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pnbuhl@hotmail.com

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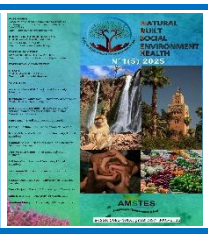

BOOK REVIEW

Greenhouse Planet: How Rising CO2 Changes Plants and Life as We Know It, by *Lewis H. Ziska, New York, Columbia University Press, 2022, xiv + 221 pp., $25.00 (hbk), ISBN: 978-0-23120-670-9.*

The mantra "CO2 is plant food" is a well-known message from people who want to downplay the negative consequences of current changes in the atmosphere. In this book noted plant physiologist Lewis Ziska attacks the mantra from many different angles. Although it contains an important truth (CO2 undeniably is plant food) those relying on it need to specify exactly how plants react to increasing CO2 levels.

It is true that yields of many crops such as wheat and rice can increase significantly with increasing CO2-levels. But there are large differences between crop varieties. Some will just respond with more leaves rather than seeds and other edible parts, and some will be significantly less rich in protein and important minerals. But the most important factor in reducing yields despite rising CO2 levels is that weeds generally are better than crops in exploiting the new conditions, and the importance of weeds as a negative factor often seems to overshadow the positive factors in rising CO2 levels.

Very little research has been done into this as well as into which crop varieties are best under the new conditions, and Ziska understandably wonders why. He describes several experiments conducted by himself and others, such as yield trials of soy bean varieties used for many decades and under the same conditions, and CO2 fumigation of strawberry fields. But experiments are few and funding very limited, though important for the future of the world's food production.

It is already common among cannabis growers to use CO2 to stimulate growth of marijuana, but again little is known about how this affects the THC concentration and how reactions differ between varieties. Ziska points out that producers of heroin and cocaine will also benefit from increased growth. It seems to me that he generally focuses on the possible negatives, despite current lack of knowledge, as well as on worst case scenarios. Of course it is better to be safe than sorry, but as he argues against the most primitive of propagandists among his climate denying opponents, he should, with his lively and rather polemical style, perhaps be more careful not to sound like Greta Thunberg. But Ziska's anger is surely understandable when he speaks of research being suppressed evidently for

political reasons, which is always wrong whatever the political colour of the suppressor! Much more research is needed, and that should be the important message, not premature doomsday scenarios which really are making so many people tired by now, rightly or not.

When weeds will be thriving relatively well with more CO2, farmers are forced to use more herbicides. That will only be one of several cascade effects. Weeds could even become more resistant to herbicides, and CO2 may in fact select for invasive species. Ziska also theorizes that a change in plant chemistry (less nutrients) caused by CO2 could be part of the explanation for the "insect collapse". As always more data are needed but the few available point to the possibility of such causal connections. Experiments with goldenrod indicate less pollen protein with rising CO2. This could affect the well-being of bees with further large consequences. Of course the well-being of human beings would be directly affected in the same process, as food quality is compromised. The same could happen to plants used in medicine, and some food plants could become more allergenic. But again this is currently extrapolations from very little evidence.

There seems to be more current real life examples of how wild nature changes with more CO2. Leafy vines such as poison ivy seem to benefit more than trees, so the composition of forests will no doubt change (I can add that here in Denmark our common ivy seems to have a much stronger growth in later years, covering more trees than earlier, but how to separate CO2 as cause from general climate change?). Elevated CO2 concentrations also seem to make some plant pollen less fertile and more sensitive to increasing temperature. It is beyond doubt that there will be plant winners and losers in a changed atmosphere, but we are very far from reaching a general fact, the reactions of plants being evidently much more complex than just the abused meme "CO2 is plant food" indicates. Like all excellent scientific dissertations Ziska's raises more questions than answers, and the only certain conclusion is that it would benefit mankind if there were more funding and some gratitude shown to the scientific community.

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pnbuhl@hotmail.com

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BOOK REVIEW

Ice Geographies: The Colonial Politics of Race & Indigeneity in the Arctic, by Jen Rose Smith, Duke University Press, Durham, 2025, xviii + 230 pages, US$28.00, pbk (ISBN: 978-1-4780-3177-2).

How are 'glacier disappearance and Native disappearance' (p. 175) related? This question is at the heart of **Ice Geographies: The Colonial Politics of Race & Indigeneity in the Arctic** by Jen Rose Smith (dAXunhyuu/Eyak). Throughout, the book presents and analyses how ice geographies are racialized geographies.

This book begins with Smith's lived experience of being raised in dAXunhyuu territory and the idyllic days spent on the land while also experiencing 'capitalist extraction points and tourist destinations of wild Alaska beauty' (p. xiv). This work is informed by loss 'of language, of homelands, of salmon, of glaciers' (p.xvi) and thoughtfully presents and analyzes how ice is tied to colonial and racial ideologies.

The organization of this work considers 'ice as analytic, …science data, …imaginary, …terrain, and …among the stars' (p. 4). Art and research of Indigenous intellectuals are woven throughout the volume; Chapter 3 provides an analysis of a poem, *Exceeding Beringia*, by Joan Naviyuk Kane (Inupiaq), which honours Bering Land Bridge National Preserve. The poem presents the themes of *us* and *bound together*. Smith points out a non-Inupiaq reader might consider these ideas as placing us communally 'at the mercy of potential destruction' (p. 102); whereas, an Inupiaq reader might consider this 'as ongoing violence' (p. 102).

For me, the most beautiful part of **Ice Geographies** is Smith's description (pp. 166-171) and images (Plate 9 and Plate 10) of hair ice. 'It is the anti-spectacle, the anti-ice core, the anti-climate table. It is a relational phenomenon: growing, morphing, transitioning in concert with a fungus that acts on and with ice' (p. 167). This is a fitting discussion for the conclusion of the book. Throughout, the reader is presented with the concepts of spectacles, ice cores, and climate tables in relation to ice. Ending with these delicate structures to contrast with the "hard" imagery brings a wonderful balance to Smith's work.

This book is well researched and thorough in its discussion of ice, forming and melting, and how it has, and continues to, shape relationships, communities, and identities. It expertly weaves history, science, philosophy, and art. I enjoyed reading this work from cover to cover.

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stagner@uwindsor.ca

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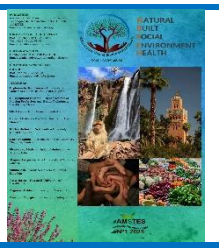

BOOK REVIEW

Dialogues for Degrowth. Transdisciplinary Perspectives for Sustainable and Inclusive Futures, *edited by Ksenija Hanaček, Marula Tsagkari and Brototi Roy, Cheltenham, UK: Edward Elgar Publishing, 2025, 235 pp., £110.00 (hardback), ISBN: 978-1-0353-2076-9.*

It was a genuine pleasure to discover, at the very beginning of the book, the moving dedication offered to women by the three editors and young migrant researchers (Ksenija Hanaček, Marula Tsagkari and Brototi Roy). I embrace this gesture of gratitude, since women, past and present, play a fundamental role as custodians of social, cultural and intellectual legacies that illuminate our path and open the way for new generations. The editors place transmission, solidarity and heritage at the very heart of their work; reaffirming the vital role of women in our societies as guardians of traditions, pillars of family life, and guarantors of national identity.

In Morocco, a country renowned for its gastronomy, this heritage endures thanks to women who, with patience and courage, have resisted the dominance of fast food in order to preserve the art of shared meals built around local produce, accessible to all and rich in social meaning.

Arpita Bisht in Chapter 13 (pp. 165–174) places food at the centre of the reflection on degrowth. Food is not only a matter of biological survival: it is intimately connected with culture, identity and social bonds. Yet contemporary food systems, shaped by colonial legacies, reproduce exploitation, unequal exchange and land grabbing, locking entire communities into debt and dependency. These logics remain inseparable from global capitalism, with its model of cheap food that sustains worker exploitation and the expansion of consumerism.

Bisht draws here on the theory of food regimes: from European colonialism and its massive exports, to American agro-industrial dominance after 1945, and finally to contemporary neoliberalism, now disguised as “green capitalism”. Bisht demonstrates that food is also a political instrument: withholding it can make it a tool of oppression, as in Gaza, but it can also be a lever of resistance and sovereignty, embodied by movements such as La Via Campesina, which defend local production, social justice and agroecology.

When women are present, memory is preserved. Where they have been excluded – as in the prestigious crafts of Fez, confined within male guilds – knowledge has been lost, weakened by oblivion and mere commerce. Where women have always acted, as in the art of sewing and the

caftan, heritage continues to shine and to renew itself through their creativity. The same applies to many other cultural expressions: the songs of the moussems, oral poetry, Atlas carpets, pottery made in rural households, and the extraction of oils and local products in cooperatives. Everywhere, their hand inscribes memory into daily life [1].

In Morocco, where educational systems shift between national, French, British or American models, and where reforms are imposed within a logic of growth and liberalisation, the school sometimes contributes to the erasure of our traditions and identity [2]. In response to this risk, the family, supported by women, slows down this movement of forgetting and keeps Moroccan culture alive, with a kindness and a beauty difficult to describe and difficult to diminish. Women uphold the last barriers against the fading of cultural landmarks. They embody transmission, resilience, justice and solidarity.

It is here that an essential idea shines through: to "unlearn" in order to learn better. Isabel Chender (pp. 207–218) argues clearly: it is not a matter of renouncing school, but of questioning what it instils as unquestionable truths – that growth is always a benefit, or that success is measured only by salary and consumption. The school, sometimes transformed into an industry, reproduces modes of thought that suffocate our heritages and our imagination. To unlearn is to reopen a mental space where the transmission of popular, feminine and community knowledge regains its place in dialogue with the ecological and social challenges of our time.

Memory, nurtured and protected by women, becomes a political force. In Chapter 5 (pp. 61–72), Lucia Muñoz Sueiro, drawing on Walter Benjamin (1892–1940), reminds us that memory is not only for preservation, but also for awakening forgotten struggles and bringing past and present into dialogue. Where women preserve the continuity of knowledge, Benjamin calls for it to be transformed into a lever of change, a weapon of justice.

The idea of "postfiguration" then opens a path: to draw from pre-capitalist inheritances, from subversive knowledge and from past struggles, in order to invent a future capable of breaking the logic of linear progress. Degrowth finds here a future of solidarity that does not erase its ancestors, but carries them along.

The orientation of the editors is not a lack of impartiality when they choose to give voice to women, young researchers, people of colour and activists (pp. 1–5). It is not a reductive bias, but an act of epistemic justice. It is about restoring a place to those who had been excluded, pushed for a long time to the margins of knowledge. It is also about opening a space of thought to voices often silenced, to complete knowledge that had long been confined within restricted, male, white and Eurocentric circles. Only by welcoming this plurality of experiences and perspectives can we build a shared knowledge that is richer, fairer and truer.

The opening chapters of the book confirm this orientation. Morena Hanbury Lemos (pp. 8–20) demonstrates how colonialism, capitalism and ecological crises are interconnected. She reminds us that a structure built on injustice cannot endure: the ecological and social disasters we face today are the direct legacies of colonial plunder. Her analysis exposes the continuity of these extractivist logics in the present global system and emphasizes that reparations cannot be reduced to financial compensation alone. She calls for profound structural transformations: to deliver economic justice, to acknowledge past wrongs, to guarantee fair redistribution, to restore the sovereignty of each people over their own resources, and to bring an end to the colonial mechanisms that still dictate the rules of the global economy. Thus, degrowth is a means to achieve justice through a systemic shift.

Riya Raphael also adds a new tool, arguing that moving beyond the logic of infinite growth requires rethinking what it means to work (pp. 21–29). Our societies rest on an organization that produces exploitation, whereas degrowth opens the way towards work founded on dignity, sharing and justice. Degrowth cannot break with injustice if it ignores the invisible and unpaid foundation – care, housework, education, transmission – that sustains daily life. To recognize this work is to understand that the true economy is not the one that accumulates, but the one that preserves and connects. Raphael reminds us that degrowth will only be just and credible if it includes women, their invisible efforts and their essential role in shaping a fairer future.

Here, Lena Weber invites us to sit within an imagined space that already carries a name: the Queer Café, a symbolic place where degrowth enters into dialogue with voices long pushed to the margins. Beyond the examples she presents (pp. 33–43), it is essential to recall that many other “non-normative” lives also endure the injustice of a system that values only performance and productivity. Autistic people, those with dyslexia, or those living with disabilities are still too often pushed into the shadows, regarded as a “burden” when in reality they embody different ways of understanding the world, unique talents and a creativity of immense value for our societies. These injustices reveal a system that judges human beings solely by conformity and output, forgetting their intrinsic worth. Social and ecological justice cannot be built without recognizing the dignity of every person.

The growth economy means that women must endure a double burden: on the one side, the daily care of dependants in difficulty, and on the other, the weight of social judgement that too often holds them responsible for what lies beyond their control. This injustice is a reminder of how readily our society prefers to accuse rather than to support. Degrowth offers another path: it calls us to break with the logic that measures human worth by productivity and conformity,

and instead to affirm that every life matters, and that true justice is born from solidarity and respect for all forms of existence.

Nogué-Algueró, Hadjimichael and Ertör insisted on shifting the dialogue from the café to the ocean (pp. 44–51). The sea is not a marginal space but a decisive ground for thinking about degrowth. The ocean covers 70 per cent of the planet, feeds millions of people and sustains terrestrial life, yet it is now dominated by the logic of the "Blue Economy", the distorted belief that economic growth can be reconciled with the protection of the seas. The authors argue that blue growth reproduces the same colonial and extractivist mechanisms that exploit coastal peoples and deplete marine resources.

In the cooperatives of coastal villages in Morocco, such as in the Tiznit region of Souss-Massa, women harvest and prepare mussels with ancestral knowledge. This simple act becomes one of resistance: by uniting, they safeguard the sea, defend their autonomy and keep their social role alive [3].

After addressing memory as a tool of justice and the ocean as a space of dialogue, the book questions both the genuine solutions, which deserve to be encouraged, and the false ones, too often promoted as miracle cures. Among the latter, the circular economy (pp. 73–83) holds a central place. Sofia Rafaella Greaves shows that it is now presented as a perfect answer to the ecological crisis, a seductive narrative that promises endless recycling while maintaining growth. Yet this promise is a myth: a loop that claims to repair what it continues to damage. In response, Greaves suggests returning to simple and fair solutions: genuinely reducing extraction and production, slowing down material flows, giving priority to repair, sobriety and local reuse. The real solutions are not to be found in industrial slogans, but in a degrowth economy, attentive to the goods already possessed, mindful of equity, and grounded in shared responsibility.

The book then offers a wealth of tools for achieving degrowth, showing that it is not only economic but also cultural, aesthetic and social. Each tool opens the way towards a different future.

Mongolian poetry (pp. 85–95), like Amazigh or Welsh songs, protects memory and nourishes the imagination of a future that refuses to erase cultures. Dance (pp. 96–104), or even sport practised outside any competitive logic, becomes a space of well-being and resistance against the frenzy of productivism.

On pages 117–126, Franciney Carreiro de França takes us to the Quilombolas of Brazil. Their way of life, rooted in memory and justice, embodies a form of degrowth already lived, fragile yet luminous. It is, however, difficult to think that a developing or developed society can degrow its economy to the levels adequate for forest dwellers in Brazil.

Then Anikó Gál (pp. 130–137) questions fashion and proposes to free it from consumerism through "defashion", transforming it into a space of creativity and sharing. Carlos Moreno Azqueta (pp. 140–147) explores the world of video games: even though born from the logic of growth, it can paradoxically become a critical laboratory for understanding and teaching degrowth.

Finally, Lee Amaduzzi (pp. 149–158) introduces the solarpunk movement. In contrast to narratives of fear and catastrophe, it offers a utopian imagination that makes ecological and solidaristic futures desirable.

Chapter 15 (pp. 195–202), by Nora Krenmayr, Monika Austaller and Luzia Strasser, highlights the strength of deep friendships. The authors explain that they can break isolation, open a space of trust and emotion, give the strength to move beyond roles imposed by society, and enable the creation of other ways of living and of being recognized.

Degrowth is also a question of rhythm. In a very fast world, the true pace is that of the pacemaker: measured, adapted, respectful of the human breath. And this rhythm is best known to women: those who carry both professional and domestic responsibilities, who rear children whilst sustaining a social and political life. Some public figures have reminded us of this with courage: in Australia, Senator Larissa Waters breastfeeding her daughter in the Senate in 2017 [4]; in Spain, Carolina Bescansa in Congress with her baby in 2019 [5]; and many other elected representatives who claim the right to integrate motherhood into public life. These gestures affirm that equality also requires respect for the real rhythms of life. To seek justice is to accept moving forward at a fair pace, a human pace. Degrowth finds here its full truth: to slow down, not in order to retreat, but to make possible a future where everyone moves forward together without anyone being left behind.

What captures attention is the form. The chapters convey the depth of singular voices, and the dialogues transform them into a living polyphony. Such rare alternation turns the book into a permanent conference set down on paper. It is a bold gesture, towards a better future.

References

[1] Davis, S.S., & Coca, J., 2024, *Women Artisans of Morocco: Their Stories, Their Lives*. (Atglen, PA: Schiffer Craft). https://www.schiffercraft.com/products/women-artisans-of-morocco?_pos=1&_sid=9ace35e8d&_ss=r

[2] DeGorge, B., 2002, The modernization of education: A case study of Tunisia and Morocco. *The European Legacy* **7**(5), 579-596. https://doi.org/10.1080/1084877022000006780

[3] Angade Khadija. Cooperative entrepreneurship in Morocco: the case study of women's cooperatives in the Souss Massa region. Liège (Belgium): CIRIEC International, Université de Liège; 2024. https://doi.org/10.25518/ciriec.wp2024.02

[4] Shankar Dakshayani. Australian Senator becomes first woman to breastfeed in Parliament. NBC News. 2017 May 9. Available from: https://www.nbcnews.com/news/world/australian-senator-becomes-first-woman-breastfeed-parliament-n757546

[5] Rodal, A. B., & Fuertes, M. S., 2018, Lo personal es político: un bebé en la sesión de constitución de las Cortes Generales. El tratamiento televisivo del caso de Carolina Bescansa y su hijo. *Vivat Academia*, 79-96. https://orcid.org/0000-0003-4081-0035

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nadia.boutaleb@fstm.ac.ma

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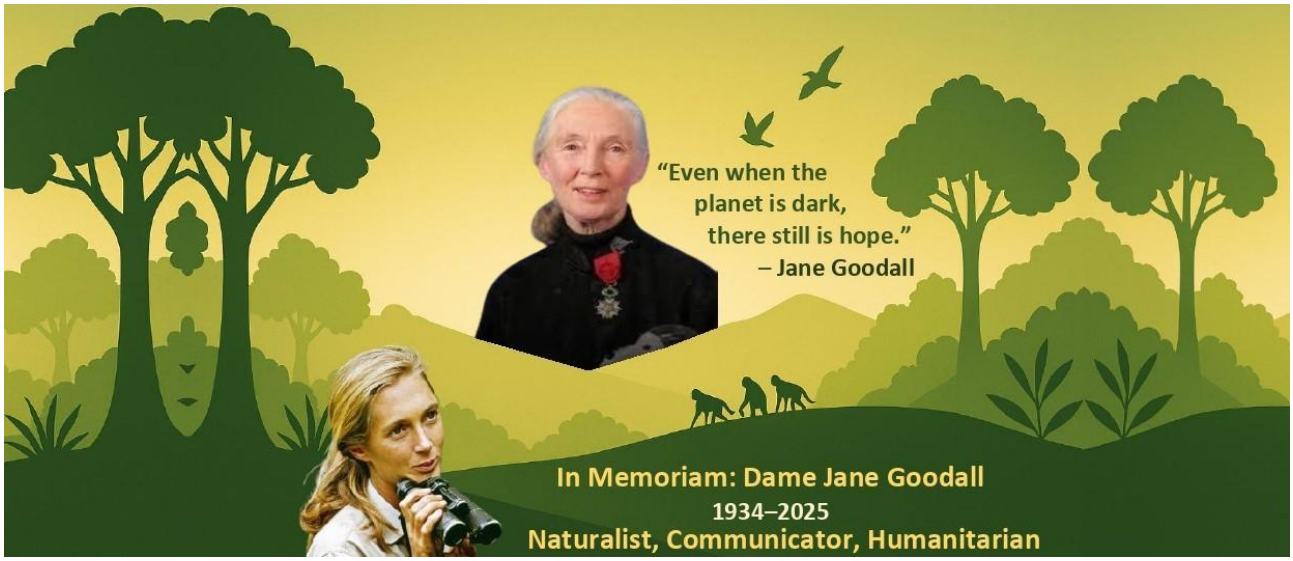
IN MEMORIAM

In Memoriam - Dame Jane Goodall, 1934-2025

This *In Memoriam* stands as both a reflection and a farewell to Dame Jane Goodall (1934–2025) — naturalist, communicator, and humanitarian. The graphical tribute, bathed in quiet greens and golds, evokes her lifelong harmony with the natural world and her message of hope when the planet seems dark. Goodall was not simply an observer of chimpanzees in Gombe but a reconciler of species, a woman who bridged the emotional distance between human beings and nature. Her gaze, her silence, and her patience became instruments of revelation. We recall her courage to challenge the hierarchies of science, her compassion and her conviction that change begins with daily acts of care. The forest silhouettes and the rising light in the composition mirror the continuity of her work — a reminder that, as she said, "Even when the planet is dark, there still is hope."



When a schoolgirl at Uplands, Poole, near Bournemouth, Jane Goodall seemed wrapped up in herself, somewhat separate from others, and this may well have become a strength in her long career as a primatologist. Self-possessed, she broke through the prejudices of male scientists to make discoveries. She may also be seen as an ethologist and anthropologist, but above all as a communicator of unifying ideas about human beings and nature. In this she resembles David Bellamy and Sir David Attenborough. Her travelling work for 300 days a year continued until the end of her highly productive life [1].

She is one of a long line of observers in British science, a naturalist, like Gilbert White, Charles Darwin, Charles Raven, David Attenborough, and Chris Packham. Her observations were so good that Louis Leakey persuaded Cambridge to admit her to take a doctorate, although she had no prior degrees, but merely an excellent set of skills as a trained secretary and her knowledge gathered from fieldwork.

Goodall accepted an invitation to visit the farm in Kenya of a friend, and seized the opportunity to introduce herself to Louis Leakey, because she wanted to study animals. Leakey believed that women would be better at studying primates than men, and so encouraged and mentored the fundamental work of Goodall, Fossey and Galdikas.

Goodall's study of chimpanzee behaviour in the Gombe forest, Tanganyika, led her to observe evidence for their being carnivores, and for using tools, notably a grass stem inserted into a termite mound. This produced a reaction which would lead to the capture of the termites as prey. She learned to approach chimpanzees with self-restraint and gentleness and befriended them, giving them names as if they were persons. Some criticized her for this. Others criticized her for recognizing that apes could approach human characteristics but were not equal to human beings [2-5].

Nevertheless, photographs show that Goodall's embrace with chimpanzees was almost sisterly or motherly and was full of love.

Her careful befriending of chimpanzees seems to have resulted from her childhood curiosity about animals and her ability to accept experience. In later years she seems to have had a mystical experience in Notre Dame, Paris [6], but her work did not cause her to take the road of a great palaeontologist and Jesuit, Pierre Teilhard de Chardin; who developed a theology and a philosophy which gave mystical interpretations to science and in particular evolution [7]. Goodall came from a Congregationalist family. She grew up in an all-female household when her father was on active service in World War II. This probably strengthened her self-reliance. When after the war her father and mother divorced, the father’s absence was not noticeable.

Goodall chose well by establishing her work in the United States. This allowed her to inculturate her fair, factual and creative thought in a way which could diffuse good through that complicated society.

The Jane Goodall Institute has developed the Roots and Shoots organization, which is a kind of Peace Corps making changes in line with Goodall's views; and another Institute endeavour is TACARE, targeting villages in Africa, promoting health, education, smart agriculture, and being environment-conscious [8].

Goodall's views included condemnation of human alpha males engaged in power politics [4]. These views were released by her direction only after her death. As she says,

"Even today, when the planet is dark, there still is hope. Don't lose hope. If you lose hope, you become apathetic and do nothing…"

"And if you want to save what is still beautiful in this world – if you want to save the planet for the future generations, your grandchildren, their grandchildren – then think about the actions you take each day. Because, multiplied a million, a billion times, even small actions will make for great change."

References

[1] https://www.thetimes.com/uk/obituaries/article/dame-jane-goodall-obituary-monkey-expert-n366fl8c0#:~:text=Dame%20Jane%20Goodall%20obituary%3A%20chimp%20expert%20dies%20aged%2091

[2] https://www.theguardian.com/science/2025/oct/02/dame-jane-goodall-obituary#:~:text=Dame%20Jane%20Goodall%20obituary

[3] https://www.nytimes.com/2025/10/01/science/jane-goodall-chimpanzees-career.html#:~:text=%E2%80%98There%20Will%20Always%20Only%20Be%20One%20Jane%20Goodall%E2%80%9

[4] https://www.theguardian.com/science/2025/oct/06/jane-goodall-trump-elon-musk-putin#:~:text=Jane%20Goodall%20said%20she%20would%20launch%20Trump%20and%20Musk%20on%20one%2Dway%20trip%20into%20space

[5] https://www.abc.net.au/news/2025-10-02/primatologist-jane-goodall-obituary/102197696#:~:text=Jane%20Goodall%2C%20who%20revolutionised%20our%20understanding%20of%20animals%2C%20dies%20at%2091

[6] https://news.janegoodall.org/2019/04/15/dr-goodalls-thoughts-on-the-fire-of-notre-dame/

[7] Teilhard de Chardin., P., 1965, The Phenomenon of Man - introduction by Sir Julian Huxley (London & Glasgow: Wm Collins Sons & Co. Ltd.).

[8] https://salempres.com>Media>SalemPress>samples>greatlives_21st_pgs.pdf

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drmichaelbrettcrowther@gmail.com

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