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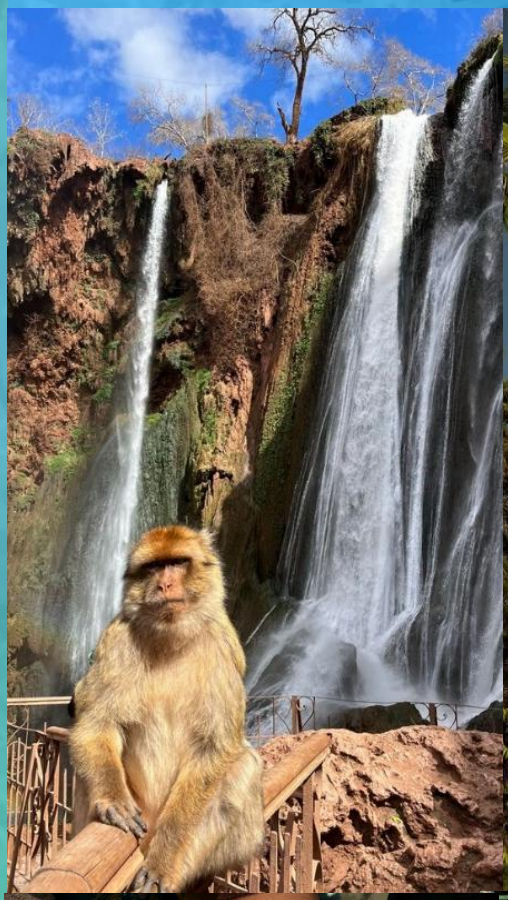

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The Enduring Moral Legacy of Pope Francis

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Pope Francis — the first pope from the Global South, the first Jesuit, and the first to bear the name of St Francis of Assisi — carried into the papacy a disarming humility and an uncompromising moral conscience, shaped by the struggles and hopes of South America. For twelve years, he was not only a reformer within the Church but one of the world's most trusted moral voices — confronting poverty, injustice, war, and exclusion without flinching.

The farewell he received on 26 April 2025 bore witness to the breadth of his impact: over 250,000 mourners filled St Peter's Square, with thousands more lining the streets of Rome. Leaders from across political and ideological divides gathered, and even groups historically opposed to the Church, such as Hamas and Hezbollah, issued condolence messages. It was not diplomacy that drew them together, but a shared recognition of a conscience that refused to be silenced by politics or prejudice. Francis's life invites us to walk the path of justice, compassion, and peace. He did not merely point to a better way — he walked it first.

A Papacy Rooted in Simplicity

From the moment he chose the name Francis — invoking the saint of poverty and peace — Pope Francis challenged the world's notions of power, wealth, and status. His papacy stood as a living reminder that leadership, at its best, is rooted not in spectacle but in service.

His decision to forgo the Apostolic Palace for the modest *Domus Sanctae Marthae*, to wear plain cassocks, and to travel in a Ford Focus rather than a papal limousine were not mere gestures. They were reflections of a spirituality that placed humility and human dignity at the centre of public life. His drive for Vatican reform — demanding transparency, enforcing financial accountability, and insisting that the Church embody justice in its structures — reflected the same moral clarity. In an age obsessed with image and dominance, Francis modelled a radically different path: true authority flows not from grandeur, but from solidarity; not from distance, but from closeness to the vulnerable. His life challenges all leaders to rediscover the moral power of simplicity, integrity, and authentic service.

A Voice for Our Common Home

In 'Laudato Si' (2015), Pope Francis offered one of the most radical teachings of modern papal history — an ecological encyclical grounded in the conviction that "the cry of the Earth and the cry of the poor" are one and the same. He challenged the world to see environmental destruction not as a distant scientific concern, but as a moral failure intimately tied to economic injustice, corporate greed, and indifference to the vulnerable.

For Francis, ecological degradation was inseparable from the exploitation of the poor. He refused the false choice between development and preservation, insisting instead on an "integral ecology" — a vision where environmental, social, and spiritual health must rise together, or fall together. 'Laudato Si' is an appeal to build an economy of care, a politics of stewardship, and a spirituality of interconnection that honours life in all its fragile, interwoven forms.

Voice of the Marginalised

Pope Francis warned consistently against the "globalization of indifference" — a world numbed to suffering and blind to injustice. He sought not merely to advocate for the poor, but to reposition them at the moral centre

of global conscience. This vision came alive through initiatives like the World Meeting of Popular Movements (WMPM), launched in 2014, which gathered slum dwellers, farmers, fisherfolk, and informal workers across continents. Francis affirmed their struggles as sacred rights — championing "*Techo, Tierra, Trabajo*" (Housing, Land, and Work) as essential pillars of dignity. In a world that discarded its most vulnerable, he called for a universal basic income and condemned economic systems that idolized profit.

His solidarity extended beyond economics. He embraced LGBTQ+ persons, prisoners, the differently abled, and those battling addiction — not as exceptions, but as integral members of the human family. His gestures, like washing the feet of migrants and prisoners, proclaimed that the Church must kneel before the wounded, not preach from a distance. Francis's legacy leaves a challenge far greater than philanthropy: to uphold justice for those underprivileged.

Listening to Indigenous Wisdom

Although many previous papacies emphasized mission and conversion, Pope Francis reoriented the Church's relationship with Indigenous peoples. He recognized them as custodians of ancestral wisdom and long-denied rights. In 2015, standing on Bolivian soil, he offered one of the Church's most direct acknowledgements of colonial violence: "Many grave sins were committed... in the name of God," he said — seeking forgiveness not just for history's wrongs, but for patterns of exploitation that still endure. This reckoning deepened with the Amazon Synod of 2019, where bishops, theologians, and Indigenous leaders gathered in Rome to address deforestation, extractive industries, cultural erasure, and climate collapse. Indigenous voices — often speaking in native languages — were treated not as ceremonial participants, but as witnesses reshaping the Church's moral vision.

Francis did not simply advocate for Indigenous rights; he repositioned their wisdom at the heart of the Church's moral vision. He leaves behind an appeal — to governments, corporations, and religious institutions alike — to move from gestures of repentance to structures of shared responsibility, and to recognise that humanity's future survival is inseparable from the survival of its first peoples.

Welcoming the Stranger: Refugee Crisis and Syrian Appeal

Many leaders hardened their borders and their rhetoric during the refugee crisis, but Pope Francis stood for openness, compassion, and shared humanity. His response — especially to the plight of Syrian refugees — was grounded in the radical belief in every person's dignity.

In 2015, as millions fled violence, he issued an urgent appeal: "May every parish, every religious community, every monastery, every sanctuary in Europe take in one refugee family." It was not a gesture of sentiment, but a call to convert empathy into shelter, compassion into policy. His visit to the Greek island of Lesbos in 2016 became a global symbol. Amid the desperation of refugee camps, he welcomed twelve Syrian Muslim refugees onto the papal plane, offering not a photo opportunity, but protection and care. It was a quiet yet forceful rebuke to rising nationalism and fear. He warned that societies which close their doors to migrants risk closing their hearts to humanity itself.

His life leaves us a test: will we continue to view the displaced as burdens to be managed, or will we dare to see them as neighbours?

Bridges Across Faith and Humanity

At a time when religious divisions were deepened by some, Pope Francis chose a different path — one of dialogue, humility, and fraternity. In 2019, he became the first pope to visit the Arabian Peninsula, signing the Document on Human Fraternity with Grand Imam Ahmed el-Tayeb of Al-Azhar in Abu Dhabi. "God does not want religions to fight each other," he declared — offering a vision of shared dignity over supremacy.

His 2021 visit to Iraq carried the same spirit. In Najaf, he met Grand Ayatollah Ali al-Sistani, one of Shia Islam's most revered clerics, in a quiet but powerful gesture of theological respect. In 2024, Pope Francis kissed the hand of Grand Imam Nasaruddin Umar, the leader of Jakarta's Istiqlal Mosque, in a gesture of mutual respect and interfaith solidarity. "*Istiqlal* Joint Declaration 2024," a document promoting religious harmony, environmental protection, a stand against violence and extremism was signed by both the leaders. In Bangladesh (2017), he broke protocol to name and embrace Rohingya refugees — affirming their humanity where political leaders remained silent. Whether in Egypt, Jordan, Turkey, Morocco, or Bahrain, his message was unwavering: dialogue is not weakness, but an act of moral courage.

Francis's outreach was not confined to religious divides alone. He addressed an extraordinary letter to *La Repubblica,* an Italian secular newspaper, affirming that conscience — not dogma — is the first guide for those seeking the good. "God's mercy has no limits if one turns to Him with a sincere and contrite heart," he wrote — an invitation that extended beyond believers to all who strive for justice and compassion.

His passing was mourned not only within the Catholic Church but across the broader human family — by Christians, Muslims, Hindus, Buddhists, atheists, and agnostics alike. In life and in death, he stood as a rare moral voice who spoke across the fractures of faith and ideology. Will we continue to build walls of fear, or will we dare to see in every stranger a fellow bearer of sacred dignity?

Moral Stand Against War and Violence

Pope Francis consistently raised a deeper moral alarm — refusing to normalise war, the arms trade, and militarised politics. He condemned the global arms industry, branding weapons manufacturers "merchants of death." He exposed how militarism perpetuates poverty and displacement, warning that every bomb dropped is a meal not served, a home not built. During the war in Ukraine, he called the invasion "a cruel and senseless war," urging moral clarity alongside humanitarian compassion. Yet he also warned: peace without justice is unsustainable, and justice without mercy risks becoming vengeance.

His stance remained uncompromising during the violence in Gaza and Israel. In his Easter messages of 2024 and 2025, he called for humanitarian corridors, an immediate ceasefire, and diplomacy grounded in human dignity. "Enough," he declared. "War is always a defeat." In Nagasaki, he declared that not only the use but even the possession of nuclear weapons is morally unacceptable. Will the world's powers continue worshipping the machinery of destruction, or choose the more difficult, life-affirming path of peace?

India's Struggles and the Echo of Conscience

Pope Francis never visited India, but his moral voice resonated across its spiritual and social landscape. In a country scarred by religious polarization, widening inequalities, and political manipulation, his call for justice, dialogue, and human dignity rang out not as distant rhetoric but as urgent moral witness.

His simplicity recalled the spirit of Mahatma Gandhi — a leadership grounded in humility rather than spectacle. His insistence on dignity for the marginalised echoed the vision of Dr B.R. Ambedkar. His openness to religious pluralism carried forward the ideals of Swami Vivekananda, who affirmed the sacredness of all faiths. At a time when dissent is stifled, democratic institutions weakened, and mistrust weaponized for political gain, Francis's life offers a difficult mirror to Indian society. Will faith continue to be a tool of exclusion, or become a force for justice, equality, and the protection of the vulnerable?

A Dream That Must Not Die

Pope Francis showed a form of leadership rare in an age of spectacle and cynicism. His strength lay not in power, but in moral clarity — the belief that justice, mercy, and dignity must shape the soul of public life.

Across twelve years, he redefined what it meant to be a global spiritual leader. He confronted inequality without rancour, bridged religious divides without compromise, and stood with the wounded without retreat. Whether facing war, ecological collapse, or the abandonment of the poor, he responded not with detachment, but with the courage of conscience. Today, in a world fractured by fanaticism, indifference, and manipulated truths, his life invites us not to choose the easier path of silence and division, but to bear the world's wounds, walk with the broken, and speak peace where silence tempts. His legacy is not just a memory, but a fragile hope — a hope that there will be others like him.

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Obituary: Christopher Charles Benninger

(23 November 1942 – 2 October 2024)

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Christopher Charles Benninger, architect and planner, died on 2nd October 2024, in Pune, India, after a long battle with cancer. Born in Ohio, USA, he chose to live and work in India from 1971 until his death. He upheld the concepts of *sustainable development and critical regionalism*. Barbara Ward, founder of the International Institute for Environment and Development (IIED), London, remained his lifelong mentor and counsel. Benninger has dedicated a library in her name in Pune, in the campus of the Centre for Sustainable Development and Activities (CSDA), which he founded in 1976. Ward's husband, Robert Jackson, who worked closely with the United Nations, gave Benninger a lifelong subscription to the journal *Ekistics -the science of human settlements,[See Note]* while Benninger was still a young student of a Bachelor of Arts course in Florida. Jackson also arranged for Benninger to attend UN Security Council meetings, as an observer. Young Benninger was also influenced by Frank Loyd Wright's architecture through his book, *The Natural House.[1]* As Benninger later recounted in his autobiographical book, *Letters to a Young Architect,[2]* he was fortunate in meeting several leading teachers and thinkers of the 1960s decade, who contributed to the philosophy of sustainable development. The list is long and covers more than 50 names, each of whom has left considerable impact on the fields of world architecture and urban planning.

Benninger received a master's degree in architecture from the Harvard Graduate School of Design, in 1967 and then a master's degree in city planning in 1971. He studied economics under John Kenneth Galbraith, past ambassador to India. His graduate thesis at MIT, *Some notes on cities and urban planning in India*, [3] was the beginning of his ideas on a sites and services approach for housing the urban poor.

In 1968, he had visited India as a Fulbright Scholar on recommendation by Josep Lluis Sert, principal at the Harvard school, to Balakrishna Doshi, founder director of the Centre for Environmental Planning and Technology (CEPT), Ahmedabad. In 1971, Doshi invited him to start a school of planning in CEPT. He joined as a Ford Foundation Consultant and stayed on to teach. His early projects focused on housing the poor in Jamnagar and Chennai, 2000 dwelling units for government employees in Hyderabad, and SOS Children's villages in Calcutta and Bawana. As a World Bank consultant, he planned for slum upgradation in Calcutta (1974), and a national rural development scheme for Indonesia (1979), He moved to Pune in 1976, with his wife Aneeta Gokhale, and founded CSDA. Together, they worked on several projects. CSDA prepared a pilot National Rural Integration Program for India, a plan of action for Bhutan's development (under the auspices of UNESCO), development plans for 6 cities in Sri Lanka (under the UNCHS). CSDA also prepared Area Development plans for Goa and Almora, and urban management and poverty upliftment plans for Thane and Kalyan. Benninger was a member of the Mumbai Port Trust Land Development

Committee. His planning expertise extends globally, contributing to projects for international organizations in India, Bhutan, Nepal, Sri Lanka, Malaysia, Indonesia, Kenya, and Zambia.

In 1993, he began a partnership with Ramprasad Akkisetti and together they established CCBA, an architecture and planning firm in 1995. He spent considerable time in Bhutan, preparing a structure plan for Thimpu, and other smaller towns, including Denchi. He also managed to persuade the Indian Government to plan for the development of towns along the India-Bhutan border. This was when Benninger developed his *principles of intelligent urbanism (PIU)*, consisting of 10 axioms. The PIU evolved from the city planning guidelines formulated by the International Congress of Modern Architecture (CIAM), the urban design approaches developed at Harvard's pioneering Urban Design Department under the leadership of Josep Lluis Sert, and the concerns enunciated by Team Ten. [4] The term was coined by Benninger and forms the basis of the course program in the School of Planning, CEPT, Ahmedabad. Benninger used these axioms for the planning of Thimpu, Bhutan and his other projects.

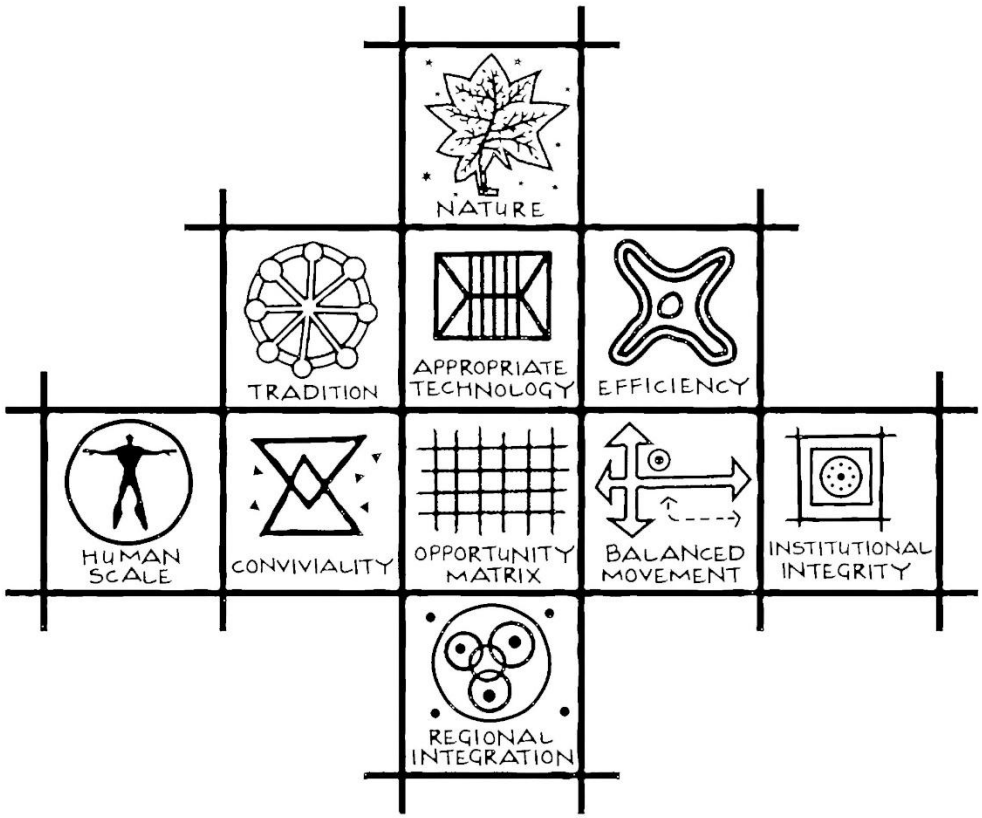

Figure 1. Principles of Intelligent Urbanism, Christopher Charles Benninger.

In the field of architecture too, Benninger has left his mark, as a prominent advocate of *Critical Regionalism.* His designs incorporate context, climate and cultural elements that create ambient and enduring environments. His notable projects are,

- Indian Institute of Technology, Hyderabad,
- Indian Institute of Management, Calcutta,
- Bajaj Institute of Technology, Wardha,
- Suzlon One Earth Global Headquarters, Pune,
- Mahindra United World College of India, Pune,
- Samundra Institute of Maritime Studies, Mumbai,
- YMCA International Camp in Nilshi,
- Kirloskar Institute of Advanced Management Studies, Pune,
- Azim Premji University, Bengaluru,
- 23 Metro Stations in Pune,
- Tata Institute of Fundamental Research, Mumbai.

The Suzlon headquarters campus stands out for its commitment to sustainability. It has received a LEED -Platinum rating and GRIHA five star certification (2009). The campus incorporates advanced systems for energy efficiency, water recycling and harvesting, and waste management systems. It uses 100% renewable energy from on-site photovoltaic panels and off-site Suzlon windmills.

Benninger's architectural firm, CCBA Designs, has produced over 300 projects across diverse sectors, including institutional, residential, industrial, health care, and master planning. Their work is characterized by a strong emphasis on sustainability and cultural context. Benninger's contribution to building significant environments that enrich life has been recognized across the world. Numerous awards have been conferred upon him, including the Great Master Architect Award and other multiple Lifetime Achievement awards, an Honorary Doctorate in Architecture bestowed upon him by CEPT University and the prestigious Baburao Mhatre Gold Medal 2024 by the Indian Institute of Architects (IIA).

Benninger's sense of a mission and his purpose to transfer what he learnt in his lifetime from numerous teachers and the challenges presented to him by his numerous projects, to future architects and planners is evident in his 2 books, *Letters to a Young Architect* [2] and its sequel, *Great Expectations: Notes to an Architect,[5]* published posthumously. He has also left as his legacy, the team of the CCBA Design firm led by 3 directors and over 50 professionals, who trained with him. It may be said that he achieved his mission, in his own words, *to place my footprint on this soil and to*

call this land my home, in a truly honourable way. CCBA has contributed selected works by Benninger to the CEPT Archives, where they may be accessed by students and researchers [6].

He is remembered well in India and will continue to inspire many future architects and planners.

Note: The renowned *Ekistics* journal (1957-2006), has evolved into a new on-line journal in 2019 as the International Journal of *Ekistics and the New Habitat: The Problems and Science of Human Settlements* . To know more about '*Ekistics, the science of human settlements',* developed by Constantinos A. Doxiadis, his paper published in *Science,* **170**, no.3956, October 1970, 393-404: 21 fig., may be accessed.

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LETTER TO THE EDITOR

Bankruptcy and Environmental Policy? Sounds Like a Job for the Fashion Police

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To the Editor,

We read with great concern the article by Copley *et al.* [1] on the Environmental Protection Agency's plans to target over two dozen environmental regulations. We also recognize that on Sunday March 16, 2025, American clothing retailer Forever 21 filed for bankruptcy for the second time due to increasing online retail competition [2].

The EPA's changes were not detailed; it is clear that the agency appears to be contradicting its original purpose to ensure environmental protection [1]. We may surmise from these changes that there will be less investment in sustainable business models, especially in the fashion industry. The result will be more pollution from textile factories, increased microplastic waste from synthetic clothing, and higher carbon output from fast fashion production. Fast fashion is a system that encourages disposability in an unsustainable business model [3]. This trendy model has encouraged international business as outsourcing manufacturing to low- and middle-income countries, such as China, allows for cheaper textiles to be mass produced [3]. Fashion brands that both manufacture and retail at the same time, such as the online retailers Shein and Temu, are able to have a rapid product cycle, which increases the variety of clothing available to consumers. In turn, they can keep up with the rapidly changing trends where last week's stock is quickly discarded and adds to growing textile waste [3].

The administration is pushing for changes quickly, with rules expected to change in the next few weeks [1]. These EPA changes are not just harmful to environmental health, but also greatly harmful to public health. Although this may seem like a business move to boost the economy, the only anticipated growth is an increase in environmental chemicals and carcinogens, especially

affecting vulnerable populations such as pregnant women and children [1]. This is very far from the intended purpose of the EPA.

The closure of Forever 21 highlights the model of fast fashion - continual growth. Unfortunately, the bankruptcy does not necessarily mean a decline in fast fashion but simply shows even greater competition in the form of faster-fashion retailers, such as Shein and Temu. As Shein and Temu are online international stores, there will be a growth in the carbon footprint of the clothing supply chain. The new US waiver of standard customs procedures and tariffs on imported items helps Chinese companies (Shein and Temu) keep costs low, while raising shipping costs for American retailers, such as Forever 21 [2]. There were many weak points in Forever 21's business model, but ultimately, it could not keep up in the fast-fashion market, where there are faster and cheaper alternatives.

We recognize that the EPA's changes could foster more aggressive growth of fast fashion. Consumers and retailers show no signs of slowing down. As observers of this developing danger, we advocate the reinforcement of environmental regulations, especially for large fast-fashion companies, as well as continued education, so consumers can make informed decisions with how they want to spend their money. We note that the sustainability idea expresses realism, since it is obvious to many - even many in the United States - that continual growth is impossible.

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Yours truly,

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Application of Machine Learning for Prediction of Solid Waste Generation

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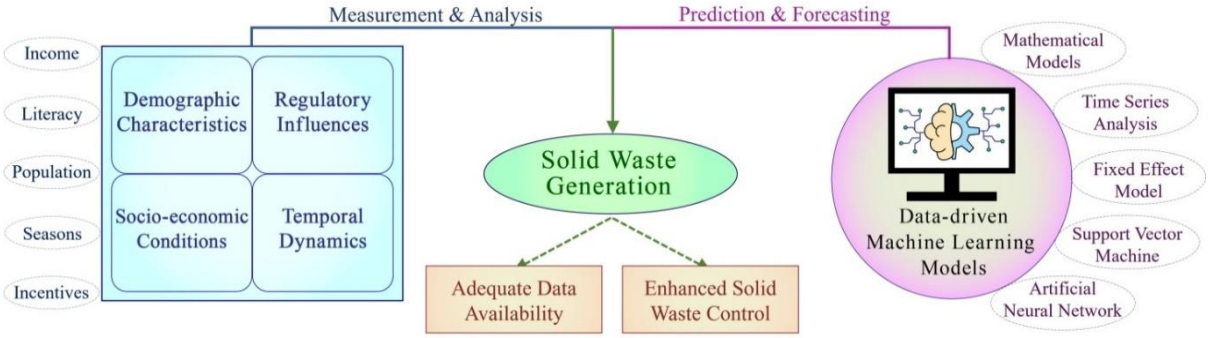
Graphical Abstract

This article provides a comprehensive review of both standalone and hybrid machine learning (ML) methodologies, emphasizing their applications in waste generation forecasting. It further examines the critical factors influencing waste generation, including demographic, regulatory, socio-economic and temporal characteristics. The use of ML in solid waste prediction modelling results from the growing complexity of influencing parameters and the expanding availability of relevant datasets.



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Abstract: Effective solid waste management requires adaptive planning and accurate forecasting of waste generation and composition. Accurate predictions require a deep understanding of key influencing factors, including population, urbanization, income, and temporal effects, which impact waste trends. Traditional models, including regression and fixed-effects analysis, struggle to capture these complex, non-linear relationships. Recently, machine learning (ML) techniques have emerged as powerful tools, leveraging large datasets and advanced computational methods to improve predictive accuracy. Nonetheless, challenges like data limitations, regional variability, and scalability hinder their practical implementation. This review explores and summarizes the significance of the essential factors for predicting solid waste generation and emphasizes new opportunities for real-time waste monitoring by integrating ML with emerging technologies like the Internet of Things (IoT). Enhanced sustainable waste management needs advances in model generalisability, data quality, and policy integration.

Keywords: *Solid Waste, Machine Learning, Prediction Model*

Introduction

Solid waste generation is a pressing global challenge, with profound environmental, economic, and public health implications. Currently, about 2 billion tonnes of municipal solid wastes (MSW) are produced globally per year, and it is projected to rise to 3.4 billion tonnes by 2050—driven by rapid urbanization, population growth, and industrialization [1]. This unregulated and poorly managed waste disposal greatly worsens pollution, impacting air, soil, and water quality, leading to severe health issues, environmental degradation, and contributing to greenhouse gas emissions, consequently amplifying climate change effects [2, 3]. For instance, untreated waste near freshwater sources introduces harmful contaminants, causing widespread pollution and threatening aquatic ecosystems [4, 5]. Similarly, the growing complexity of waste composition makes treatment more difficult [6, 7]. Allocating adequate resources for waste collection, and determining waste collection routes necessitate adequate spatial, population, and waste density data. Similarly, the selection and management of landfill sites depend on the availability of data on solid waste generation and composition. The economic viability of material recovery facilities (MRFs) and waste-to-energy (WtE) plants further depends on precise and reliable data regarding waste generation rates and material composition. Therefore, the datasets available from various forecasting models enable effective data-driven strategies and evidence-based policies to mitigate health risks, and enhance resource recovery. Ultimately, this contributes to achieving Sustainable Development Goals (SDGs), including clean water and sanitation (SDG 6), responsible consumption and production (SDG 12), and climate action (SDG 13) [8].

Reliable predictive analysis is necessary to achieve efficient and sustainable waste management data-driven initiatives. The forecast outputs from such predictive modelling enable waste management authorities to optimize resources for collection and treatment systems, and design policy interventions that tackle adverse environmental impacts. Without reliable forecasting methods, cities risk underestimating waste volumes, leading to inefficiencies in waste treatment infrastructure and increased pollution. Traditional methods, such as correlation analysis and statistical models, have provided crucial insights into waste trends in the past but often fail to capture the intricate relationships between socio-economic and demographic variables influencing waste production [9, 10].

These models typically rely on factors such as average waste generation per capita and population growth only as the primary predictors [11], making them inaccurate for multidimensional scenarios. Additionally, the limited scope of input variables constrains the ability of predictive models to account for variations in industrial waste generation patterns.

Unlike household waste, which follows relatively consistent consumption behaviours, industrial waste is influenced by sector-specific activities, production cycles, and regulatory frameworks, making it more complex to predict with standard forecasting models.

In recent years, machine learning (ML) has become widespread across various geographical regions worldwide, including Australia [12], Turkey [13], Vietnam [14], China [15], and Malaysia [16], and Ghana [17]. ML's adoption stems from its ability to rectify the drawbacks of conventional methods, and to capture non-linearity, high-dimensionality, and dynamic changes in waste generation. By leveraging large datasets and advanced algorithms, ML models can predict waste generation and composition trends with greater accuracy and adaptability [18]. ML applications in solid waste management include forecasting waste generation trends, classifying waste based on composition, optimizing collection routes, predicting best waste treatment methods, and improving resource recovery, aligning with circular economy principles [19, 20]. Studies across numerous regions, have demonstrated the potential of ML models such as Artificial Neural Networks (ANNs), Decision Trees (DTs), Support Vector Machine (SVM), Random Forest (RF), and Gaussian Process Regression (GPR) in enhancing waste management practices [12-17]. Such models can not only predict MSW generation but also address secondary challenges such as landfill leachate management and contamination risks, thereby supporting sustainable urban development [21].

Although there have been numerous modelling efforts and successes in specific regions, a substantial gap still exists in accurately predicting global solid waste generation and composition. There is need for a global model because of the increasing interconnectivity of economies, trade, and waste management policies, which necessitate a broader understanding of waste generation patterns. An extensive literature review revealed that most studies have concentrated on forecasting MSW within a single region or country, with only a limited number incorporating multi-national data for model development. To date, the only existing global model [19] has considered the parameters such as respective GDP, Population Size, Population Density, Household (HH) Size, Educational Attainment Levels, and Unemployment Levels; this resulted in a moderate R^2 value ranging from 0.61 to 0.68 at the country level, highlighting the need for further advances in predictive accuracy. Another multi-regional study [10] on Organization for Economic Co-operation and Development (OECD) countries also failed to consider important factors such as literacy rate, urbanization, etc. Therefore, incorporating key influencing variables, expanding datasets for diverse contexts, and designing dynamic models for enhanced predictive accuracy is crucial.

This present review mainly explores key influencing factors, including population growth, urbanization levels, income levels, HH sizes, seasonal variations, and waste collection efficiency, signifying the requirement of their inclusion while developing a solid waste trend prediction model. It also examines the progression of solid waste prediction models, tracing their general development from traditional approaches to advanced hybrid models, with a particular emphasis on the role of ML in tackling global waste management challenges. Furthermore, the review discusses the potential challenges associated with applying ML in solid waste prediction in real-world scenarios. The study provides a solid basis for future improvements in model generalisability, data accuracy, and policy integration to strengthen sustainable waste management.

Models Developed for Solid Waste Prediction

The increasing complexity of waste streams and their environmental impacts have driven significant advances in predictive modelling for solid waste generation. Although traditional statistical methods have been widely applied, ML techniques have revolutionised waste prediction by enhancing accuracy and adaptability. Various studies have explored different modelling approaches, with notable variations in performance, based on dataset size, model complexity, and methodological frameworks. Table 1 reviews those key studies on different solid waste prediction models, and highlights the input parameters adopted, models used, data used, output parameters, and the evaluation matrices of those studies.

Table 1. Comparison of solid waste generation prediction models across different regions.

Locations	Models used	Input Parameters	Data Used	Output Parameters	Evaluation Matrices	Reference
Mexican city	Mathematical (Statistical) Model	Avg. education per HH, No of residents per HH, Income per HH	52, 53 & 56 HH for 1st, 2nd & 3rd stage	Per-capita production of residential solid waste (RSW) per day	R^2 = 0.45 for 2 variables, 0.5 for 3 variables & 0.51 for 4 variables	[9]
Mashhad, Iran	Feedforward ANN model	Weekly waste generation, No. of waste-carrying trucks	From 2004 to 2007	Weight of MSW generation	Best R^2 = 0.938 in training, 0.716 in testing	[22]

Guwahati, Assam, India	DT, RF, gradient boosting (GB)	demographic and socio-economic parameters	Data size=1936	MSW generation	R2 for GB, RF and DT = 0.981, 0.972 and 0.967, respectively	[23]
Vietnam	RF, kNN	urban population, average monthly income per person, Average size of home per person, population density etc.	detailed data =63 sets abridged data =189 sets	total solid waste collected per day	R^2 for kNN=0.96 RF=0.97	[14]
China	XGBoost, SVM, RF	Population, Urban Population %, HHs, HH Size, Gender Structure, Age Structure, per capita Disposable Income, GDP, GDP/Capita, etc.	From 2000 to 2019	MSW generation	R2 for XGBoost=0.9450 RF=9264 SVM=0.8269	[15]
Turkey	GPR Bayesian optimisation (BO)	Population, Inflation rate, GDP per capita, and Unemployment rate	From 1994 to 2017	Municipal waste generation	R^2 = 0.9914 in training, R^2 = 0.9841 in testing	[13]
Malaysia	GPR, Ensembles of trees, feedforward ANN	GDP, Population, Age groups, Employment and unemployment rates,	From 2012 to 2020	Annual solid waste generation	R^2=1 for GPR	[16]
Logan city, Australia	ANFIS, ANN, SVM & kNN	Population growth, Avg. per capita waste generation	From July 1996 to June 2014.	Monthly MSW Generation	R^2 = 0.98 for ANFIS, 0.71 for SVM, 0.46 for ANN	[12]
	Time Series Analysis	Waste Generation of current year		Waste Generation of next year		
OECD countries	Fixed-effect model FGLS model	Average HH size, No. of children in the HH, No. of working age people, Population in urban areas	From 1980 to 2000	Generation of HH Solid Waste	R^2 within 0.5649 and 0.1215; overall = 0.3370	[10]
Global	MLR & AM	GDP, Population, Population Density, HH Size, Education, Unemployment	Not specified.	Total Waste Generation	R^2 = 0.61–0.68 for country level	[19]

In the Mexican city study, a Regression Analysis model was employed to examine the relationship between socio-economic factors (education and income) and per capita waste generation [9]. Even though the predictive accuracy slightly improved with a comparatively large sample size, because of limited data availability it demonstrated relatively low predictive accuracy (R^2 ~ 0.51). Similarly, a study in Mashhad, Iran, used weekly MSW data collected from 2004 to 2007 in order to develop a Feedforward ANN prediction model and analyse non-linear patterns in weekly waste generation and transportation data [22]. Although the ANN model achieved strong predictive performance during training (R^2 = 0.938) its performance declined significantly in testing (R^2 = 0.716), indicating potential overfitting and challenges in generalization. In contrast, studies leveraging extensive, long-term datasets and advanced ML methodologies achieved significantly higher predictive accuracy. A study in Turkey, with data collected from 1994 to 2017, applied GPR with Bayesian Optimization (BO), successfully integrating multiple socio-economic indicators and optimizing hyper-parameters, resulting in exceptionally high R^2 values (>0.98 in both training and testing) [13]. In Guwahati, India [23], models like Gradient Boosting (GB), Random Forest (RF), and Decision Tree (DT) were trained on a dataset of 1,936 records, with GB achieving the highest R^2 of 0.981.

Research in Vietnam [14] used RF and k-Nearest Neighbours (kNN) to predict total solid waste collected per day based on variables like urban population, income, and consumption patterns, achieving R^2 values of 0.97 (RF) and 0.96 (kNN). In China [15], XGBoost, RF, and Support Vector Machine (SVM) were employed to analyse MSW generation from 2000 to 2019 using factors such as GDP, household size, and income levels, where XGBoost performed best with an R^2 of 0.9450. Furthermore, Abbasi *et al.* [12], using the monthly time series MSW generation data of eighteen years in Logan City, Australia [12], demonstrated that hybrid approaches, particularly Adaptive Neuro-Fuzzy Inference Systems (ANFIS) (R^2 = 0.98), outperformed standalone ML models such as ANN (R^2 = 0.46) and SVM (R^2 = 0.71), emphasizing the importance of adaptive learning frameworks in capturing complex waste generation dynamics. In Malaysia [16], machine learning models, including Gaussian Process Regression (GPR), Ensembles of Trees, and Feedforward Artificial Neural Networks (ANN), were used to predict annual solid waste generation from 2012 to 2020. The study incorporated socio-economic indicators such as GDP, population, age distribution, and employment rates. Among the models tested, GPR achieved an exceptional R^2 value of 1, indicating a perfect fit to the data. This suggests that GPR effectively captured the underlying patterns in waste generation trends, emphasizing its potential for high-accuracy forecasting in solid waste management.

On a macroeconomic scale, studies employing statistical models to analyse regional waste trends exhibited comparatively lower predictive capabilities. A fixed-effect model—a statistical technique controlling unobserved heterogeneity, assuming time-invariant characteristics of individuals or entities do not vary over time—and a Feasible Generalized Least Squares (FGLS) model—another statistical method to estimate the parameters of a regression model—were employed on OECD countries in order to assess the impact of factors such as HH size and urban population on MSW generation [10]. But, with overall R^2 values as low as 0.3370, the study highlights the limitations of traditional econometric models in capturing non-linear and region-specific waste generation patterns. Collectively, these findings indicate that model performance is contingent upon dataset comprehensiveness, the complexity of input variables, and the capacity of ML algorithms to accommodate regional variability and temporal fluctuations.

Influencing Factors in Waste Prediction

There are several variables that collectively influence and shape solid waste production trends and composition. These factors can be grouped into distinct categories, such as demographic, economic, policy & infrastructure, and environmental & temporal elements, each influencing waste production in unique ways. As illustrated by Table 1 and Figure 1, solid waste prediction models must account for a variety of factors that shape waste generation patterns.

Demographic Factors

Population Growth

Population growth increases waste generation, as a rising population leads to higher consumption and disposal activities. Models from Turkey [13], Australia [12], China [15], Malaysia [16], and the global model [19] etc. have used this parameter as a primary predictor for waste generation, revealing that densely populated areas experience greater demand for goods and services, which in turn results in higher volumes of MSW.

Household (HH) Size

The effect of HH size has been incorporated in studies such as those from OECD countries [10], a Mexican city [9] and China [15] as well. Additionally, the global study [19] and Vietnam model [14] have included HH size as a crucial parameter in their modelling since HH size is a significant determinant of per capita waste generation. Larger households typically produce less waste per individual, as resources such as food, packaging materials, and household goods are shared among multiple members. This phenomenon, often referred to as the "economies of

scale" in household consumption, results in a lower per capita waste output despite an overall increase in total waste generation as household size expands.

Literacy Rate

With literacy rate adopted as a major influencing factor in the global model [19], generally, higher literacy levels are shown to be linked to improved waste management practices, including better waste segregation, increased awareness of sustainable consumption, and greater adherence to recycling initiatives. Higher educational attainment is often accompanied by increased income levels, which can lead to greater consumption of packaged goods, electronic devices, and other materials. This, in turn, contributes to a rise in packaging waste and electronic waste (e-waste). Consequently, although higher literacy can promote more effective waste management, it may also inadvertently lead to an overall increase in waste generation. Furthermore, literacy rate, as a parameter, remains an underused factor in many prediction models.

Urbanisation Trends

As indicated by OECD model [10], Vietnam model [14], and China [15], urbanization significantly influences waste generation by increasing the diversity and volume of waste streams, particularly non-biodegradable materials such as plastics and electronic waste (e-waste). Urban areas typically exhibit higher levels of industrial, commercial, and consumer activity, leading to increased consumption and disposal of packaged goods, electronics, and other manufactured products. Moreover, the correlation between urbanization and economic growth, measured by Gross Domestic Product (GDP), further amplifies waste production, as rising incomes and improved living standards drive higher consumption rates. As a result, managing waste in rapidly urbanizing regions requires robust infrastructure, efficient recycling systems, and sustainable waste management policies to mitigate environmental impacts. This parameter has not been used in most of the prediction models so far, which thus could be an opportunity to explore in future studies.

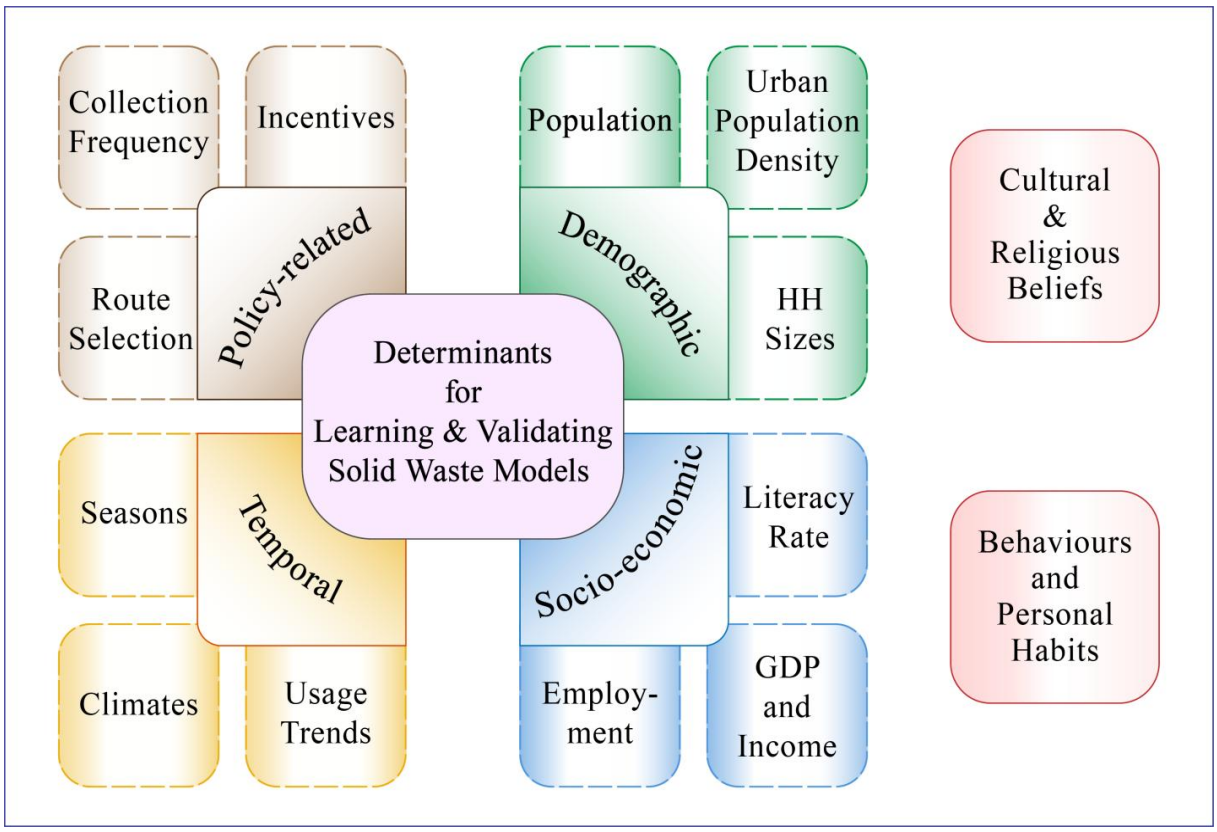

Figure 1. Key factors influencing waste generation categorised into demographic, economic, policy-related, and temporal variables, illustrating their interdependencies.

Socio-economic Factors

Income Levels

The impact of income levels has been explored in the study from a Mexican city [9] in 2008 and in Vietnam model [14]. Those studies emphasized that higher-income households typically generate more non-biodegradable waste, including plastics, metals, and electronic waste, because of the increased consumption of packaged and luxury goods. Conversely, lower-income households may produce more organic waste, but less packaging waste, as their consumption patterns are often limited to essential goods. Moreover, wealthier populations may have better access to waste management services, affecting waste disposal behaviour. Global data [1] indicate that high-income countries tend to have a lower proportion of organic waste in their overall waste composition than do lower-income nations.

Gross Domestic Product (GDP)

Economic growth, often mirrored by an increase in GDP, is associated with higher consumption, which in turn raises the demand for goods and packaging, thus contributing to waste generation. The relationship between GDP and waste production is not linear, as indicated by models from Malaysia [16] and the global model [19], since higher GDP per capita often correlates with shifts in waste types, such as an increase in electronic waste (e-waste) [1].

Employment Rates

Higher employment levels contribute to increased generation of industrial, office, and commercial waste because of greater economic activity and business operations. Household waste production may decline during working hours as people spend less time at home generating waste. This temporal shift in waste generation patterns poses challenges for waste collection schedules and resource allocation for waste management services. At the same time, higher employment rates enhance individuals' purchasing power, potentially leading to greater consumption of packaged goods and, consequently, an increase in solid waste generation. Additionally, changes in consumption patterns may alter the composition of waste, influencing the proportion of different waste types. The study from Turkey [13] and Malaysia [16] assessed these effects on waste generation trends. Since the Covid-19 pandemic, working at home has become normal, in many countries and this complicates the assessment.

Inflation

Inflation could affect waste generation patterns in complex ways, varying across different income groups. For lower-income households, rising prices may limit overall consumption, leading to a reduction in waste generation. Inflation-driven fluctuations in food prices can also contribute to increased food waste, as consumers may over-purchase perishable items when prices are low or discard food that becomes unaffordable to store and consume efficiently. Additionally, inflation can influence packaging waste as manufacturers may alter product sizes or packaging materials to offset rising production costs, potentially impacting waste composition. The model from Turkey [13] attempted to establish a relationship between inflation and MSW using GPR BO, but its effects on solid waste generation and composition remain underexplored.

Policy & Infrastructure Factors

Waste Collection Efficiency

The effectiveness of waste collection systems is apparent in the lack of illegal dumping and the unregulated accumulation of waste, particularly in areas with inadequate waste management infrastructure. Efficient collection also plays a significant role in the segregation of solid waste at the source, directly influencing the accuracy of waste composition data. Additionally, government regulations and policies on waste segregation, recycling, and disposal are key determinants of waste generation patterns. Strict policies, such as mandatory source separation, and landfill bans on specific materials, can substantially reduce the volume of waste destined for landfills, promoting more sustainable waste management practices. Nevertheless, these are theoretical opinions, since it is well known that the United Kingdom is afflicted with illegal dumping in many areas and with a wide range of undesirable refuse materials.

Regulatory Policies

Policies on waste segregation, recycling, and disposal affect both the amount and type of waste generated. Strict regulation can reduce the volume of waste through recycling initiatives and efficient waste treatment technologies. Again, these are theoretical views.

Incentive in Waste Management

Incentive-based waste management strategies, such as pay-as-you-throw away (PAYT) systems, tax rebates for recycling, and deposit-return schemes, encourage responsible waste disposal and reduction. Financial incentives can influence consumer and industrial behaviours, promoting waste minimization and higher recycling rates. Governments and municipalities implementing subsidies for composting, landfill taxes, and producer responsibility programmes have demonstrated improvements in waste segregation and resource recovery.

Environmental & Temporal Factors

Seasonality

Seasonal variations significantly influence waste generation patterns as consumption behaviours fluctuate throughout the year. Organic waste typically increases during harvest seasons and food-related festivals; packaging waste and discarded consumer goods peak during holidays and major shopping events. Additionally, seasonal tourism in certain regions can lead to temporary spikes in waste production, posing challenges for waste collection and disposal systems.

The frequency of organic waste collection also varies with seasonal changes. In warmer months, organic waste requires more frequent collection because of its higher decomposition rate at elevated temperatures, which can accelerate odour generation and attract pests. Moreover, residential organic waste tends to increase in hot weather, as stored food spoils more quickly compared to colder seasons. Understanding these seasonal trends is essential for optimising waste management strategies, ensuring efficient resource allocation, and maintaining environmental hygiene. Since comprehensive data on seasonal variations of solid waste are lacking, this is still an underexplored factor in prediction modelling.

Climate Change and Global Warming

Climate change affects waste generation, decomposition rates, and emissions, particularly methane released from landfills and plastic degradation in marine environments. Rising temperatures accelerate organic waste decomposition, increasing greenhouse gas (GHG) emissions, and extreme weather events disrupt waste collection and disposal systems. The integration of ML in climate-adaptive waste management can optimize waste processing by predicting landfill emissions and improving the efficiency of waste-to-energy (WtE) facilities which can help to mitigate environmental impacts, and can generate economic benefits [24].

Trends in Waste Management

Recent trends in waste management focus on circular economy models, zero-waste initiatives, and AI-driven waste sorting technologies. The shift from linear disposal systems to sustainable waste processing, such as biodegradable packaging, extended producer responsibility (EPR), and AI-powered robotic sorting, is reshaping global waste management practices. Several cities around the world have successfully deployed IoT-enabled smart bins that provide real-time waste data [25]. Integrating ML with these IoT systems allows for dynamic waste collection scheduling, reducing operational costs and improving efficiency. Advances in the blockchain for waste tracking, IoT-enabled smart bins, and decentralized waste treatment are further improving efficiency, transparency, and sustainability in modern waste systems.

Interaction Effects and Non-linear Relationships

Waste generation is often influenced by non-linear interactions between these factors. For instance, the combined effects of urbanization and rising GDP have been shown to cause a significant increase in the generation of e-waste. ML models excel at detecting these complex, non-linear relationships and can provide more accurate forecasts by capturing these interactions, which traditional models might overlook.

As seen in Table 1, solid waste prediction models have mainly incorporated population growth, GDP per capita, household size, urbanization, and income levels, as these variables exhibit strong correlations with waste generation patterns. Less frequently considered factors, such as waste collection efficiency, seasonality, unemployment rate, literacy rate, and inflation, have been included in selective studies but remain underused. Conversely, key determinants, including cultural influences, incentive-driven waste management policies, behavioural and personal habits, and climate variability, have yet to be integrated into predictive frameworks despite their potential significance. Incorporating these underexplored parameters could enhance model robustness, predictive accuracy, and applicability across diverse waste management contexts.

Discussion

The present review of global studies on solid waste prediction modelling emphasizes the growing role of ML techniques in overcoming the limitations of traditional statistical models. Conventional approaches, such as MLR and fixed-effects modelling, have provided valuable insights into regional waste generation trends by correlating socio-economic factors, such as income, education, and HH size, with waste generation.

But, these methods often struggle with non-linear relationships and high-dimensional datasets, as observed in studies from OECD countries and on a Mexican city [9, 10]. In contrast, ML models, including ANN, Support Vector Machine (SVM), and GPR, offer superior adaptability and higher predictive accuracy. For example, ANN has been widely used in regions such as Iran and Australia, where it effectively captures the complex interdependencies among variables like waste transport data and population growth [12, 22]. Moreover, BO improves ML models by automatically adjusting hyper-parameters to minimize prediction error. In the Turkish study, this technique enhanced the GPR model's ability to integrate socio-economic indicators, improving accuracy over standard regression techniques. Input parameters such as GDP, urbanization, population density, and demographic attributes have also emerged as critical determinants of waste generation and composition.

For example, higher GDP levels are often associated with increased non-biodegradable waste because of shifts toward packaged goods, and urban areas tend to produce diverse waste streams driven by industrial and commercial activities [13]. Therefore, illustrating these parameters, Figure 1 highlights the importance of the integration of macro-economic indicators and individual behaviours also, which are often overlooked but significantly influence waste patterns [26]. Despite all the potential that ML application has shown in recent years for solid waste

generation prediction, the required accuracy in predicting the amount and composition of solid waste has not yet been achieved.

Data Pre-processing Challenges

One of the core challenges in ML-based waste prediction modelling is the pre-processing of data. Waste datasets, particularly from developing regions, often suffer from missing values, inconsistent reporting, and poor data quality. It is desirable to have sensitive pre-processing techniques, such as imputation methods to fill in missing data, normalization to scale input features consistently, and data augmentation to increase the dataset size artificially. For instance, imputation can use the mean, median, or more advanced techniques such as kNN to handle missing data points. Normalization techniques, such as Min-Max scaling or Z-score standardization, are essential to ensure that variables with different units (e.g., GDP vs. waste volumes) do not disproportionately affect a model's performance. Addressing these pre-processing challenges is critical for improving the accuracy and robustness of ML models in waste prediction.

Regional Adaptability of ML Models

ML models demonstrate significant promise, but their effectiveness is often region-specific, which limits their transferability across different geographical locations. This limitation arises for several reasons:

Data Availability

In many regions, particularly in developing countries, there is a lack of consistent and comprehensive datasets that are necessary for the training of robust ML models. Data gaps often result in models that are less accurate or even biased when applied to new regions. Bias in ML-based waste forecasting arises from data collection inconsistencies. For example, in developing regions, informal waste disposal may not be recorded, leading to underestimations in prediction models.

Waste Categorisation Methods

Waste categorization methods vary significantly across regions, leading to discrepancies in how solid waste is classified. Some areas may classify waste into only two categories - organic and inorganic - but others may adopt a more detailed classification, distinguishing between various types of non-biodegradable materials such as plastics, metals, paper, and electronics, or even based on how the waste is processed. These differences in classification systems can have a

considerable impact on the performance of ML models, especially if they are trained on datasets with varying categorization approaches. Inconsistent waste categorization can affect the accuracy and generalizability of prediction models, making it essential to standardize classification methods for more reliable and comparable results in waste management studies.

Cultural Influences and Personal Habits

Consumption patterns, waste behaviours, and recycling habits are deeply influenced by cultural and personal habits, which can vary widely across regions. For example, countries with a higher number of festivals may generate more waste compared to those with fewer festivals. This does not seem to affect France, which has more festivals than the United Kingdom. The religion and cultural habits are rooted directly in waste generation and more so in the composition and variety of waste. These differences must be considered when adapting models to different regions.

Hybrid ML Models

To address the challenges posed by complex and multi-variable datasets, hybrid ML models have emerged as a promising solution. Hybrid models combine the strengths of different ML techniques, offering better accuracy and more reliable predictions than single-method models. For example, combining ANN with time series forecasting models enables better prediction of waste generation over time, particularly in the face of temporal fluctuations such as seasonality and economic cycles. The ANN approach possesses the ability to capture the non-linear relationships among input variables because of their hidden layers and complex nature, while the time series component accounts for temporal dependencies in the data. Similarly, SVM can also be integrated with BO techniques to fine-tune model parameters and improve prediction performance, particularly in datasets with complex, non-linear relationships. This hybrid approach has been applied successfully in studies [13] in order to enhance the robustness of waste prediction models by optimizing kernel functions and hyper-parameters for better accuracy. Studies incorporating hybrid ML models, such as the combination of ANN with time series methods or SVM with BO, have demonstrated improved prediction accuracy and greater adaptability across diverse datasets [5, 20]. These models have shown promise in overcoming the limitations of traditional models and enabling more precise and scalable waste management solutions.

Conclusions and future research direction

This study surveys the challenges in implementing ML for effective solid waste management while highlighting possible strategies to enhance ML-based models in both local and global contexts. In summary, integrating prediction models with technologies like deep learning and big data analytics offers transformative potential for waste management by improving prediction accuracy, optimizing collection routes, and enhancing recycling efficiency. The performance of machine learning models depends on dataset quality, making waste disposal predictions highly sensitive to the availability of waste data and the efficiency of the data collection process [27]. Other issues such as scalability challenges, high computational requirements and region-specific adaptations, must be addressed through cloud computing and decentralized approaches. Moreover, AI-based predictive models can support evidence-based policymaking, enabling more efficient waste collection strategies, recycling incentives, and sustainable waste management practices.

Future research should prioritize the development of hybrid ML models that integrate deep learning and ensemble techniques to enhance predictive accuracy and adaptability. The incorporation of IoT-enabled smart sensors can enable real-time waste monitoring, facilitating dynamic optimization of collection and disposal systems which helps to reduce data inadequacy. Additionally, globally adaptable models should be designed to account for regional variability by incorporating socio-economic and behavioural factors that influence waste generation patterns. AI-driven frameworks should also be explored to advance waste reduction strategies, promote the circular economy and waste-to-energy principles, and improve resource recovery efficiency. Finally, addressing data-related challenges such as standardizing waste classification, improving pre-processing techniques, and filling data gaps will be essential for ensuring the reliability and applicability of ML models in sustainable waste management.

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Pyrolysis of the Plastics: Catalysts, Product Applications, and Techno-economic Assessment

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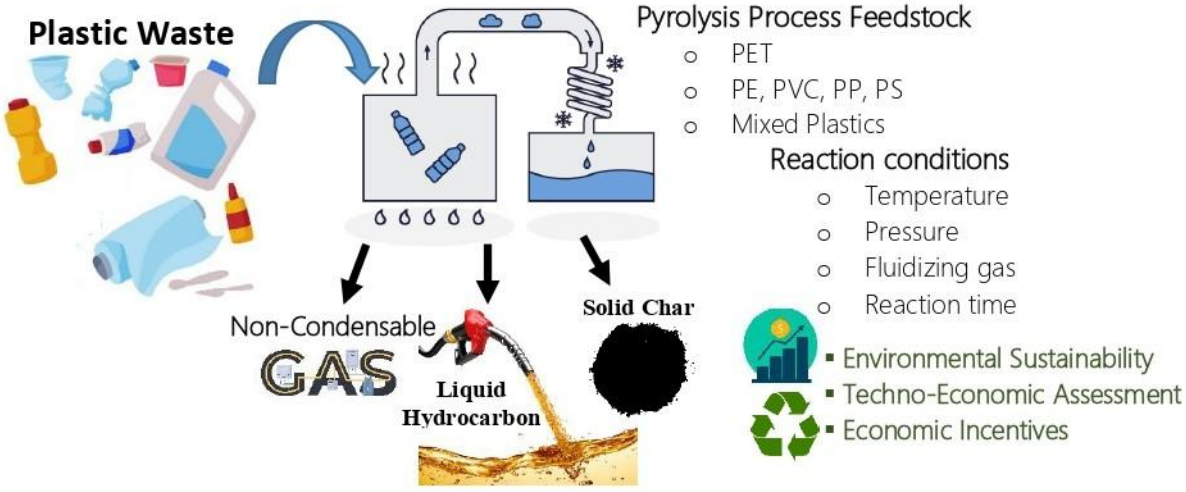
Graphical Abstract

This article presents a comprehensive review of the pyrolysis of various types of plastics, emphasizing the role of different catalysts in improving product yield and quality. It also examines the key factors influencing the pyrolysis process. Furthermore, the article discusses the applications of pyrolysis products and offers a techno-economic evaluation, providing insights into the potential for commercial implementation.



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Abstract: The growing plastic waste problem and dwindling fossil resources highlight pyrolysis as a promising method to convert plastics into fuels and valuable chemicals. This review explores the pyrolysis of common plastics (PET, PE, PVC, PP, PS) and their mixtures, focusing on reaction mechanisms and product outputs. Catalytic pyrolysis using zeolites, clays, and alkali catalysts improves efficiency over thermal cracking by breaking polymer bonds more effectively. Although it yields useful liquid hydrocarbons, further processing—like distillation and hydrogenation—is needed to meet fuel standards. Gases produced can be used for energy or converted into products like ethylene and carbon nanotubes. A techno-economic analysis addresses feedstock, co-products, and costs, outlining a path to incorporate pyrolysis into a circular economy, promoting both sustainability and economic value.

Keywords*: Plastic Wastes, Catalytic Pyrolysis, Techno-economic assessment.*

Abbreviations

PET (Polyethylene Terephthalate); PVC (Polyvinyl Chloride); PE (Polyethylene); PP (Polypropylene); HDPE (High Density Polyethylene); PS (Polystyrene); LDPE (Low Density Polyethylene); ZSM-5 (Zeolite Socony Mobile-Five); HZSM-5 (Hydrogen Zeolite Socony mobile-5); PAHs (Polycyclic aromatic hydrocarbons); RPMs (Revolution per minutes); NPV (Net Present Value); IRR (Internal Rate of Return).

Introduction

Plastics have become indispensable in modern society owing to their lightweight, cost-effectiveness, and versatility. Global plastic demand is projected to surpass 500 million tonnes by 2050, driven by their widespread utility [1]. Such high demand for plastics inevitably results in increased plastic waste, much of which accumulates in unmanaged landfills, gradually degrading into microplastics that enter the food chain [2]. The exponential increase in plastic production and consumption has resulted in massive accumulation of plastic waste, with over 8.3 million metric tons of plastic produced globally till 2015, and only a 9% of it being recycled [3]. There have been suggestions from experts to ban plastics, however, the prohibition of plastics could potentially cause greenhouse gas emissions to rise three times if they were to be replaced with alternative materials like glass, wood, and metals, due to the significantly higher energy requirements for producing these substitutes [4].

Plastic waste management approaches include mechanical, primary, and thermochemical routes, with varying efficiency and feasibility. These methods could not alter the chemical composition of the plastics after recycling. However, the method of chemical recycling can modify the chemical integrity of the polymer plastics. Chemical recycling via pyrolysis can offset significant fossil resource demand—up to 3.5 billion barrels of oil annually [5]. Pyrolysis has gained recognition as viable solution, capable of managing diverse and contaminated plastic waste from consumers more efficiently than mechanical recycling and generating high-calorific gas products with controlled emissions, depending on feedstock composition and operating parameters [6]. Figure 1 schematically illustrates thermal pyrolysis, where plastics are decomposed in a cylindrical vessel to yield condensable vapours and gases. Those plastic vapor are passed through the condenser where it is condensed into liquid oil. Cold water is passed to the condenser for condensation.

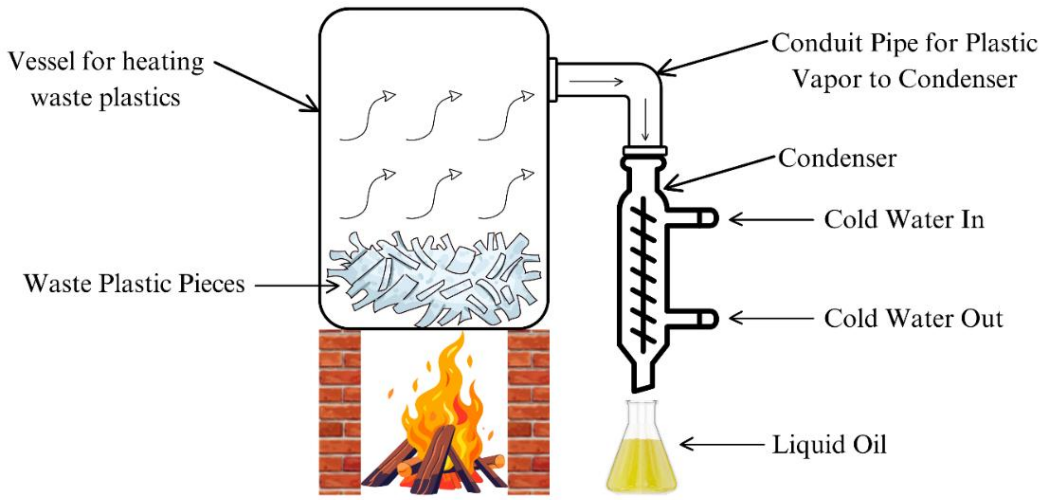

Figure 1. General schematic diagram of plastic pyrolysis process.

Despite the advancements in pyrolysis technology, there remains a gap between research and industrial implementation. The optimal performance of a plastic to fuel system depends on various critical factors, like types of the plastics used, conditions of the catalyst used and other process optimizing parameters. While many reviews have focused on altering the yield and composition of products, there is still a need for a cohesive system that bridges the gap between research and practical application [7].

This review summarizes the pyrolysis performance of diverse plastic materials with varying catalysts and operational parameters, offering theoretical support for future developments. It also discusses further refining and purification processes aimed at producing valuable fuel which can be utilized in mechanical engines and for manufacturing fresh plastics. Following this approach an in depth and systematic techno-economic analysis of catalytic pyrolysis is conducted, considering factors such as feedstock logistics, utilization of liquid fuels, and the full use of co-products.

Review Methodology

This review synthesises evidence from scholarly databases, scientific journals, and grey literature to evaluate catalytic plastic pyrolysis. The primary sources include peer-reviewed articles (2000–2023), review papers, and scientific databases (e.g., ScienceDirect, Scopus, Google Scholar). Existing review papers and meta-analyses were reviewed to identify trends, gaps, and common themes, providing a historical perspective on the topic.

To enhance the robustness of the review, a systematic literature search was conducted using relevant keywords such as Plastic Pyrolysis, Catalytic Pyrolysis, techno-economic assessment and review on plastic pyrolysis. Studies were selected based on their relevance, methodological rigor, and contribution to the field. Key information, such as types of plastics, catalysts, process conditions, and product yields, was extracted and analyzed to identify significant findings and trends. A comparative analysis was performed to evaluate the efficiency of different pyrolysis methods and catalysts, considering factors like product yields, energy requirements, and environmental impacts. The quality and reliability of sources were assessed to ensure the inclusion of credible information. This comprehensive methodology aims to provide a balanced understanding of plastic pyrolysis, highlighting its potential benefits, challenges, and future directions. A flowchart (Figure 2) summarises the review methodology adopted in this study. This approach provides a coherent framework for assessing the potential of catalytic pyrolysis as a viable waste-to-energy and resource recovery pathway in the context of a circular economy.

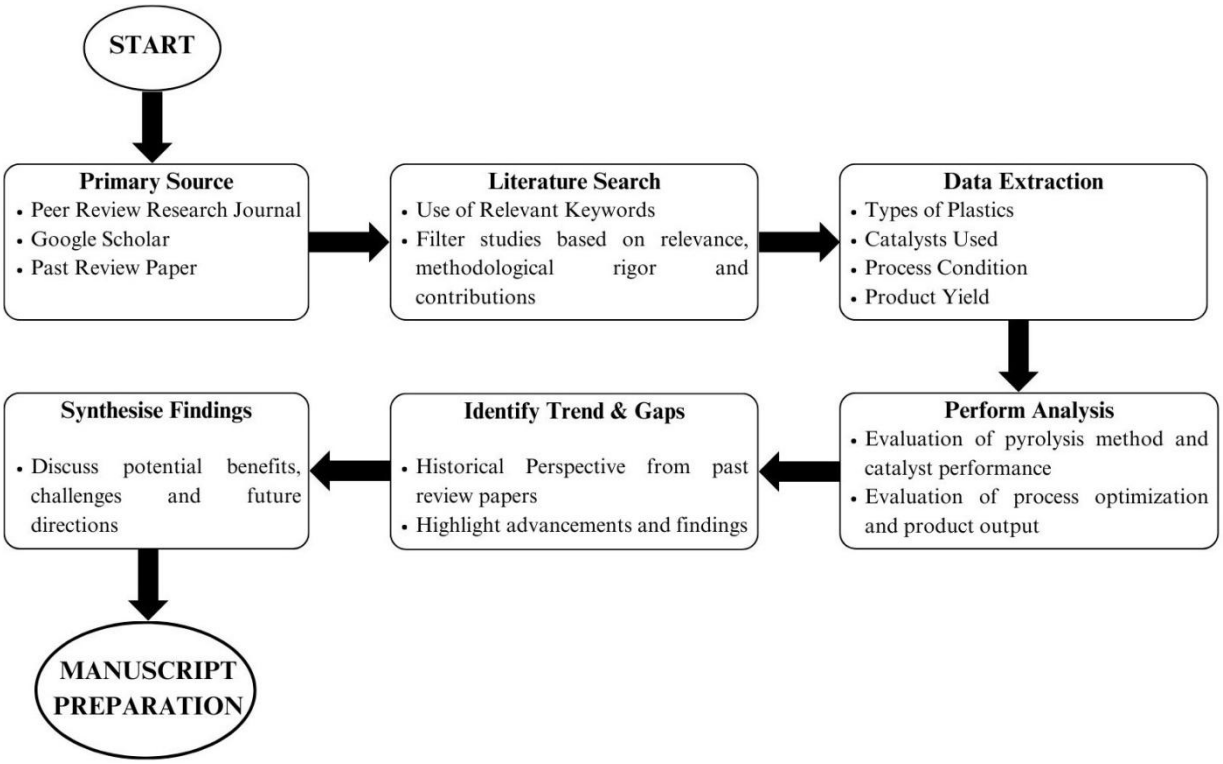

Figure 2. Methodological framework for literature review.

Pyrolysis of Plastics

Pyrolysis product yields are influenced by feedstock characteristics such as carbon content, ash content, volatile matter and moisture [8]. High volatile matter (> 86.83%) and low ash content (< 2%) in plastics like PET [9], HDPE [10], LDPE [11], PVC [12], PP [13], and PS [14] show great potential for producing abundant liquid oil. Real-world plastic waste often consists of mixed plastics, and researchers are increasingly studying these mixtures to examine how the different components interact with each other [15]. Table 1 provides the percentage of different products from thermal pyrolysis of different types of plastics.

Table 1. Distribution of products on non-catalytic pyrolysis of plastics.

SN	Plastic Type	Operating Conditions	Quantity (in % by weight)			Reference
			Non-Condensable Gas	Pyrolysis Oil	Other Products	
1	PET	T = 500°C	76.9	23.1	-	[16]

SN	Plastic Type	Operating Conditions	Quantity (in % by weight)			Reference
			Non-Condensable Gas	Pyrolysis Oil	Other Products	
2	HDPE	T = 650°C Time = 0.8 sec	20.3	-	Wax (51.9)	[17]
3	HDPE	T = 650°C Time = 1.5 sec	31.5	-	Wax (34.1)	[17]
4	HDPE	T = 780°C Time = 0.8 sec	90.4	-	-	[17]
5	PP	T = 746°C	65.9	29.6	Char (4.5)	[13]
6	PE	T = 728°C	59.3	38.2	Char (2.5)	[13]
7	PS	T = 450°C Time = 1 Hour	0.4	80	Char (6.2)	[18]
8	70% PE + 30% PS	T = 450°C Time = 1 Hour	12.8	93.7	Char (3.5)	[18]
9	15% PET + 45% PE + 20% PS + 20% PP	T = 600°C Time = 1 Hour	18	45	Wax (36)	[19]

Polyethylene Terephthalate (PET)

Polyethylene terephthalate (PET) undergoes a unique pyrolysis process due to its polyester structure, resulting in terephthalic and benzoic acids as major products [20]. In the absence of catalysts, PET pyrolysis results in high solid residue and oxygenated tar yields, particularly within 373–753 K[21]. Due to its relatively low volatile content (~86.8%), PET produces a high proportion of gas (~76.9 wt%) and lower liquid oil yields (~23.1 wt%). However, the liquid oil is often unfavorable due to its high benzoic acid content [16]. The addition of catalysts like ZSM-5, FeOOH [22], and different

oxides of metal [23] significantly improves the process, converting PET into oil enriched with aromatic compounds and reducing the formation of terephthalic acid. Notably, ZnO promotes the decarboxylation of pyrolysis products, increasing the ratio of benzene in oil mixture to 88.8% [24].

Polyethylene (PE)

The pyrolysis of polyethylene (PE) involves a mechanism where free radicals are randomly generated in the backbone of polymer, along with reaction involving transfer of hydrogen and breakdown of molecules [25]. In conventional method of thermal degradation, inefficient heat transfer results in the production of waxes or high-viscosity liquids [17]. Optimal conditions to reduce the production of wax involve higher retention time at above 500℃ which causes the formation of gases and light hydrocarbons [9]. Wax yield reduces from 51.9% to 34.1% as residence time increases at 650°C, while complete cracking occurs at 780°C [17]. The use of catalysts shifts the pyrolysis mechanism to produce aromatic compounds, alkenes, alkanes and napthenes [26]. Specifically, pyrolysis using NiO and HY increases the production of mono-aromatics and isomerized hydrocarbons significantly [27]. Reforming reactions favor the production of alkanes and aromatic compounds in in-situ process of catalytic pyrolysis, while ex-situ catalytic mode favors the cracking to olefins [28].

Polyvinyl Chloride (PVC)

The Polyvinyl Chloride undergoes multi-step degradation, releasing HCl and producing char and chlorinated volatiles [29]. PVC pyrolysis is environmentally challenging due to chlorinated emissions and low liquid yields [16]. To mitigate this, a de-chlorination process is essential [30]. Lopez et al. demonstrated that using red mud can significantly reduce chlorine content in chlorinated oils [31]. Catalytic de-chlorination methods are categorized into thermal cracking combined with catalytic de-chlorination, catalytic hydro-de-chlorination, and a non-catalytic de-chlorination step followed by catalytic pyrolysis. The optimal recycling configuration for PVC is a staged pyrolysis process to avoid HCl reactions. Additionally, using hydrogen and helium can help suppress catalyst deactivation by removing HCl from the catalyst surface [32].

Polypropylene (PP)

Polypropylene (PP) undergoes pyrolysis through random chain scission mechanisms, similar to PE, predominantly forming olefins. However, The activation energy for PP pyrolysis (176 kJ/mol) is lower than that for PE (225 kJ/mol), due to the presence of tertiary carbon atoms that promote more efficient bond cleavage[13]. Due to its branched structure, PP yields a lower concentration of aliphatic compounds in pyrolysis oil (2.9 wt% at 746 °C) compared to PE (20 wt% at 728 °C). PP also produces a higher gas yield than PE, attributed to the degradation of side groups and the formation of stable tertiary radicals [13]. PP pyrolysis typically yields 42% liquid, 3.5% char, and 54.6% gas. Although

the liquid yield is relatively low, the process produces a more complex liquid composition and high gas output [33]. PP pyrolysis exhibits enhanced cracking behaviour and greater aromatic production compared to PE under similar conditions [34]. Catalytic fast pyrolysis (CFP) of PP yields benzene, toluene, ethylbenzene, and xylene (BTEX) up to 49.41% using Hβ zeolites [35].

Polystyrene (PS)

Polystyrene (PS) pyrolysis proceeds primarily via end-chain scission and random chain breaking mechanisms, generating monomeric products[36]. Owing to its linear homopolymer structure, PS exhibits high liquid oil yield—up to 80.8%—with 13% gas and 6.2% char at optimal temperatures[37]. Because of the simpler structure of PS with respect to other types of plastics, lower energy is sufficient for the breakdown of the polymer molecules [38]. PS pyrolysis primarily yields monomer units, unlike the low monomer yield in PP and PE [39]. Catalytic pyrolysis over natural zeolites at 450 °C yields oil containing 99% aromatics, of which styrene constitutes 60.8% [40]. Styrene and mono-aromatics constitute around 80 wt% of the oil fraction [18]. While PS tends to favour aromatic product formation, elevated temperatures and catalytic de-alkylation can convert styrene to ethylene and benzene[41]. Styrene yield increases with temperature, reaching a peak of 43.45% at 450 °C, before declining due to secondary degradation [42].

Mixed Plastics

Mixed plastic pyrolysis typically yields less than 50% liquid oil, with certain mixtures achieving around 45% yield—comparable to single-polymer systems in energy content[19]. Char yield from mixed plastics (e.g., 3.5%) is also lower than that from pure PS[31]. Synergistic reactions occur between hydrogen-rich (PE, PP) and hydrogen-deficient (PS, PET) polymers, promoting olefin and aromatic formation while enhancing catalyst stability [43]. Hydrogen from PE/PP-derived olefins boosts single-ring aromatic hydrocarbon yields from PET/PS. Alkenes and alkanes react with benzene-derived radicals to form alkylated aromatics. Higher PET content in the mixture increases selectivity towards mono-aromatic compounds. During co-pyrolysis, PVC releases dehydrochlorination intermediates that alter the decomposition pathways of PP, PE, and PS, often increasing oil yield. Effective chlorine control in PVC-containing feedstocks is essential for producing cleaner pyrolysis oil with properties closer to conventional petroleum fuels.

Role of Different Catalysts on Pyrolysis Process

Thermal degradation of plastics demands significant energy and high temperatures to prevent the formation of wax and char. The resulting diverse range of products complicates industrial applications, especially when dealing with mixed plastic waste. Attempts to enhance plastic pyrolysis without catalysts have led to either minimal improvements or increased system complexity and costs

[44]. Thus, downstream catalytic upgrading of pyrolysis vapor is necessary to address these challenges and improve efficiency.

Being endothermic, pyrolysis requires high activation energy, which catalysts help reduce, thereby enhancing conversion rates.[45]. For plastics like PS, PP and PE, the introduction of catalysts alters the pyrolysis mechanism from free radical chain scission to carbonium ion intermediate chain scission. Catalysts' effectiveness in reducing the optimum temperature varies with the size of substituents: PE (-H) > PP ($-CH_3$) > PS ($-C_6H_5$), with larger substituents causing steric hindrance. The PET plastics are less affected by catalysts due to the similar initiation steps involving hydride shifts [46]. Catalysts shift product distribution by enhancing gas-phase aromatics and reducing heavy waxes, improving fuel-quality fractions [47]. For instance, using ultra-stable Y zeolite catalyst (USY) significantly increases the selectivity of benzene and ethylbenzene [48]. Table 2 provides the percentage of different products from catalytic pyrolysis of different types of plastics using various catalysts.

Table 2. Distribution of products on catalytic pyrolysis of plastics.

SN	Plastic Type	Catalyst	Operating Conditions	Quantity (in % by weight)			Reference
				Non-Condens-able Gas	Pyroly-sis Oil	Other Products	
1	PVC	Red Clay	T = 325°C Time = 30 min	46.8	53.2	-	[31]
2	PS	Natural Zeolite	T = 450°C Time = 75 min	13.0	80.8	Char (6.2)	[40]
3	70% PS + 30% PET	Al-Al_2O_3	T = 450°C	71.8	22.5	Char (5.7)	[21]
4	HDPE	Ultra stable Y Zeolite	T = 450°C Time = 30 min	71.5	27	Coke (1.5)	[49]
5	PP	HZSM-5	T = 360°C	94.44	2.31	Coke (1.25)	[50]
6	5% PET+ 42% HDPE +	Fe-Modified Pillared Clay	T = 550°C Time = 30 sec	-	79.3	Char (2.7)	[51]

SN	Plastic Type	Catalyst	Operating Conditions	Quantity (in % by weight)			Reference
				Non-Condens-able Gas	Pyroly-sis Oil	Other Products	
	35% PP + 18% PS						
7	LDPE	ZSM-5	T = 375°C	72.73	24.94	Char (1.78)	[52]

Zeolites

Zeolite catalysts are crucial in plastic pyrolysis due to their unique pore structures and effective acid sites [53]. Microporous zeolites such as HZSM-5 are renowned for shape-selective catalysis, efficiently converting LDPE into gasoline-range hydrocarbons and mono-ring aromatics [54]. HY, with larger pores, enhances gasoline-range hydrocarbon production but deactivates faster than HZSM-5, which has a longer lifespan due to better aromatic hydrocarbon diffusion. Catalytic pyrolysis of PP produces significant C1-C4 and C5-C9 hydrocarbons, with HZSM-5 showing low deactivation rates. Mesoporous zeolites like MCM-41 (Mobile Crystalline Material-41) and SBA-15 (Santa Barbara USA-15), with larger uniform pores, process heavier feedstocks but have lower stability [55]. Incorporating metals like aluminum improves their performance, as demonstrated by Al-SBA-16's production of huge quantity of gasoline and diesels along with minimal formation of coke in HDPE pyrolysis [56]. Overall, HZSM-5 remains preferred for its efficiency and longevity in catalytic pyrolysis.

Base Catalysts

To improve monomer recovery for the re-production of new plastics, catalysts such as alkali carbonates, metal complexes and metal oxides are employed. While plastic decomposition over base catalysts results in higher oil yields compared to solid acids, the process is slower. The oil obtained is predominantly composed of 1-olefins, with minimal aromatic and branched isomer content. BaO catalysis during PS pyrolysis yields ~90% dimers and monomers, while solid acid catalysts favour aromatic products such as benzene and indene [57]. In polyester pyrolysis, base catalysts facilitate the deprotonation of benzoic acid, leading to the production of phenyl radicals and aromatics [58]. The calcinated calcium oxide at 900°C increases the selectivity of aromatic hydrocarbons in PET pyrolysis up to 83.6%, maintaining 65% after multiple repetitions [23]. Among alkaline metal carbonates, oil yield follows the order $MgCO_3$ > $CaCO_3$ > $BaCO_3$, whereas oil selectivity increases in the reverse order. Due to its strong basicity and high proton affinity, $MgCO_3$ effectively abstracts hydrogen from acidic intermediates, enhancing conversion efficiency [59].

Clay

Recent focus has diverted to montmorillonites and their analogs to decrease costs and promote green revolution in pyrolysis. Though clay is not active as zeolites below 326℃, these clays perform better at higher temperatures [59]. Their moderate acidity suppresses secondary cracking, promoting saturated hydrocarbons in the liquid phase. [60]. Clays typically produce gasoline-range liquids from PS and diesel-range liquids from other plastics [61]. The arrangement of layers in clay minerals can be altered by inserting pillars between the sheets, forming a two-dimensional framework of linked micropores that are more extensive than those found in zeolites [60]. In contrast to zeolites, the interlayer spacing of pillared clays remains stable during calcination. The Brønsted acid sites are associated with the hydroxyl groups in the clay structure, while the Lewis acid sites are located within the pillars [51]. Fe-modified pillared clays yield higher oil (79.3% by weight) and hydrogen (47.7% by volume) in mixed plastic pyrolysis, with excellent diesel fraction selectivity (80.5%) [62]. These clays favor aliphatic compounds, while HZSM-5 and HY are selective towards aromatics.

Factors Affecting Pyrolysis Process and Applications of Pyrolytic Products

In catalytic pyrolysis, factors like residence time, pressure, temperature, fluidizing gas type, and flow rate significantly impact product yield and composition. Table 3 summarises the influence of key operating variables on product distribution and reaction selectivity in catalytic pyrolysis.

Table 3. Influence of operational parameters on catalytic pyrolysis performance.

SN	Operational Parameter	Influence on Pyrolysis	Observations & References
1	Temperature	Controls decomposition kinetics, product yield, and selectivity	Different plastics degrade at different temperatures: PVC (250–350°C), PS (~450°C), PET/PP/PE(450–500°C). [63] Optimal for oil yield: 400–550°C [64]. Ideal for aromatics: ~600°C without forming PAHs [65].
2	Pressure	Alters reaction pathways, product selectivity and yield	Vacuum condition (90–95 kPa below atmospheric) allows full PP conversion at 450°C [11]. Increased pressure favors diesel-range hydrocarbons. Boosts aromatization and oligomerization but may form coke precursors [66]. High pressure in LDPE increases BTEX yield to 70.94% [67].

SN	Operational Parameter	Influence on Pyrolysis	Observations & References
3	Residence Time	Impact product phase (liquid and gas) and extent of secondary reactions	Major product-forming reactions occur in the first 15 minutes [68]. Prolonged time favors secondary cracking and coke formation [69].
4	Fluidizing Gas Type	Determine reaction environment, product selectivity and catalyst stability	N_2, He, Ar commonly used for inert atmosphere [11]. H_2 reduces coke formation and increases aromatics (hydrocracking) [46]. CO_2 promotes aromatics formation and enhances catalyst stability [70]. CO_2 reduces acidic byproducts in PET pyrolysis [71].

Due to complex reaction pathways and high molecular weight polymers, catalytic pyrolysis produces a spectrum of hydrocarbons analogous to crude oil distillates. These products include refinery gases, gasoline/naphtha, diesel, and solid residues [72]. Since the condensable and non-condensable fractions are primarily hydrocarbon-based, they require upgrading to meet fuel standards, Table 4 summarises the properties, upgrading routes, and end-use applications of major pyrolysis-derived products.

Table 4. Properties, upgrading methods, and applications of major pyrolysis products.

SN	Product	Key Characteristics	Upgrading Methods	Applications
1	Liquid Oil	Calorific Value > 40 MJ/kg [73]. Without further refining it cannot be used commercially [74].	Filtration, Hydrogenation, distillation and blending with conventional fuels [75]. Hydrogenation of PP pyrolysis oil in Ni/ZSM-5 catalyst meets EN590 standards [74].	Blending pyrolysis oil with conventional diesel enhances engine performance and reduces emissions [76]. 20% blend of pyrolysis oil with diesel improves brake thermal performance at higher RPMs [77].

SN	Product	Key Characteristics	Upgrading Methods	Applications
2	Non-Condensable Gas	High Heating Value (42-50 MJ/Kg) [13]	Acid gas removal by use of catalyst like CaO, $Ca(OH)_2$, and $CaCO_3$ [78].	The gases can be further used as heat energy source for the pyrolysis process.
3	Carbon Nanotubes (CNTs)	High mechanical strength and conductivity formed by catalytic chemical vapor decomposition [79]	Use of metal catalyst	Lubricant Additives [80].

Techno-Economic Assessment of Pyrolysis Process

Plastic waste management has become a critical environmental and industrial challenge globally. Governments and industries are increasingly supporting pyrolysis-based solutions through policy incentives and start-up incubation [72]. A detailed techno-economic analysis (TEA) is essential to determine the practical feasibility and profitability of pyrolysis technologies. Sensitivity analyses are often employed to identify the key factors influencing financial performance. Catalytic pyrolysis has demonstrated economic viability at commercial scale [81]. However, Key profitability drivers—summarised in Table 5 —include feedstock characteristics, liquid product utilisation, co-product recovery, and cost structures. Nonetheless, these economic indicators vary across plant scales, feedstock purity, and regional policy frameworks.

Table 5. Techno-economic assessment of pyrolysis process.

SN	Aspect	Key Points
1	Feedstock Logistics	a. Higher feedstock throughput reduces the payback period and improves net present value. [82] b. Waste management policy reduces the feedstock costs. c. Clean feedstock improves liquid yields: 80% from PE film, 72% from semi-contaminated plastic, and ~23% from mixed dirty waste. d. Agilyx's system achieved a 72%-75% oil yield but required the PET and PVC content in vessel to be below 10%. e. Quantafuel's integrated recycling process, which combines mechanical and chemical recycling, demonstrated high efficiency and significant environmental savings, such as reducing CO_2, NO_x, and SO_x emissions [83].

SN	Aspect	Key Points
2	Liquid Fuel Utilisation	a. A 200-ton/day mixed plastic plant generated $11.53 million/year in revenue [81]. b. Typically, mixed plastic waste pyrolysis yields 67-80% bio-oil, 2-15% biochar, and 8-10% gas [84]. c. IRR = 33% for 16 kilotons/year molten salt pyrolysis plant [85]. d. IRR = 20% for 40,000 tons/year plant where 65% liquid oil yields [86]. e. Even during market fluctuation, 15-year low price of €210/ton shows 20% IRR [87].
3	Co-Product Utilisation	a. Byproducts like gases and carbon black can be further refined and marketed [88]. b. A pilot plant converting 700 tons of plastic waste per year into heavy fuel oil demonstrated self-sustainability, recovering 156.7 kWh of thermal energy from burning non-condensable gases and char [82]. c. Char, although produced in smaller quantities, can replace fossil fuels, carbon black, and pigments, contributing to a "plastic-closed-loop economy". d. Non-condensable gases can be converted to high-value multi-walled carbon nanotubes (MWCNTs) [89]
4	Capital and Operating Expenditures	The formula for the Fuel Production cost is calculated as: [82] Fuel Production Costs = $\frac{TCI \times \frac{r \times (1+r)^N}{(1+r)^N - 1} + OPEX}{Pyrolysis\ Fuel\ Annual\ Production}$ The formula for calculating the annuity of capital investment (TCI), incorporating interest rate (r) and plant lifetime (N), underscores the financial sensitivity of pyrolysis plants. Increases in TCI and operational expenditure (OPEX) drive up fuel production costs, impacting financial returns. a. A $1 million rise in total project investment (TPI) a plant with use of HDPE plastics in a quantity of 0.5 kilotons per day decreases the (NPV) by $0.5 million [90]. b. A 20-year plant life analysis showed that operating expenditure, at $177.93/ton, significantly outweighs capital expenditure at $33.27/ton [81]. c. Large-scale plants face technological challenges due to increased reactor numbers and maintenance needs. Efficient reactor design, especially continuous flow types, is crucial.

Conclusions and Future Prospects

The valorisation of plastic waste through catalytic pyrolysis has garnered growing attention as a sustainable waste-to-energy strategy, enabling the production of valuable outputs such as liquid fuels, hydrogen, and carbon nanotubes from waste-derived feedstocks. Optimisation of the process requires careful selection of feedstock composition, catalyst type, operating temperature, pressure, residence time, and the use of an inert gas atmosphere to maintain oxygen-free conditions. Among common polymers, polystyrene offers the highest yield of aromatic-rich liquid oil under catalytic pyrolysis. Base catalysts are preferred for polyester depolymerization, while zeolites and clay-based catalysts are favoured for polyolefin cracking. Multi-modal pore catalysts, integrating mesophases for pre-cracking and microphases for further cracking, offer enhanced potential for industrial applications. Although catalytic pyrolysis produces complex hydrocarbon mixtures that require further upgrading, the non-condensable gases generated can be utilised for heat recovery, steam reforming, or as feedstocks for carbon nanotube synthesis. Techno-economic analyses reveal promising returns driven by reduced fossil fuel dependence and plastic waste valorisation, though they highlight sensitivity to feedstock quality and process scale. Nevertheless, commercialization faces challenges with contaminants, variability in plastic composition, and fluctuating waste quality, underscoring the need for innovative reactor designs and catalysts capable of adapting to diverse feedstock logistics and operating parameters.

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Exploring the Potential of *Codium sp*. Algal Residues as a Biofertilizer to Enhance Bean Plant Growth in Sustainable Agriculture

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Graphical Abstract

This study explores the use of *Codium sp.* seaweed residues as a biofertilizer to enhance the growth of *Phaseolus vulgaris L.* By combining optimal ratios of seaweed residue (4%) and compost (12%), we achieved improved plant development and yield. This approach offers a sustainable and eco-friendly solution for agricultural soil enrichment.

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Abstract: This study investigates, for the first time, the valorization of green algae residues as a soil biofertilizer. The effect of *Codium* sp. seaweed residue, obtained from chemical hydrolysis, was assessed on the aerial growth, root development, and yield of *Phaseolus vulgaris* L. Various combinations of algae residue and compost were tested to optimize the residue quantity. Compost was used to prevent clogging caused by the direct addition of residue. Five concentrations of residue (0%, 2%, 4%, 6%, and 8%) were combined with four compost doses (0%, 4%, 8%, and 12%), resulting in 16 combinations tested on 96 plants, with six replicates per treatment. The results indicate that the residue positively impacted growth and yield up to 4%, beyond which it had a detrimental effect on the plants. The best results were obtained with 4% *Codium* sp. residue and 12% compost, presenting a sustainable biofertilizer solution for agriculture.

Keywords: *Macroalgae, Codium sp., Phaseolus vulgaris L., Biofertilizer.*

Introduction

The global seaweed aquaculture industry, led by marine macroalgae, experienced a half-million-tonne increase in 2020, reflecting a growth of 1.4% compared to the 34.6 million tonnes reported in 2019 [1]. Similarly, national seaweed production rose from 19,071 tonnes to 22,219 tonnes in 2020, according to a recent African Development Bank analysis [2]. Morocco, with its dual Atlantic and Mediterranean coastlines extending over 3,500 km, boasts significant algal diversity of considerable ecological and economic importance [3]. This wealth, which remains underused, represents substantial potential for both research and industry. Algae are an inexhaustible source of secondary metabolites with significant pharmacological, medical, industrial, and agricultural value [4-6]. Indeed, Morocco is renowned for its expertise in agar-agar production, with the quality of this product considered the best on the European Union market [7].

Given this significant production and algal biodiversity, various industries are investing in the exploitation of this natural resource. The bioactive molecules found in algae provide a sustainable and effective alternative in multiple fields, including agriculture [8,9]. To counteract the harmful effects of chemical fertilizers, several alternatives have been developed to reduce inputs and promote sustainable soil management [10,11]. This has led researchers to explore more cost-effective methods for sustainably managing soil fertility and crop yields, such as composting and algal amendments [12]. Recently, several bioactive substances extracted from marine macroalgae have been used in vegetable and horticultural crops for soil amendment and fertilization to enhance crop yield, quality, and appearance [13,14].

The industries exploiting algae generate significant amounts of waste following the extraction of the desired material. Despite their richness in bioactive compounds that are lost during the extraction process, these residues are generally untreated and underused, potentially harming the environment if discarded in their raw state. Green algae, when decomposing anaerobically, emit toxic gases, including hydrogen sulphide, which can cause serious illness or even death if inhaled in high concentrations. Additionally, among the problems caused by these residues is eutrophication, which occurs when marine industry waste (rich in nitrogen) is discharged into lakes, leading to massive algal blooms and the subsequent disruption of the ecosystem [15,16].

Many studies have been conducted on the valorization of seaweeds in their raw form, but few on the beneficial effects of their residues on plant growth and development. Hence, our study, conducted at the Ecolink R&D laboratory, aims to valorize the dry residues of the green algae genus Codium sp. Ecolink produces biofertilizers based on marine algae after the extraction of active compounds; but,

the residual waste remains unexploited and is typically discarded into nature. The goal of our work is to valorize these residues in agriculture to minimize environmental damage and make use of the remaining bioactive molecules. The experiment was carried out on bean plants (Phaseolus vulgaris L.) grown in soil amended with these residues to assess their effect on plant growth stimulation and yield.

Materials and Methods

Experimental Setup and Location

To evaluate the beneficial effect of an amendment based on *Codium sp*. dry residues on the growth of green beans, a study was conducted at the Ecolink Research and Development laboratory and its experimental farm. The field trials were carried out at an experimental farm in the province of Chtouka Aït Baha, located at the following geographical coordinates: 30°06'45.6"N, 9°27'00.8"W.

Experimental Design

The tests were conducted in an experimental greenhouse of the Canarian type, measuring 22.15 m in length, 15 m in width, and 5.66 m in height to the trellising. The experimental plot, as shown in Figure 1, measured 16 m in length and 2.80 m in width. The pots were arranged in three randomized blocks, with a spacing of 110 cm between blocks and 25.5 cm between each pot within a block. Each block contained a total of 32 pots, each equipped with a drip irrigation system (see Figure 2 for the randomized experimental design). Each pot was also fitted with a string, serving as a stake to keep the plant upright. This setup facilitates weed removal and allows for easier monitoring of plant height growth.

Figure 1 . General view of the experimental plot.

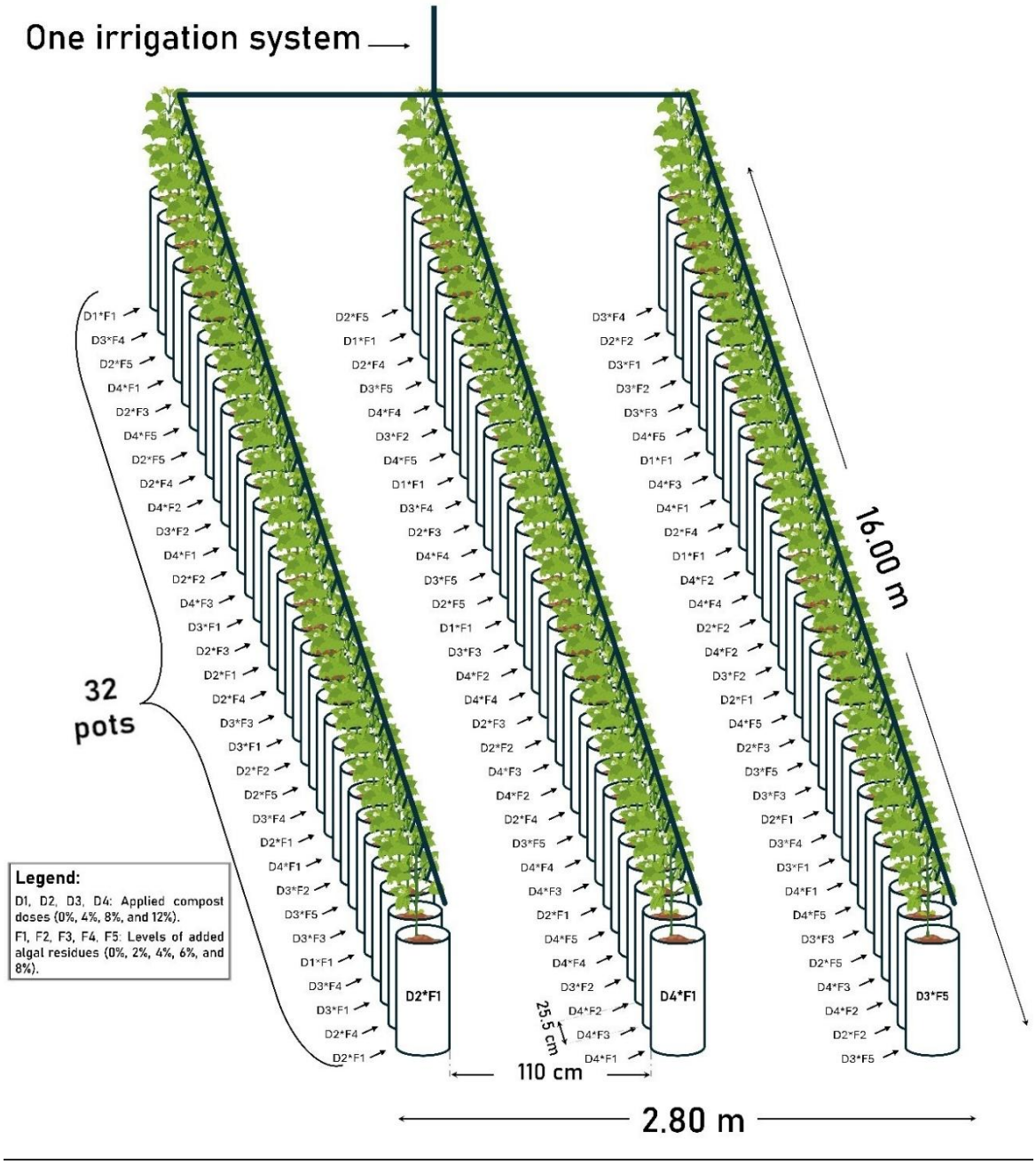


Figure 2. Randomized experimental design.

Growth Conditions

During the trial period from 20 April to 20 June 2022, the average daily temperatures at the experimental site were monitored to assess any potential influence of this parameter on the crops. The recorded temperatures were provided by the Yobeen weather station, supplied by Green Solutions Ltd. During the study period, temperatures ranged from a minimum of 10°C to a maximum of 30°C**.**

Table 1. Physico-chemical characteristics of the soil at the study site.

Parameter	Values	Unit	Method
Chemical Properties			
pH (water, 1:2.5)	8.82	-	pH Meter [17]
Electrical conductivity	1.22	µS cm^{-1} (20°C)	Conductivity Meter [18]
Carbon-Nitrogen ratio (C/N)	19.40	mg kg^{-1}	Calculated from C and N values
Nitrogen (N)	1.62	mg kg^{-1}	Kjeldahl Method [19]
Oxidisable organic matter (OM)	5.43	%	Dumas Method [20]
Active limestone $CaCO_3$	4	%	Bernard Calcimeter [21]
Available Phosphorus (P)	182.00	mg kg^{-1}	Olsen Method [22]
Available Potassium (K)	0.53	meq $100g^{-1}$	Ammonium Acetate Method [17]
Cation Exchange Capacity			
Available Calcium (Ca)	18.90	meq $100g^{-1}$	
Magnesium (Mg)	2.43	meq $100g^{-1}$	Ammonium Acetate Method [17]
Sodium (Na)	0.88	meq $100g^{-1}$	
Trace Elements			
Iron (Fe)	< 4.00	mg kg^{-1}	
Manganese (Mn)	15.20	mg kg^{-1}	
Zinc (Zn)	10.40	mg kg^{-1}	Diethylenetriaminepentaacetic Acid DTPA Extraction + ICP [23]
Copper (Cu)	0.71	mg kg^{-1}	
Boron (B)	< 0.50	mg kg^{-1}	
Physical Properties			
Clay	20.00	%	
Silt (Limon)	0.00	%	Bouyoucos Hydrometer Method [24]
Sand	80.00	%	

An analysis of the soil used for bean planting was conducted to assess its chemical and physical properties. The pH and electrical conductivity were measured using an Extech pH meter and a conductivity meter, following the 1:2.5 and 1:5 extraction methods, respectively. Oxidizable organic matter was quantified using the Dumas method [17,18]**,** and nitrogen content was determined by the Kjeldahl method [19]**.**

Available phosphorus was assessed using the Olsen method [22]**,** and available potassium was measured using ammonium acetate extraction [17]**.** Cation exchange capacity was evaluated for calcium, magnesium, and sodium using the same ammonium acetate method. Trace elements, including iron, manganese, zinc, copper, and boron, were analysed using inductively coupled plasma

(ICP) following extraction with diethylenetriaminepentaacetic acid (DTPA) [23], a common extractant used to assess the availability of trace metals in soils.

The active limestone content was determined using a Bernard calcimeter [21]. Soil texture, including clay, silt, and sand fractions, was analysed using the Robinson Pipette method [24] for granulometry. Based on the soil texture analysis, the soil was classified as sandy, consisting of 80.0% sand, 20.0% clay, and 0.0% silt, indicating a sandy loam type. Table 1 summarizes the results of all these analyses.

Preparation of Amendment

The prepared amendment consists of a blend of organic compost and powdered residue from green algae of the genus *Codium sp*. These seaweed residues, provided by the company Ecolink Ltd., are by-products of a chemical hydrolysis process used in the production of an agricultural biofertilizer. The compost and seaweed residues were mixed in various proportions, denoted by "D" for the compost dose and "F" for the powder dose, as summarized in Table 2. Each combination was tested in six replicates.

Table 2. The different blends of the prepared amendment.

Treatment	Description	Compost (%)	Algal Residue (%)	Replicates
D1*F1	No amendment (control)	0	0	6
D2*F1	Compost-only control	4	0	6
D2*F2	4% compost + 2% algal residue	4	2	6
D2*F3	4% compost + 4% algal residue	4	4	6
D2*F4	4% compost + 6% algal residue	4	6	6
D2*F5	4% compost + 8% algal residue	4	8	6
D3*F1	Compost-only control	8	0	6
D3*F2	8% compost + 2% algal residue	8	2	6
D3*F3	8% compost + 4% algal residue	8	4	6
D3*F4	8% compost + 6% algal residue	8	6	6
D3*F5	8% compost + 8% algal residue	8	8	6
D4*F1	Compost-only control	12	0	6
D4*F2	12% compost + 2% algal residue	12	2	6
D4*F3	12% compost + 4% algal residue	12	4	6
D4*F4	12% compost + 6% algal residue	12	6	6
D4*F5	12% compost + 8% algal residue	12	8	6

The quantities of amendment needed for each trial were weighed beforehand by using a Brehm BS200SS precision balance and mixed well in the laboratory; then, kept in labelled and well-sealed plastic bags until they were mixed with the soil for transplanting the bean.

Selection of Test Plant

The experiment used green bean plants of the *Phaseolus vulgaris* L species, from seeds from the Efforia variety. This variety is characterized by its dwarf, determinate growth type with pink pods, belonging to the snap beans group and mainly intended for fresh consumption. The selection of this particular variety for the experiment was based on two criteria: the availability of the seeds and the short life cycle.

Experimental Trials

Preparation of Seeds: Green bean seeds were carefully selected and pre-sterilized. They were rinsed with sterile distilled water, soaked in 97% ethanol for 2 minutes, then in 10% sodium hypochlorite for 3 minutes with agitation, followed by rinsing with sterile distilled water to remove any excess sodium hypochlorite.

Germination: The sterilized seeds were germinated in sterile plastic Petri dishes lined with filter paper, with six seeds per dish to prevent overlap of the radicles. The dishes were moistened with sterile distilled water, covered with parafilm and aluminium foil, and placed in a culture chamber at 27°C for 72 hours. Germination was confirmed when the radicle emerged and grew to a length of 2 mm.

Transplantation of Germinated Seeds: After 72 hours, the germinated seeds were transplanted into an alveolar forestry tray. Each seedling was planted in a tray hole, which had been previously disinfected with ethanol and filled with a well-humidified mixture containing 2/3 peat and 1/3 coconut fibre as a substrate. One seedling per hole was placed at a suitable depth (0.5 to 1 cm) with light packing and immediately watered with distilled water to ensure good contact between the substrate and seed. The seedlings were then placed in a sunny environment at a suitable temperature (25 ± 3°C).

Seedling Stage: Seedlings with two leaves were transplanted into 7 L plastic pots filled with a substrate composed of soil mixed with the prepared amendment. Ninety-six pots were used for the study, with six repetitions for each treatment. The pots were placed on bricks for support and marked accordingly. Throughout the trial, the seedlings were watered as required and placed in a suitable environment with adequate sunlight and temperature (25 ± 3°C).

Data Recorded

Vegetative Growth Characteristics

The diameter of the stem was measured at 1 cm from the collar at the end of the experiment using a digital calliper and expressed in mm [25].

Growth kinetics were assessed by noting plant height as a function of different concentrations of the tested amendment. Measurements were taken weekly, starting from the first week after sowing, using a tape measure from the base of the stem to the top of the aerial part and expressed in cm.

To study the effect of the tested amendments on the growth of the leaf system of the bean plants, the final number of developed leaves per plant was counted at the end of the experiment.

The fresh weight of the aerial part was measured after cutting the plants at the collar immediately after harvesting the pods, using a Breme BS200SS precision balance. To evaluate the dry weight of the aerial part, the plants were dried in a Memmert UF110 universal oven at 80.0°C for 24.0 hours. The weight was then measured immediately after removal from the oven to avoid any possible weight changes caused by laboratory storage conditions**,** using a Breme BS200SS precision balance [26].

After separating the aerial and subterranean parts, the roots were carefully removed from the soil, gently rinsed with a stream of water to remove any attached soil, and blotted dry between two filter papers before measuring root biomass. The length of the main root was measured with a tape measure and expressed in cm. The fresh weight of the roots was measured using a Breme BS200SS precision balance**.** The dry matter of the root system was obtained by drying it in a Memmert UF110 universal oven at 65.00°C for 72.0 hours until the weight was constant. The weight was then measured using a Breme BS200SS precision balance [27].

Yield and Pod Quality

The effect of the tested amendments on green bean production was evaluated by counting the number, length, and weight of the pods. The number of pods was counted for each amendment concentration. The length of the pods was measured with a graduated ruler and expressed in cm. Pod weight was determined by weighing with a Brehm BS200SS precision balance and expressed in grammes [26].

Statistical Analysis

Data were subjected to a one-way analysis of variance (ANOVA) followed by multiple comparisons of means using the Tukey test at the 5% level. Differences were considered significant when $P \leq 0.05$. Results for each study variable were expressed as mean ± standard deviation. All plant analyses were performed in six replicates. Statistical calculations and analyses were carried out using R software. Additionally, Principal Component Analysis (PCA) was performed using Primer/Permanova software (version 6.1.13).

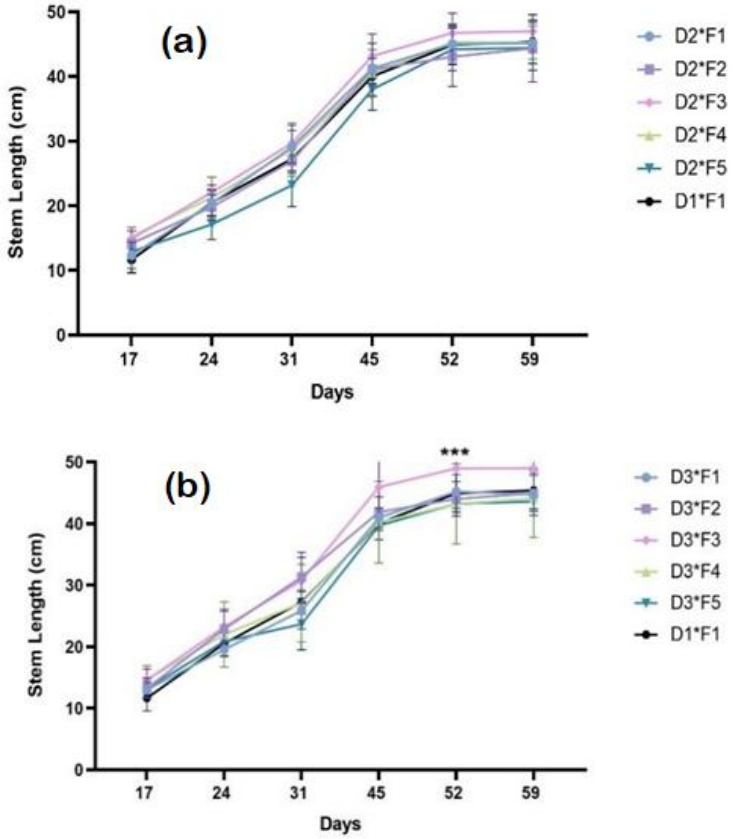
Results

Kinetics of growth

In order to study the effect of the tested amendments on the growth of green bean plants, growth kinetics were monitored by measuring the main stem height once a week throughout the trial period. Figure 3 shows the results obtained. The curves below illustrate the growth kinetics of green bean plants treated with the amendment at different concentrations. A steady growth of the plants was observed over time, reaching a plateau after 52 days, at which point the stem length stabilized.

At all concentrations tested, the plants grew in parallel throughout the trial period, with a few centimetres of difference between treatments. Optimal growth was achieved with the D3*F3 treatment, which positively influenced the growth of the bean plants compared to the other treatments, followed by the D4*F3 treatment.

These results demonstrate that the use of the tested amendment improves bean growth when applied at low doses, particularly at 4.0% *Codium* sp. algae residue. But, at the highest concentrations, growth was delayed compared to the control.



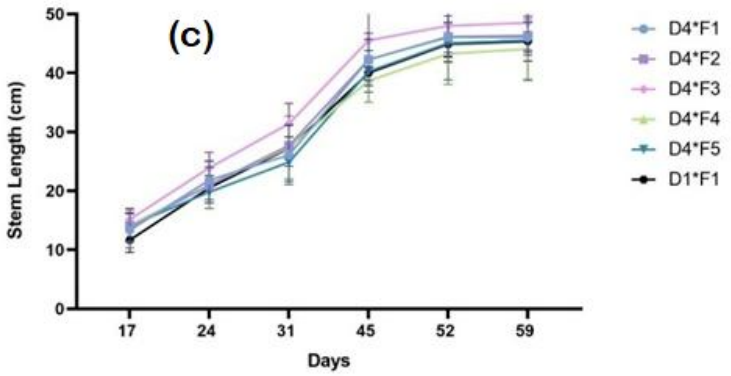


Figure 3. Effect of different amendments on the growth kinetics of green bean plants. Growth trends are presented for (a) D2, (b) D3, and (c) D4. The treatment that resulted in the best growth performance (D3F3) is indicated with "***"

Effect on Aerial Parts

The analysis of variance of the main stem length in relation to the different concentrations of the amendment applied shows a highly significant effect **(**$P \leq 0.05$**)** between the different treatments. The Tukey's test revealed the presence of four homogeneous groups.

The amendments with 4.0% algal residues gave the best results in terms of main stem length, namely: D3*F3**,** followed by D4*F3 and D2*F3**,** with lengths of 49.0 cm, 48.5 cm, and 47.0 cm**,** respectively. The lowest heights were obtained with the amendments D3*F4 (40.7 cm), D4*F4 (41.3 cm), D4*F5 (42.0 cm), and D3*F5 (43.5 cm), at 8.0% and 6.0% algal residue.

Plants amended with compost alone at different concentrations showed average lengths ranging from 44.0 cm to 46.0 cm**.** These results demonstrate that the biofertilizer based on *Codium* sp. residue has a positive effect on the height of bean plants, *but at low doses* (2.0% and 4.0%)**.** This can be explained by the richness of seaweeds in vitamins, amino acids, micronutrients, and growth hormones (cytokinins and gibberellins), which can accelerate plant growth at low doses [28,29].

Regarding the effect of the amendment on the fresh weight of the aerial part (Table 3), the control group**,** without any amendments, gave the lowest fresh weight of the aerial part, with an average of 124.0 g**.** The most notable results were obtained with the D4*F3 treatment **(**167.4 g), which ranked highest**,** followed by D4*F1 **(**163.6 g**),** D3*F1 **(**154.9 g**),** D4*F4 **(**152.6 g**),** and D4*F5 **(**152.4 g**).** This confirms that the combination of 4.0% residues with 12.0% compost promotes better development of the aerial part of the bean plants.

The results obtained show that, in terms of the dry weight of the aerial part, the D4*F3 amendment, as previously mentioned, gives the best results with 23.3 g**,** followed by D4*F1 and D3*F1, with 22.9 g and 22.3 g**,** respectively. The other amendments gave similar results, ranging from 19.0 g to 20.0 g**.**

This confirms the previous conclusion that the use of the residue at a low concentration of 4.0% positively affects plant growth.

The total leaf count supports the previous results, showing an improvement in the development of the aerial part with the D4*F3 amendment, which gave the best results, followed by D3*F4**.** The controls D1*F1, D2*F1, D3*F1, and D4*F1 gave the lowest results, confirming that the improved growth of the aerial part observed in this study is mainly owing to the effect of the residue and not the compost.

Effect on growth parameters

The variation in bean growth characteristics under the influence of different treatments was studied. Growth both above and below ground was considered as well as biomass in assessing the stimulating effect of the treatments upon common bean. Table 3 shows the results of the growth parameters.

Table 3. Effect of the different amendments tested on the growth parameters of the aerial part of green bean plants.

	Growth parameters				
Treatments	**Length of stem (cm)**	**Fresh weight of aerial part (g)**	**Dry weight of aerial part (g)**	**Diameter of stem (mm)**	**Final number of leaves**
D1*F1	45.38±3.34^{ac}	124.00±2.76^{a}	20.75±1.27^{ab}	8.01±0.43^{ab}	27.83±1.17^{ab}
D2*F1	45.16±3.18^{ac}	141.20±4.98^{be}	21,42±1.10^{ab}	7.73±0.21^{ab}	29.01±1.41^{abd}
D2*F2	46.20±2.40^{ac}	137.08±12.91^{bc}	19.95±2.71^{ab}	7.36±0.21^{a}	27.50±3.89^{ab}
D2*F3	47.00±2.58^{bc}	142.93±2.13^{bef}	21.35±1.24^{ab}	8.07±0.19^{ab}	30.67±3.72^{ae}
D2*F4	45.28±2.58^{ac}	134.04±5.92^{ab}	19.73±1.65^{ab}	7.74±0.25^{ab}	32.83±2.40^{cde}
D2*F5	44.41±3.44^{ac}	137.88±5.24^{bcd}	21.42±1.80^{ab}	7.67±0.34^{ab}	28.30±1.90^{ab}
D3*F1	44.76±3.42^{ac}	154.89±1.53^{gh}	22.32±1.21^{b}	8.08±0.32^{ab}	28.17±0.75^{ab}
D3*F2	44.91±2.92^{ac}	142.80±3.60^{bef}	21.01±1.39^{ab}	7.82±0.33^{ab}	28.83±1.60^{abc}
D3*F3	49.01±4.74^{c}	148.52±3.79^{eg}	21.60±0.50^{ab}	8.27±0.54^{b}	33.17± 1.94 ^{de}
D3*F4	40.08±2.80^{a}	147.03±3.92^{cefg}	19.13±0.20^{ab}	7.98±0.29^{ab}	34.17±1.94^{e}
D3*F5	43.58±1.18^{ac}	148.00±3.27^{deg}	18.92 ± 2.00^{ab}	7.89±0.35^{ab}	31.17±1.17^{be}
D4*F1	46.08±2.54^{ac}	163.75±3.50^{hi}	22.40±1.80^{b}	8.10±0.30^{ab}	28.00±1.41^{ab}
D4*F2	46.33±3.34^{ac}	153.20±3.00^{fg}	21.40±0.90^{b}	8.27±0.47^{b}	30.01±1.41^{ae}
D4*F3	48.53±4.64^{c}	167.43±6.47^{i}	23.30±1.60^{b}	8.23±0.37^{b}	33,33±1.96^{e}
D4*F4	41.30±2.91^{ab}	152.60±0.91^{fg}	20.93±2.73^{ab}	8.04±0.45^{ab}	32.67±1.03^{cde}
D4*F5	42.00±1.60^{ab}	152.4±5.45^{fg}	20.87±1.34^{ab}	7.98±0.57^{ab}	30.00±2.09^{ae}

**Means ± Standard deviation. In each column, the values followed by the same letters do not differ significantly* (one-way ANOVA; α=0.05; n=6).

Effect on root biomass

Table 4 summarizes the obtained results. The ANOVA and the comparison of means test at the 5% threshold show the presence of three homogeneous groups. The shortest lengths were obtained with the controls D3*F1, followed by D1*F1, with lengths of 19.6 cm and 30.8 cm, respectively. The other controls, D4*F1 and D2*F1, gave average lengths of approximately 34.5 cm and 35 cm, respectively. This confirms that the growth-stimulating effect on the root system is mainly caused by the residues and not the compost used as a formulation medium. The best results (39.4 cm and 39.7 cm, respectively) were obtained with the D4*F3 and D4*F2 amendments, containing 4% and 2% algal residues, respectively (Fig. 4). This correlates with the results obtained in the previous section regarding aerial growth, which revealed stimulation of plant growth with the low residue amendments.

Figure 4. Effect of various treatments on the root development of green bean plants.

After clearing the root systems of the soil, the fresh weight was measured directly after rinsing and blotting the roots between two filter papers**.** Contrary to the previous results, the measurement of root fresh weight revealed a higher fresh weight for the D3*F1 amendment, which was approximately 33.5 g **,** followed by D4*F2 with 28.8 g. The other treatments gave values ranging from 18.0 g to 24.0 g**.**

The results obtained for D3*F1 as a control can be explained by greater water retention in the roots rather than actual root system development. To confirm this hypothesis, the dry weight of the root system of the 96 plants was measured.

The ANOVA analysis and the comparison of means test at the 5% significance level showed that there was no significant difference between the different treatments applied. The dry weights obtained were similar for all treatments, ranging from 2.5 g to 2.9 g, with a slight increase observed for the D4*F2 treatment, which gave a dry weight of approximately 3.3 g. The control D3*F1 gave a dry weight of about 2.5 g**,** not differing from the other values obtained, which confirms the previous hypothesis that water retention is the only reason for the higher fresh weight observed with this amendment.

Table 4. Effect of the different amendments tested on the growth parameters of the root biomass of green bean plants.

	Growth parameters		
Treatments	**Main root length (cm)**	**Fresh weight of the root (g)**	**Dry weight of the root (g)**
D1*F1	30.75±6.06^{ab}	18.56±3.89^{a}	2.97±0.32^{a}
D2*F1	35.00±4.60^{b}	24.40±7.08^{ab}	2.87±0.62^{a}
D2*F2	38.83±6.67^{b}	20.90±4.43^{ab}	2.57±0.46^{a}
D2*F3	38.00±5.29^{b}	18.86±6.56^{a}	2.43±0.46^{a}
D2*F4	33.33±4.46^{b}	16.33±4.32^{a}	2.50±0.37^{a}
D2*F5	38.16± 4.40^{b}	21.93±7.61^{ab}	2.57±0.45^{a}
D3*F1	19.60±6.29^{a}	33.50±2.17^{b}	2.50±0.11^{a}
D3*F2	33.00±2.68 ^{b}	21.65±5.02^{ab}	2.77±0.34^{a}
D3*F3	40.50±5.24^{b}	18.47±4.51^{a}	2.70±0.72^{a}
D3*F4	38.60±7.63^{b}	18.37±7.51^{a}	2.58±0.20^{a}
D3*F5	38.50±8.75^{b}	24.20±5.85^{ab}	2.57±0.43^{a}
D4*F1	34.50±3.20^{b}	19.93±4.10^{a}	2.43±0.37^{a}
D4*F2	39.67±3.93^{b}	28.80±1.91^{ab}	3.33±0.99^{a}
D4*F3	39.42±7.68^{b}	18.28±6.21^{a}	2.60±0.22^{a}
D4*F4	38.17±4.40^{b}	20.10±6.11^{a}	2.90±0.46^{a}
D4*F5	38.33±5.28^{b}	21.76±6.09^{ab}	2.73±0.43^{a}

**Means ± Standard deviation. In each column, the values followed by the same letters do not differ significantly* (one-way ANOVA; α=0.05; n=6).

Effect on Yield and Pod Quality

The effect of the different tested amendments on yield and pod quality was assessed. Table 5 summarizes the results. The number of developed pods per plant (out of 96 plants) was counted. Statistical analysis showed a significant difference between the different treatments tested.

The highest yield was obtained with the D4*F3 treatment, which gave an average of 79.8 pods, followed by D2*F5 with 78.3 pods, then D2*F4**,** D4*F4, and D3*F4 with 76.0 pods. The lowest yields (63.0 pods) were obtained with the D1*F1 and D2*F1 controls, containing 0.0% and 4.0% compost, respectively. The D3*F1 and D4*F1 controls gave average yields of approximately 68.6 and 73.6 pods, respectively. This confirms that the combination of 4.0% residue with 12.0% compost produces the best results in terms of yield.

The results obtained from the pod weights confirm that the D4*F3 treatment had the most positive effect on bean plant yield**;** this result correlates with the number of pods obtained for this same treatment. Treatments D4*F5, D4*F2, D4*F1**,** and D3*F5 gave similar weights, ranging from 221.0 g to 231.0 g**.** The lowest weights were obtained with the controls D1*F1 and D2*F1**,** with 206.0 g and 210.4 g, respectively.

Treatment D3*F4 gave the lowest yield in terms of pod weight. This result contradicts the number of pods obtained for the same treatment. This may be explained by differences in pod size (length and diameter of the fruits).

The average length of the harvested pods was calculated for each treatment. The statistical analysis of the results showed no significant difference between the different treatments applied. All pods had a similar length, ranging between 12.0 cm and 13.0 cm**.** This shows that the application of algal residue as a biofertilizer has no effect on pod length.

Table 5. Effect of the different amendments tested on the yield and pod quality of green bean plants.

	Yield and Pod Quality		
Treatments	**Weight of pods (g)**	**Number of the pods**	**Length of the pods (cm)**
D1*F1	206.87±9.14^{ace}	63.00±1.10^{a}	13.71±0.3^{a}
D2*F1	210.43±2.33^{bcef}	63.25±2.13^{a}	13.82± 0.55^{a}
D2*F2	199.35±12.35^{ac}	67.33±4.22^{ac}	13.65±0.54^{a}
D2*F3	208.66±13.85^{ace}	72.80±0.63^{bcde}	13.82±0.54^{a}
D2*F4	203.16±15.80^{ace}	76.75±4.96^{ef}	13.51±0.80^{a}
D2*F5	215.93±1.49^{cg}	78.33±2.51^{ef}	13.49±0.31^{a}
D3*F1	219.35±1.39^{cg}	68.60±3.51^{acd}	14.67±0.45^{a}
D3*F2	192.52±22.36^{ab}	64.80±4.3^{ab}	14.42±0.22^{a}
D3*F3	201.60±0.00^{acd}	73.60±6.4^{cf}	13.80±0.70^{a}
D3*F4	188.48±2.34^{a}	76.00±0.11^{df}	13.63±0.49^{a}
D3*F5	221.33±12.51^{deg}	75.70±1.30^{df}	13.44±0.90^{a}
D4*F1	223.97±15.92^{eg}	73.21±1.60^{cf}	14.32±0.70^{a}
D4*F2	229.70±6.67^{fg}	74.00±3.30^{cf}	13.85±0.67^{a}
D4*F3	234.60±1.26^{g}	79.80±4.80^{f}	14.50±0.60^{a}
D4*F4	206.93±4.86^{ace}	76.40±7.30^{ef}	13.90±1.00^{a}
D4*F5	231.00±1.40^{fg}	72.33±1.60^{cf}	13.70±0.40^{a}

**Means ± Standard deviation. In each column, the values followed by the same letters do not differ significantly* (one-way ANOVA; α=0.05; n=6).

Principal Component Analysis (PCA)

Principal Component Analysis **(**PCA**)** was used to assess the impact of *Codium* sp. residues at varying concentrations, combined with different doses of compost, as a biofertilizer on the growth of *P. vulgaris*. The aim was to determine the appropriate residue concentration to be added to the soil.

Applying PCA to biometric data and various doses resulted in the extraction of two principal components, which accounted for 71.6% of the cumulative variance (Figure 5)**.** Our focus was on interpreting the first two dimensions of the PCA.

The first principal component (PC1) explained 38.3% of the total variance. The second (PC2) contributed 33.3% to the overall variance.

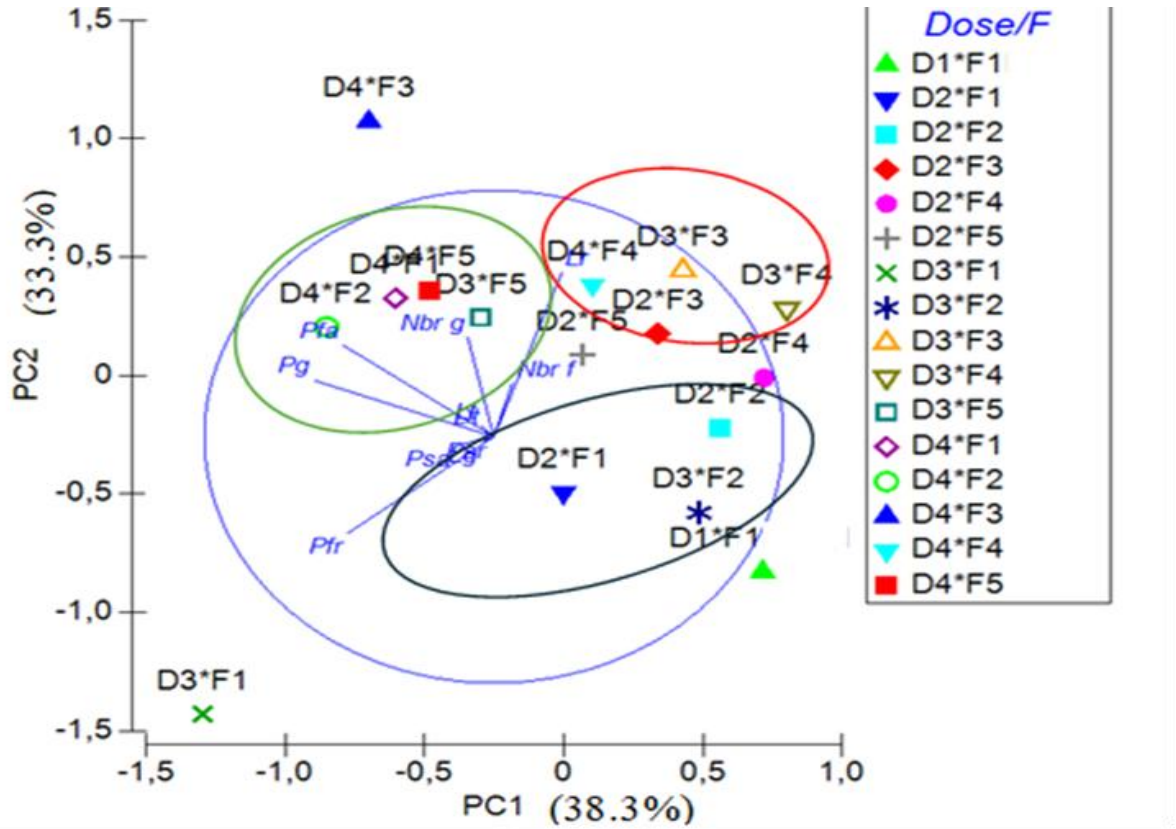


Figure 5. Principal component analysis scatter plot representing the scores for the biometrical data. Abbreviations in the figure are as follows: Pfa: Fresh aerial weight, Psa: Dry aerial weight, Dt: Stem diameter, Nbr f: Final leaf count, Lr: Length of the main root, PFR: Fresh root weight, Psr: Dry root weight, Pg: Pod weight, Lg: Pod length, Nbr g: Number of pods, Lt: Length of stem.

The PCA analysis of *P. vulgaris* growth variation revealed a clear trend in treatment preference. Specifically, the D4*F2**,** D4*F1, D4*F5, and D3*F5 treatments had a positive impact on pod weight, fresh aerial weight, number of pods, final leaf count, and stem diameter**.** The D2*F1, D1*F1, D3*F2, and D2*F2 treatments were more associated with an increase in fresh root weight and dry aerial weight**.** In contrast, the D3*F3, D2F3, D3*F4, and D4*F4 treatments were characterized by an increase in the main root length**.**

Discussion

Because of mounting concerns with effects on health from chemical inputs and effects on the environment, organic/biological fertilizers have become a research focus. Whatever is generally recognized as safe must be tested in real life, not only the laboratory. One particularly promising resource is marine algae to produce fertilizers **[**30]. These algae, abundant in bioactive compounds and growth hormones, offer significant agricultural benefits by promoting plant growth and enhancing plant defences against various pathogens [28,31,32].

Once the active ingredients are extracted from the raw algae material, they leave behind a non-usable residue that is released into the environment. This residue holds potential as a valuable soil amendment. To the best of our knowledge, our study represents the first attempt to explore the recovery of residue from green algae, including the genus Codium sp., for the preparation of a biological soil amendment.

The results obtained demonstrate that increasing the quantity of residue in the applied amendment correlates positively with both aerial and root growth, as well as plant productivity. This positive effect reaches a threshold at 4%, beyond which the residue begins to impact plant growth negatively. Current literature suggests that the application of amendments has a significant effect on germination and plant growth when administered at lower doses [33].

Among all the parameters assessed, the most favourable results were consistently observed when employing a combination of 4% Codium sp. algae residue and 12% compost. This combination resulted in superior growth of green bean plants, evident in both aerial and root system development, as well as overall production. These findings show that algal residues are valuable biofertilizers. The observed benefits are attributed to the presence of biostimulant compounds in algae, including phytohormones, vitamins, phlorotannins, polysaccharides, and trace elements, as substantiated by various studies [34,35].

Similar results were obtained by Ouhssine *et al.* [36], using the waste of the alga *Gelidium sesquipedale* (currently *Gelidium corneum*) as a biofertilizers for the cultivation of maize plants. This treatment resulted in significant crop growth compared to the control, allowing substantial root growth as well as aerial development, confirmed by the increase in the number of leaves, stem diameter, stem length, and yield. These findings provide further evidence of the potential agricultural applications of this alga following the extraction of agar-agar.

Furthermore, Zhenrui *et al.* [37], aiming to improve soil structure and nutrient deficiencies in Guangdong Province's tobacco fields, investigated the impact of different algae residue quantities on soil properties and tobacco growth. The results indicated that applying algae residues, ranging from 2.5% to 5.0% of soil weight, not only increased soil aggregates and improved soil pH, nutrient content, and enzymatic activity, but also significantly enhanced tobacco growth and leaf yield.

Similarly, Jin *et al.* [38] examined various substrates, including algae residues, for cucumber plant growth. They found that optimal cucumber growth occurred with 18.0% algae residue content, highlighting the importance of balancing substrate characteristics for enhanced plant development.

Additionally, Shen *et al.* [39] explored the influence of seaweed residues on spinach growth and quality by mixing seaweed residue substrate with a finished vinegar grain matrix across 15 treatments. The findings revealed increased bulk density and total porosity with seaweed residue addition, with varying effects on water retention, porosity, and spinach biomass. The highest spinach yield and quality were observed with a 15.0% seaweed residue addition, accompanied by reduced nitrogen content and significant increases in soluble protein and organic acid content.

In line with these findings, Li Yue *et al.* [40] evaluated the effectiveness of an organic fertilizer derived from industrial algae residues on the germination, growth, and salt-alkali resistance of Chinese cabbage. The results indicated that a 1,000-fold dilution of this fertilizer promoted the highest germination rate. In a 5‰ saline environment, a 3,000-fold dilution was most effective. Optimal growth was observed with a 2‰ addition of this fertilizer in ordinary soil, increasing germination rates by 28.9%. In saline-alkaline soils, the addition of 1‰ of this fertilizer significantly improved Chinese cabbage growth, with germination rates up to three times higher than the control group.

Additionally, Meilin *et al.* [41] focused on using seaweed residues to create a seaweed residue extract (SRE) for use as a foliar fertilizer. Various dilutions of SRE were tested on coloured peppers and wild rice in field experiments. The results indicated that SRE treatments significantly enhanced plant growth and development in both crops. Coloured peppers treated with SRE exhibited greater plant height, increased leaf growth, and higher fruit weight than the control group. The SRE10 treatment significantly increased vitamin C content, reduced nitrate levels, and boosted soluble sugar and protein content in the coloured peppers.

The findings reveal that amendments containing high doses of algal residue resulted in less pronounced growth of green bean plants, both in terms of aerial and root biomass, compared to the control groups. This observation aligns with existing literature, which indicates that as the concentration of algal amendments increases, the growth-promoting effect diminishes. These results are consistent with those reported by Baroud *et al.* [33], who investigated the effects of treating bell pepper plants with various brown algae, including Fucus spiralis. Baroud *et al.* [33] demonstrated that algal powder derived from Fucus spiralis positively influenced root growth in bean plants, particularly at doses of 5.0% and 10%.

This phenomenon can be attributed to the beneficial effects provided by algae, which enhance the physico-chemical characteristics of the soil, leading to improved water retention and increased nutrient availability [42].

In line with these findings, Tantaraico *et al.* [43] investigated the combined effect of algae and compost on lettuce yield and quality. Their study used a factorial experimental design with varying doses of compost and marine algae. The results showed a synergistic relationship, with higher concentrations of both leading to improved yield and quality parameters such as leaf size, colour, weight, and collar diameter. There is potential for using compost and marine algae in combination to enhance lettuce production in nursery settings**.**

Unfortunately, there remains a shortage of studies demonstrating the effect of algal residues, especially in combination with compost Yet these studies collectively contribute to our understanding of the potential of organic fertilizers derived from algae and seaweed residues in promoting crop growth and quality. They underscore the importance of exploring environmentally sustainable alternatives to conventional fertilizers and highlight the promising potential of marine-derived fertilizers in enhancing agricultural productivity and sustainability.

In conclusion, our study revealed the potential use of algal residues, particularly from the genus Codium sp., as valuable soil amendments in agricultural practices. We have demonstrated positive effects on plant growth, particularly when algal residue is combined with compost. Dosage must be well regulated to avoid diminishing returns. This work bears on the need for sustainable and environment-friendly alternatives to traditional chemical inputs in agriculture. Further investigation is warranted to optimize application methods and dosage, thereby enhancing the efficacy and scalability of algal-based biofertilizers in sustainable agriculture practices.

Conclusion

Our study highlights the promising potential of using algal residues to stimulate plant growth, offering a sustainable solution for enhancing crop development and quality while addressing environmental concerns related to residue disposal. The results clearly indicate that applying residues from the green alga *Codium sp.* at a 4% dose, formulated with 12% compost, serves as an effective biofertilizer, promoting the growth and production of *Phaseolus vulgaris L.* plants without compromising soil physicochemical properties. This approach not only addresses environmental concerns associated with algal residue disposal but also improves crop development without adverse effects on soil properties. These significant findings are a preliminary step, and further work includes evaluating the impact on fruit development, testing reproducibility on a larger scale, isolating bioactive compounds, and optimizing application methods. Such developments are congruent with sustainable agriculture.

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Competing Interests

The authors declare that they have no competing interests, whether financial or personal, that could have influenced the design, execution, analysis, or interpretation of this scientific study.

Authors' Contributions

Conceptualisation: **H.A., N.B., M.A., N.R., and T.O.B;** Methodology: **H.A., N.B., and M.A.;** Field-testing, Investigation, Data Collection, and Formal Analysis: **H.A. and N.B.;** Software: **H.A. and A.A.;** Statistical Analysis: **H.A. and A.A.;** Writing—Original Draft Preparation: **H.A.;** Writing—Review and Editing: **H.A., A.A., N.B., N.R., and T.O.B.;** Supervision: **N.B. and T.O.B.**

All authors have read and approved the final version of the manuscript.

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Data Availability

The data presented in this study are contained within the article.

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Frontiers in Encapsulation Science: Advanced Strategies, Mechanisms, and Multidisciplinary Applications

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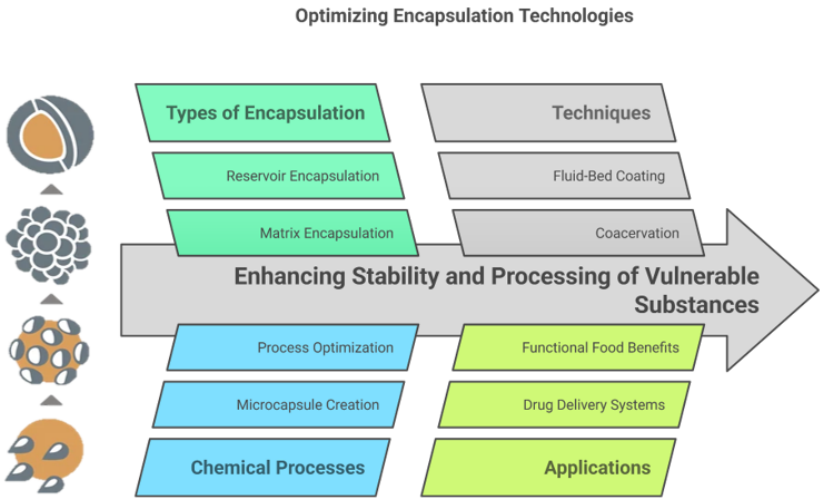
Graphical Abstract

This review focuses on encapsulation technologies and their role in protecting sensitive substances. It highlights two types of encapsulation: reservoir encapsulation and matrix encapsulation, along with key techniques such as fluid bed coating and coacervation. The process aims to optimize chemical reactions to produce stable microcapsules, which are then used in the food and pharmaceutical industries to enhance the efficacy and stability of active ingredients.



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Abstract: Technological encapsulation has emerged as a crucial technique for optimizing the stability and processing of vulnerable substances in several fields, including medicine and nutritional sciences. This paper examines the various types of encapsulates, including matrix and reservoir, and their applications in food and pharmaceutical technologies. We explore the main chemical processes present in creating microcapsules and encapsulation techniques such as fluid-bed coating and coacervation. This review highlights the significance of encapsulation technologies in enhancing drug delivery systems and the health benefits of functional foods by synthesizing recent research and developments in this field.

Keywords: *Encapsulation, Nanoparticles, Bioactive compound, Medical application.*

Introduction

In recent years, encapsulation has attracted attention. Encapsulation incorporates food ingredients, enzymes, cells, or other materials in small capsules, e.g., to preserve foodstuffs [1]. The vulnerable encapsulated agents (pure substances or mixtures of multiple agents) may be described as coated materials, base materials, payloads, and internal phases. The covering materials may be called shells, wall materials, capsules, carriers, membranes, films, the outer shell, or packing materials [2]. There are two main types of encapsulates: matrix and reservoir types. The active ingredient in the reservoir type is encased in a shell. Other terms include capsule, single-core, mono-core, and core-shell [3,4]. Encapsulation can serve several purposes: (i) protecting sensitive substances from the external environment; (ii) masking the organoleptic properties of the substance, such as colour, taste, and odour; (iii) achieving controlled release of the drug substance; (iv) ensuring the safe handling of toxic materials; (v) enabling targeted drug release; and (vi) improving flow characteristics and simplifying handling, as they exist in solid rather than liquid form [1,4].

A variety of encapsulation methods—ranging from chemical to physical—have been developed, notably spray drying, fluid-bed coating, extrusion, coextrusion, molecular encapsulation, and multiple emulsions. Key chemical processes for forming microcapsules include phase separation, solvent evaporation, interfacial polymerization, coextrusion, coacervation, nanoencapsulation, and the use of liposomes.

Encapsulation has been extensively investigated by the pharmaceutical, food, cosmetics, textile, personal care, agricultural, chemical, biotechnology, biomedical, and sensor industries [5]. In medicine, one main advantage of using these materials is their ability to protect cells from immunological and inflammatory reactions that can occur after transplantation. Numerous applications for encapsulated cells are currently being researched for various illnesses, including diabetes, haemophilia, liver disease, anaemia, and central nervous system deficiencies [6]. When encapsulation technologies were first developed almost 60 years ago, they were intended to improve biotechnology production processes. These technologies enabled the more effective separation of producer cells and their metabolites by enclosing the cells in a protective matrix. These methods are much used in the food industry and have grown in importance in the pharmaceutical sector for the administration of drugs and vaccines [7]. In addition, the bioactive ingredients in functional foods provide health benefits, but it is crucial to preserve their properties during processing and absorption. Encapsulation protects these compounds by a coating material [8]. Delivering functional chemicals—particularly bioactive elements and micronutrients such as vitamins, polyphenols, and carotenoids—is best achieved through encapsulation technology. Despite their limited water solubility and susceptibility to degradation by light, oxygen, moisture, and temperature, these compounds exhibit

important biological activities, including antioxidant, anti-inflammatory, antibacterial, and antiviral properties [9].

The encapsulation of active compounds is growing in both academic and commercial research environments [10]. This review examines the medical applications of encapsulation technologies, specifically concerning nanoparticles, plant extracts, and essential oils. It provides a summary of the properties and selection criteria of wall materials and their effect on the release profiles of encapsulated substances. Furthermore, it discusses how these technologies enhance the stability and bioavailability of therapeutic agents, ultimately leading to improved treatment outcomes. By offering insights into these advances, this review aims to demonstrate that encapsulation improves the delivery and efficacy of therapeutic agents.

Encapsulation Processes

The design and effective use of encapsulation systems require a thorough understanding of the underlying physico-chemical mechanisms, possible interactions between active compounds and coating matrices, the stability of active compounds, and the release profiles from the coating matrix. The selected encapsulation method must ensure high encapsulation efficiency and optimal loading capacity for the active ingredients. The capsules must not aggregate or adhere. In addition, they must have a uniform particle size distribution, with no irregularities such as tails, threads, or bumps on the surface. Finally, the process must be suitable for large-scale production. The choice of encapsulation technique will depend on the characteristics and physical properties of both the core and shell materials [1,11].

Three major classes of processes can be employed to produce the most effective capsules (Table1):

- **Physico-chemical processes** based on variations in the solubility of coating agents.
- **Chemical processes** in which both the synthesis of the membrane or matrix and the encapsulation of the active ingredient occur simultaneously.
- **Physical processes**, such as extrusion or coating.

Table 1. Encapsulation methods.

Technique	Principle	Pros and cons	Core and wall material	Reference
Spray drying	This technique is used for microparticle formation because it is easy to implement on an industrial scale and allows continuous production.	- This technique can encapsulate both hydrophilic and hydrophobic base materials, a fast, flexible, and highly reproducible process. - The chief disadvantages are high operating temperature, difficulty in controlling particle size, and moderate yields for small-batch production	– Flavours and oils – Lipids (mono and diglycerides), proteins (casein, milk serum, and gelatin), and polysaccharides (starches, maltodextrins (MD), gum Arabic (GA), and corn syrups)	[9,12,13]
Pan-coating	In the food and pharmaceutical industries, one of the most basic physical encapsulation methods is coating granules, pellets, or tablets with a coating material solution by spinning them in a pan or other comparable device.	- Precise control of the coating thickness ensures a controlled release of the active ingredients. - Improved shelf life protects sensitive molecules (essential oils, probiotics, nanoparticles) from light, moisture, and oxidation. - Using solvents can pose problems of toxicity and evaporation, with some coatings requiring organic solvents. - the high cost of specific polymers and coating agents. - The potential impact on bioavailability must be taken into account, as a coating that is too thick can slow or prevent the release of the active ingredient.	– Microcrystalline Cellulose pellets – Starch octenyle succinate	[14,15,11]
Air suspension coating	The coating process disperses solid particles in a stream of air, followed by the application of a spray coating to the suspended particles. It differs from spray drying encapsulation, which creates particles with a uniformly mixed polymer matrix encasing the particle.	- The pharmaceutical and cosmetic sectors have established air-suspension particle coating, and the high cost of their finished product allows them to offset the process's expenses. - Coating airborne particles has been slow to develop in the food industry because of the economic constraints associated with the use of inexpensive ingredients and manufacturing processes	– Probiotic *Lactobacillusparacasei* cells – Maltodextrin, proteins (milk, nut), carbohydrates (starches, starch derivatives, gums), latexes (e.g., Eudragits®) and pseudolatexes (ethyl cellulose).	[105.102]
Centrifugal extrusion	Extrusion encapsulation is an efficient method of producing very dense encapsulated products. This method works well for creating particles with a diameter of 400–2,000 μm (16–79 mils).	- This is a simple technique that can be carried out. The advantage of extrusion is that the material is completely insulated by the die wall, allowing effective cleaning of the outside of the extruded product	– Vitamins, spices, and flavourings – Gum Arabic, maltodextrin, and modified starch	[9,35]
Ionic gelation	It is a gentle method because it avoids the use of organic solvents and potentially toxic surfactants. It is mainly based on the use of hydrophilic natural polymers for the preparation of particulate supports, such as chitosan, gelatin, agarose, and alginate.	- It is inexpensive and does not require organic solvents, high temperatures, or specialist equipment. This approach works better when encasing hydrophobic materials	– Betaxanthins (Opuntia *megacantha*), the probiotic *Lactobacillus acidophilus* – Phytic acid (PA) and chitosan	[5,62]
Coacervation	This is the separation of two liquid phases in a colloidal solution. The technique can differ in complexity, being simple when a single polymer is used and more complex when there are two polymers..	- The major disadvantages of simple coacervation by salting are the difficulty in controlling the size of the capsules and the risk of their agglomeration.	– Protein (β-galactosidase, Bovine serum albumin (BSA), Ergosterol) – Poly(ethylene glycol)-block-poly(α,β-aspartate acid), Chitosan, whey protein	[14,64]

Sol-gel method	Almost all reactions with a metal or metalloid element that can form polymer structures in solution through the formation of organic bonds can be called sol-gel reactions. The sol-gel technique is an effective method for creating a host matrix.	- It requires little capital investment and respects the environment. Silica-based sol-gel microparticle encapsulation is regarded as an economically viable method of production	– Enzymes, antibodies, and proteins – Poly(ethylene glycol) (PEG), poly (vinylimidazole) (PVI), or poly(ethyleneimine) (PEI)	[8,46]
Polymerization In situ	The in situ polymerization process, which is mainly used to manufacture nanocomposites, emulsifies the monomer, generally a vinyl or acrylic compound such as styrene or methyl methacrylate, in an aqueous phase enriched with a suitable surfactant.	- High loading capacity for both hydrophilic and hydrophobic compounds because of strong encapsulation efficiency. - Polymer residues: Purification procedures might be necessary for unreacted monomers. - Possible Effect on Bioactivity: Severe polymerization conditions could change how encapsulated compounds function.	– Peptides, proteins, enzymes, drugs, and aluminium nanoparticles – Polyvinylidene fluoride (PVDF)	[33,34]
Polymerization Interfacial	Interfacial polymerization is a step-growth polymerization process that takes place at the interface of two immiscible phases. In contrast to bulk polymerization, it produces polymer materials with unique topological and chemical properties, such as anisotropic shapes, hollow structures, and distinct surface chemistry. This makes it a key technique for producing polymer particles and membranes.	- Sustainable Development: Techniques for interfacial polymerization have improved as a result of developments in polymer chemistry. - Controlled Interface Formation: With the reaction limited to the interface between two immiscible liquids, the characteristics of the film or capsule may be precisely controlled. - Dependency on Solvents: The procedure makes extensive use of solvents, which can be hazardous and cause evaporation problems. -.Cost and Efficiency: It can be difficult to find greener alternatives or reduce the use of solvents, which could raise production prices.	– Drugs, dyes, enzymes – PANI, PPy, poly(3,4-ethylenedioxythiophene) (PEDOT), and polythiophene (PTh)	[35,36]
Polymerization Emulsion	The emulsion is a common method for encapsulating bioactive substances in aqueous solutions. Emulsions split into two immiscible liquids with droplet sizes ranging from 50 to 1,000 nm, one of which is spread inside the other.	- Emulsion polymerization offers the advantage of producing a final product that is normally ready to use without modification. - The principal disadvantages of this method are that surfactants and other additives can adhere to the polymer or be difficult to remove.	– Drugs, peptides, proteins, dyes, pigments, fragrances, photo-initiators, magnetite, and DNA – Chitosan (CHI), alginate sodium (ALG)	[79]
Polymerization Suspension	In order to create polymer particles, suspension polymerization uses an oil-soluble monomer and initiator distributed as liquid droplets with a steric stabilizer and rapid stirring.	- The advantages of this technique are that it is simple, cheap, robust, and environment-friendly. - Restricted to insoluble polymers: its application is limited to polymers that are insoluble in the continuous phase. - Post-processing needed: the finished polymer beads require drying, washing, and occasionally further purification procedures.	– Paraffin wax (core) – Polystyrene shell	[92,97]

The Main Materials Used in the Nano-encapsulation Process

Proper manufacturing using the appropriate wall materials is one of the most important processes in the formulation of nano-encapsulation. Many substances are used to encapsulate solid or liquid components. The materials chosen for encapsulation are selected according to the type, origin, and characteristics of these components, potential coating material limitations, the concentration of encapsulates, the type of release, and stability requirements [7,21]. The materials most commonly used for encapsulation include carbohydrates, gums, polysaccharides (e.g., cellulose, starch, chitin, alginates, pectin), polymers, proteins (e.g., gelatine, corn zein, wheat gluten, soy protein, casein, keratin, collagen, whey), lipids (e.g. wax and oil-based coatings, fatty acids and monoglycerides, resins and rosins, emulsions, and composite bilayer coatings consisting of polysaccharides, proteins, and lipids), as well as other organic and inorganic materials. In this section, we describe some of the most commonly used materials (Table 2) [42,43].

Table 2. General view of encapsulation technologies.

Encapsulant Material	Example	Uses	Reference
Carbohydrate	Starch	The delivery of sensitive ingredients through food	[44]
	Alginate (Alg) hydrogels	Encapsulating probiotics.	[45]
	Celluloses and derivatives	It has been used to immobilize bacteria and yeasts for the production of wine and beer.	[9]
	Gums	Used as a flavour-encapsulating material	[46]
	Chitosan	It has been used in the food industry to encapsulate probiotics and prebiotics, flavours, enzymes, antioxidants, and vitamins.	[9]
	Pectin	Encapsulates the bioactive compounds.	[9]
Proteins	Gelatin	Low moisture or oil phase food components and medications are encapsulated in gelatin.	[47]
	Whey proteins	They offer a useful foundation for spray drying to microencapsulate volatiles.	[43]
Lipids	Waxes and Paraffin	Aroma encapsulation barrier films to gas and moisture (skin on fresh fruits)	[46]
	Liposomes	Encapsulating any compound	[48,50]
	Shellac Resins	Used in coatings for the pharmaceutical industry	[50]

Carbohydrates

Carbohydrates constitute more than 90% of the dry mass of all biomass, with over 90% existing as carbohydrate polymers known as polysaccharides. These natural homo- and copolymers are formed from sugar residues and/or their derivatives [48]. Carbohydrates are commonly used as wall materials

or carriers in spray-dried encapsulations for culinary components [51]. The most widely used carbohydrate-based wall components include starch and starch derivatives (such as maltodextrin), cellulose derivatives (such as carboxymethyl cellulose), gums (including gum Arabic, guar gum, and chia seed gum), and β-cyclodextrin [21]. Starch can be used as a wall material for encapsulating bioactive molecules via electrospinning, allowing the creation of nanocapsules or nanofibres [52]. Starch derivatives, such as succinylated, acetylated, and phosphorylated forms, are effective encapsulating agents during the spray drying of flavours and pigments.

These materials exhibit excellent solubility and reduced viscosity in solution, as well as good emulsifying and drying properties [53]. Poly-β(1,4)-D-glucose units form the long, linear, polydispersed biopolymer known as cellulose. Its biodegradability, abundance as a renewable resource, and compatibility with biological systems make it highly valuable. But, because of their potential for absorption and associated harmful effects, cellulose-based nanocarriers that are not degraded by microbial or colonic enzymes and remain at the nanoscale should be used with caution [52,54]. β-cyclodextrins, alginates, and chitosan are newer carbohydrate-based wall materials that are being researched for various applications in the food industry [20]. One of the most widely used polyanions for microencapsulation is alginate, a natural polysaccharide derived from various species of algae [9,56]. Cyclodextrins are a type of cyclic oligosaccharide composed of six to eight glucose molecules (α-(1→4)-D-glucopyranoside units). Cyclodextrins absorbed in the upper gastrointestinal tract are not digested; instead, they are fully broken down by the colon's microbiota [48]. Because fat-soluble vitamins and hormones have very poor solubility in aqueous solutions, cyclodextrins are used as excipients to enhance their solubility [57]. Chitosan (CS), a cationic polymer composed of D-glucosamine and N-acetylglucosamine residues connected by β-(1→4) linkages, is produced commercially by the partial deacetylation of chitin, which is extracted from crustaceans [58]. Every terrestrial plant organ contains pectin, both in the parenchyma and meristematic tissue. Pectins are non-toxic, poorly soluble in the upper gastrointestinal tract, and resistant to degradation by intestinal or gastric enzymes [47,59]. Gum Arabic is one of the most commonly used wall materials in spray microencapsulation. Although thickeners and gums are generally bland or tasteless, they can significantly influence the flavour and taste of food [46]. Although gum Arabic exhibits many desirable characteristics of an ideal encapsulant, such as high solubility, low viscosity, and good emulsifying properties, it also has drawbacks, including high cost and limited availability [60]. Alginate, a linear polysaccharide derived from brown sea algae, consists of alternating blocks of β-D-mannuronic acid (M residues) and α-L-guluronic acid (G residues), which are joined by a single linkage [54]. Because of its unique colloidal properties—such as gel formation, film formation, stabilization, thickening, and emulsion stabilization—alginate can be used to create biopolymer films

or coating materials [61]. Additionally, alginate, when combined with other wall materials, helps prevent capsule rupture in situ [62].

Proteins

Natural macromolecules (proteins) are composed of linear chains of amino acids. The great diversity of amino acids in the chain arises from the possible sequences and frequency of the 20 amino acids known to exist, or more specifically, from 19 amino acids [48]. Generally speaking, proteins are derived from both plants and animals. Whey protein, casein, gelatine, and collagen are the most commonly used animal proteins in encapsulation; soy protein, zein, and gliadin are the most frequently employed plant-derived proteins [63]. Finding pharmaceutically active proteins for drug delivery research can be challenging. To maintain the biological activity of proteins, the encapsulation mechanism must ensure that they are delivered in their natural folding state [64]. Collagen is a fibrous, insoluble protein mainly found in skin, bones, and connective tissue. It may be hydrolysed under controlled conditions to yield gelatine [43]. Gelatins vary considerably in terms of size and filler distribution. Their specific primary structure is defined by the base collagen. All chains contain almost one in three glycine units, followed by proline and 4-hydroxyproline, which are the most common residues [48]. This material is soluble in water and can form walls when a mixture of water, volatile fragrance compounds, and wall material is spray-dried [65].

Gelatine (20–30%), plasticiser (10–30%) (glycerin or sorbitol), and 40–70% water can be used to produce gelatine films. The gelatin gel can then be dried [66]. Whey proteins, derived from the cheese-making process, account for approximately 20% of the total proteins in bovine milk. As soluble milk proteins, they have high nutritional and biological value, and also they are also rich in essential amino acids. These functional properties make them sought-after ingredients in a variety of food and health products [67,68].

Lipids

Lipids are hydrophobic and insoluble in water. They are widely used to encapsulate hydrophilic substances [21]. Lipids encompass a wide range of structurally diverse compounds and substances, including phospholipids, oils, fats, and waxes. In nature, these are widely distributed [70]. Beeswax and paraffin stand out as the most efficient among them [43]. Waxes are esters of fatty acids. Unlike fats and oils, fatty acids in waxes are esterified with long-chain monovalent primary alcohols rather than glycerol [48].

Liposomes and nanoliposomes are phospholipid bilayer structures composed of a hydrophilic head and two hydrophobic fatty acid tails. Liposomes are synthetic vesicles made of cholesterol and lecithin, naturally occurring phospholipids, which serve as wall components [49]. They are

considered promising vectors for the food industry because they can encapsulate water-soluble, lipid-soluble, and amphiphilic substances [9]. According to Kim *et al.* [73], the use of liposomes in the food sector remains limited because they are unstable, leak the active agent during storage, yield low levels of encapsulation, and their raw materials have a high cost.

The insect *Laccifer lacca* secretes shellac resins, which consist of a complex blend of aliphatic and alicyclic hydroxyl acid polymers. This resin is soluble in alcohols and alkaline liquids. Shellac is only permitted as an indirect food additive in food coatings and adhesives, as it is not classified as a generally recognized as safe (GRAS) substance [43].

Advances in Encapsulating Technologies and Applications

Encapsulation of Nanoparticles

The application of embedded or encapsulated nanoparticles is extremely promising for the controlled delivery of drugs, genes, and other bioactive agents [74]. Microencapsulation provides an efficient solution to the challenges faced by the food, textile, cosmetics, and pharmaceutical industries. It enables the targeted delivery of chemicals in their active state. In the pharmaceutical sector, microencapsulation technology is commonly used for flavour masking, improved stability, and controlled drug release [75]. The encapsulation of drugs is a viable approach to overcoming the drawbacks of traditional dosage forms, including inadequate bioavailability, stability, taste, and odour [76]. In many cases, bioactive drugs must be encapsulated in coating materials to protect them from harsh environmental conditions and treatments, while ensuring their absorption occurs at the right place and time [6].

For example, nanoparticles derived from the polymer poly(D, L-lactide-co-glycolide) (PLGA) have been developed to create safe and effective vectors for carboplatin. Carboplatin is commonly used to treat various malignant tumours, such as ovarian, lung, head, and neck cancers. These nanoparticles are small enough to be efficiently taken up by tumour cells, facilitating the controlled release of the encapsulated payload [78,79]. The precise targeting and controlled activity of anti-cancer drugs in nanocapsules (NCs) make them a highly promising option. They can be employed as agents or vectors for targeted drug delivery, as well as biosensors or tools in medical imaging for cancer detection [80]. As a result, both in vitro and in vivo studies have demonstrated improved coordination with various cancer cells compared to non-targeted liposomes. Liposomes have generally been used as drug carriers within the body, leading to reduced toxicity and enhanced tolerance to administration [81].

One natural phytochemical that has attracted significant interest in cancer prevention and anti-cancer treatment is curcumin (diferuloylmethane) [82]. But, curcumin has limited systemic bioavailability and poor pharmacokinetics, perhaps because it is lipophilic, which has restricted its effectiveness in vivo [83]. To enhance its efficacy in cancer treatment, curcumin was incorporated into nanoparticles

of poly(lactic-co-glycolide) (PLGA), a biodegradable polymer, using nanoprecipitation, with the addition of stabilizers such as poly(vinyl alcohol) and poly(L-lysine) [84]. Most drug delivery systems are designed to improve treatment efficacy by encapsulating active molecules. The local and sustained release of active molecules enhances the stability of therapeutic agents, improves their targeting properties, and prolongs their pharmacological activity through encapsulation [85].

In the field of cell encapsulation, significant advances have been made over the past fifty years. This technology has become essential for eliminating the need for regular medication administration, offering a biocompatible matrix for controlled drug release [86]. Challenges remain, particularly regarding organ transplant rejection, the shortage of functional organs, and the adverse effects of immunosuppressive drugs [87]. Nanoparticles have been employed as a physical approach to modifying and enhancing the pharmacokinetic and pharmacodynamic properties of various drug molecules. In vivo, they have been used to protect the active ingredient in systemic circulation, restrict drug access to specific sites, and facilitate controlled and sustained drug release at the site of action [88].

Lactic acid bacteria are among the many bacteria that produce bacteriocins, which are polypeptide compounds with antimicrobial activity (AMAs). Several techniques have been employed to encapsulate the bacteriocins produced by lactic acid bacteria to protect them from unfavourable environmental conditions and incompatibilities. A process known as electrospinning has been used to incorporate bacteriocins into nanofibres. The potential application of these nanofibres in biomedical fields has been studied, with most research highlighting their promising relevance for scaffold creation in tissue engineering [89,90]. Additionally, liposomes have gained popularity as efficient carriers for DNA, siRNA, and antisense oligonucleotides, further expanding their role in drug delivery [81].

Bimetallic metal nanoparticles play a crucial role because of their unique properties, which differ from those of individual metals. These materials are of particular interest in catalysis [91]. But, during the catalytic process, coalescence migration may readily deactivate them [92]. Therefore, researchers have incorporated metal nanoparticles into nanoshells or nanopores. This physical isolation prevents the particles from merging, thereby enhancing their catalytic stability [93].

For biological applications, gold nanoparticles (GNPs) are the most widely used inorganic nanoparticles because of their distinctive chemical and physical characteristics [94,110]. Biological molecules provide essential interfaces for interactions between the nanoparticles and the biological environment while also conferring biological functionality. Self-assembled protein nanoparticles (SAPNs) have therefore been selected to encapsulate gold nanoparticles [95].

Retinol and its derivative complexes are widely used in the pharmaceutical and cosmetics sectors. Furthermore, retinoids stimulate dermal fibroblasts to produce extracellular matrix proteins such as

collagen I [96]. But, retinol and its analogues, including retinoids, retinol, and retinyl palmitate, have problems of stability and solubility. To overcome these, researchers have incorporated retinol into chitosan nanoparticles for intravenous delivery, which can improve its aqueous solubility and therapeutic efficacy [97].

One of the main problems in developing polymer-based injectable delivery systems is the initial release of the drug, which occurs within the first few minutes of contact with the external environment [98]. Microparticulate systems often experience burst release, which is unpredictable and difficult to control. This can be mitigated by modifying the drug distribution within the polymer matrix or by developing more advanced drug delivery systems [99]. For example, liposomes encapsulated in dextran and alginate microcapsules can control drug release, avoiding the burst effect and improving stability [100,102]. This approach is particularly valuable for treating chronic diseases that require long-term medication, as it ensures sustained therapeutic effects and improves drug retention.

Encapsulation of Essential Oil

Interest in essential oils (EO) is growing in various fields. As natural products, their physicochemical characteristics offer high added value and are environmentally friendly. Moreover, essential oils have various and significant biological activities. For example, they are used in the medical sector for their bactericidal, virucidal, and fungicidal properties, as well as their medicinal virtues [28]. Nevertheless, their volatility, low solubility in water, and sensitivity to oxidation limit their use. Encapsulating essential oils can mitigate these features and enhance their biological activities [103].

Microbiological contamination is a major cause of food spoilage, leading to the deterioration of nutritional, health, and sensory qualities. But, essential plant oils (EO), which are generally recognized as safe (GRAS) by the FAO/WHO (2008) and often have antimicrobial properties, could represent a promising natural alternative to the use of chemical preservatives in food [104,105]. Currently, there are several methods to preserve food: (a) the use of aseptic techniques during handling and packaging, (b) the mechanical elimination of micro-organisms by washing or filtration, (c) the destruction of micro-organisms by disinfection processes, whether physical or chemical and finally, (d) the inhibition of pathogens or saprophytes by controlling environmental conditions [98]. Natural antimicrobials are gaining interest because of growing consumer awareness of food safety. Encapsulation can enhance the concentration of bioactive substances in food matrices, particularly in water-rich phases or liquid-solid interfaces, where microorganisms thrive [99]. There is a project on the encapsulation of essential oils in nanometric delivery systems for use in fruit juices. The aim is to improve their antimicrobial activity while reducing the impact on the quality characteristics of the final product [101].

Beyond food applications, essential oils are also being studied as potential solutions to combat multidrug-resistant (MDR) bacteria, a major global health threat. According to the US Centers for Disease Control and Prevention, MDR infections affect approximately 2 million people annually, resulting in nearly 23,000 deaths [102]. Many plant-derived bioactive compounds, including essential oils, have demonstrated strong antibacterial activity, even against biofilms [103]. For example, ionotropic gelation was used to encapsulate essential oils of Schinus molle, thyme, and cinnamon (*Cinnamomum zeylanicum*) at concentrations of 125, 250, and 500 µg/mL in chitosan nanoparticles. In comparison to chitosan and essential oils alone, chitosan nanoparticles with these oils showed a stronger antimicrobial effect against *Pseudomonas aeruginosa*, which produces carbapenemase, *Staphylococcus aureus ATCC 25923*, *Enterococcus sp.*, *Escherichia coli ATCC 25922*, and *Klebsiella pneumonia* (BLEE +) [104].

Encapsulation of Bioactive Compounds

Since ancient times, herbs have been used as foods, medicines, and cosmetics. These bioactive compounds can be sensitive to environmental stresses such as oxygen, water, and light during processing, storage, and transport. Encapsulation provides effective protection, preserving their nutritional value, bioavailability, solubility, and functionality [105].

Studies have shown that plant extracts can be encapsulated and used as functional ingredients in food matrices. Additionally, they are employed in the production of active packaging, edible films, and food coatings. Among the many benefits that cyclodextrins, which are ring-shaped oligosaccharides, offer to the substances they encapsulate are: i) flavour and odour masking, ii) enhanced water solubility, and iii) regulated release of the encapsulated substance. The use of these cyclodextrins to encapsulate hydrophobic compounds has facilitated the development of functional foods with improved physicochemical and sensory properties [106].

In traditional medicine, various disorders are treated with species of the genus *Plectranthus*. Extracts from *Plectranthus ecklonii*, *P. grandidentatus*, *P. ornatus*, *P. porcatus*, and *P. saccatus* were obtained using infusion, decoction, microwave-assisted, and ultrasonic extraction methods. A comparative study aimed to identify the most bioactive extract for encapsulation in alginate beads. The microwave-assisted extraction of *Plectranthus ecklonii* yielded the highest concentration of polyphenols and exhibited strong antioxidant activity as well as effective acetylcholinesterase inhibition. This bioactive extract was successfully encapsulated in polymer particles [107].

Other plant-derived compounds have also been successfully encapsulated. Research was conducted on the encapsulation of extracts from raspberry, hawthorn, ground ivy, yarrow, nettle, and olive

leaves. This encapsulation was achieved using electrostatic extrusion in microbeads composed of alginate and chitosan, with ascorbic acid used to dissolve the chitosan. Ascorbic acid was employed to improve the solubility of the chitosan, thereby enhancing the antioxidant potential of the encapsulated plant polyphenolic extracts [108]. A study evaluated how encapsulating antimicrobial substances (e.g., herbs, spices, lysozyme, and nisin) affected their efficacy and stability. Two Gram-positive (*Bacillus subtilis* and *Micrococcus luteus*) and two Gram-negative (*Escherichia coli* and *Serratia marcescens*) bacteria were used to investigate the antimicrobial activity. Successful encapsulation was achieved in various polysaccharide particles and liposomes. Liposomes containing plant and spice extracts demonstrated highly effective inhibition against all the bacterial strains examined [109].

The use of microencapsulation is also expanding in the personal care and cosmetics industries. Many physiologically active compounds used in personal hygiene and cosmetic products are unstable and highly sensitive to pH changes, light, temperature, and oxidation. Plants contain phenolic compounds, secondary metabolites with ideal structural characteristics that act as antioxidants and anti-inflammatories. They can deteriorate through sensitivity to light and temperature. An effective method for enhancing their bioavailability and solubility is encapsulation in liposomes [111]. Liposomes also facilitate deeper penetration into the skin, reaching the dermis and epidermis before being absorbed into the bloodstream [112]. Nanoliposomes (PEF-NL) have been used to encapsulate the phenolic-enriched fraction, providing a new delivery system. PEF-NLs offer promising potential in the cosmetics industry for addressing skin pigmentation problems and as a skin whitening agent [113].

The cosmetics industry has also taken an increasing interest in the encapsulation of natural ingredients. This industry is now using another delivery system: the dendrimer. This delivery system consists of highly branched, compact, symmetrical, and spherical polymers [114]. As skincare products continue to evolve, ensuring high quality and rigorous scientific validation becomes increasingly important. Nanoparticles, with their small size and large surface area, are particularly well-suited for delivering active ingredients. A study by Lages *et al*. [59] highlighted the role of lipid nanoparticles in transdermal drug delivery, emphasizing their widespread use in modern cosmetic formulations.

Conclusion

This study investigates the diverse applications of encapsulation technologies in medicine, with a specific focus on nanoparticles, plant extracts, and essential oils. We highlight the critical role of wall materials in determining the efficacy and stability of these therapeutic agents. The integration of encapsulation into medical practices is leading to more effective strategies and improved patient

outcomes. To enhance patient care and develop innovative treatments that fully harness the benefits of encapsulated bioactive compounds, research and development should continue.

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Eryngium Ilicifolium: A Review of its Botanical, Chemical, and Medicinal Properties

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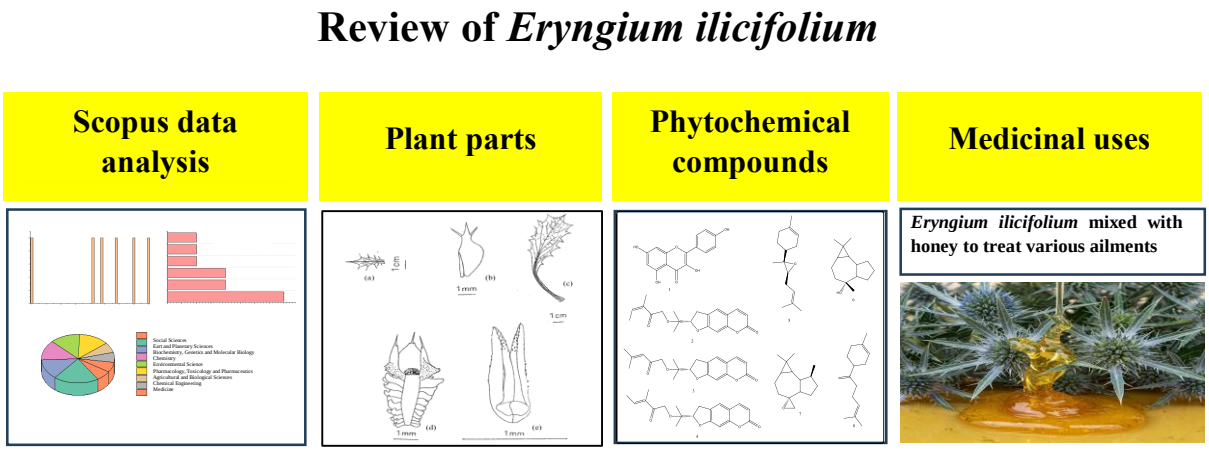
Graphical Abstract

This study is the first bibliographic review of *Eryngium ilicifolium*. We consulted Google Scholar, Elsevier, Medline, Web of Science and Scopus databases to gather information. We then reviewed the botanical, chemical and medicinal properties of this plant.



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Abstract: Researchers identified 250 species in the *Eryngium* genus used as traditional medicines. These plants have been exploited to treat various diseases like hypertension, asthma, digestive issues, and infections. Studies show promising biological activities and bioactive compounds in many *Eryngium* species. The aim of the present study was to review the literature on *Eryngium ilicifolium*. The databases used were Google Scholar, Elsevier, Medline, Web of Science and Scopus. *Eryngium ilicifolium*, belonging to Apiaceae, a common plant in the Mediterranean (Morocco, Algeria, Tunisia), has a long history of use in traditional medicine. *Eryngium ilicifolium* has been used as a mixture with honey or orange juice to treat digestive issues, gastritis, colds, rheumatoid arthritis, treatment of angina, laryngitis and pharyngitis. Chemical analysis of this plant reveals the presence of potentially beneficial compounds (Oxygenated Sesquiterpenes, Terpenes Sterols, Gallic Tannins, and Saponins Quinones). Studies using extracts of *Eryngium ilicifolium* show some effectiveness against microorganisms.

Keywords*: Eryngium ilicifolium, Antibacterial activity, Bioactive compounds.*

Introduction

Eryngium boasts over 250 identified flowering species [1,2], found across North Africa, western and southwestern Eurasia, the Americas, and Australia [3]. Research has revealed a wealth of biological activities associated with *Eryngium* oils and extracts. These include antioxidant [4,5], antifungal [4], antibacterial [5-7], and anti-inflammatory [8] properties. Excitingly, recent studies have successfully isolated and identified new bioactive natural compounds from *Eryngium* plants. These include phenols [9], triterpene saponins [9,10], flavonoids [11], monoterpenes [12], and oxygenated sesquiterpenes [13].

The genus *Eryngium* (Apiaceae) is present in Morocco with 20 species [14]. This botanical richness represents a significant opportunity for the exploitation of the plants as medicinal agents. Within this diverse genus, the rich Moroccan flora conceals several species of *Eryngium*, including *Eryngium ilicifolium* (Fig. 1, [14]), which appears to be a subject of particular interest. *Eryngium ilicifolium* is found across West and North-West Africa according to climate zones [15,16], with a presence even in Spain [17]. This plant, also known as Al ausfour [18], Chouk aj-jmil or Chouka zerga [19], Tasnant or Iglifen [20], and Zerriga [21].

Traditionally, *Eryngium ilicifolium* has been used in Morocco to treat various ailments like digestive disorders, gastritis, colds, rheumatoid arthritis, angina, laryngitis, and pharyngitis [16,18]. People often prepare remedies by mixing the plant with honey or orange juice. Honey made solely from *Eryngium ilicifolium* flowers (unifloral honey) is considered to be of high quality [22].

The rise of antibiotic resistance necessitates the discovery of new antimicrobial compounds with novel mechanisms of action. *Eryngium ilicifolium* has emerged as a promising candidate because of its reported antibiofilm [23], antibacterial and antifungal activities [5,24]. The present study aims to review the scientific literature on the botanical, chemical, and medicinal properties of organic extracts of *Eryngium ilicifolium*, covering its botanical description, traditional uses, extraction methods, phytochemicals of biological activities (antibacterial activity and cytotoxic effect).

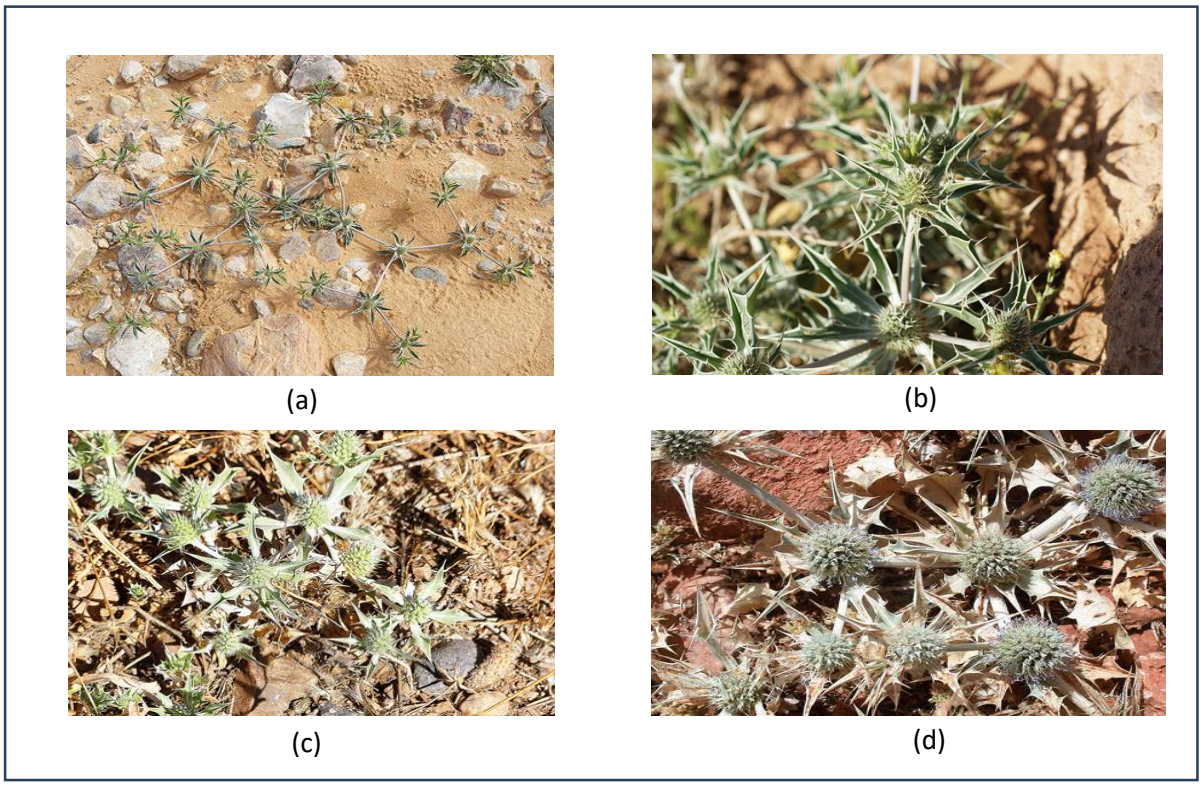

Figure 1. Morphological characteristics of *Eryngium ilicifolium* observed in its natural habitat.

Methodology

This research was based on Google Scholar, Elsevier, Medline, Web of Science, and Scopus databases to extract all data about Phytochemical Analysis, Antimicrobial Activity and Cytotoxic Effect of Organic Extracts from *Eryngium ilicifolium* plant. The search terms used were "*Eryngium ilicifolium*", "traditional uses of *Eryngium ilicifolium*", "antimicrobial activity of extracts from *Eryngium ilicifolium"*, "antioxidant activity of extracts from *Eryngium ilicifolium*", "bioactive phytochemicals and compounds isolated from *Eryngium ilicifolium*". Analysis of Scopus data with the keyword "*Eryngium ilicifolium*" (search in article title, abstract, and keywords) revealed a limited number of documents (A); only six countries have studied this plant (B) in different fields (C), as shown in (Fig. 2).

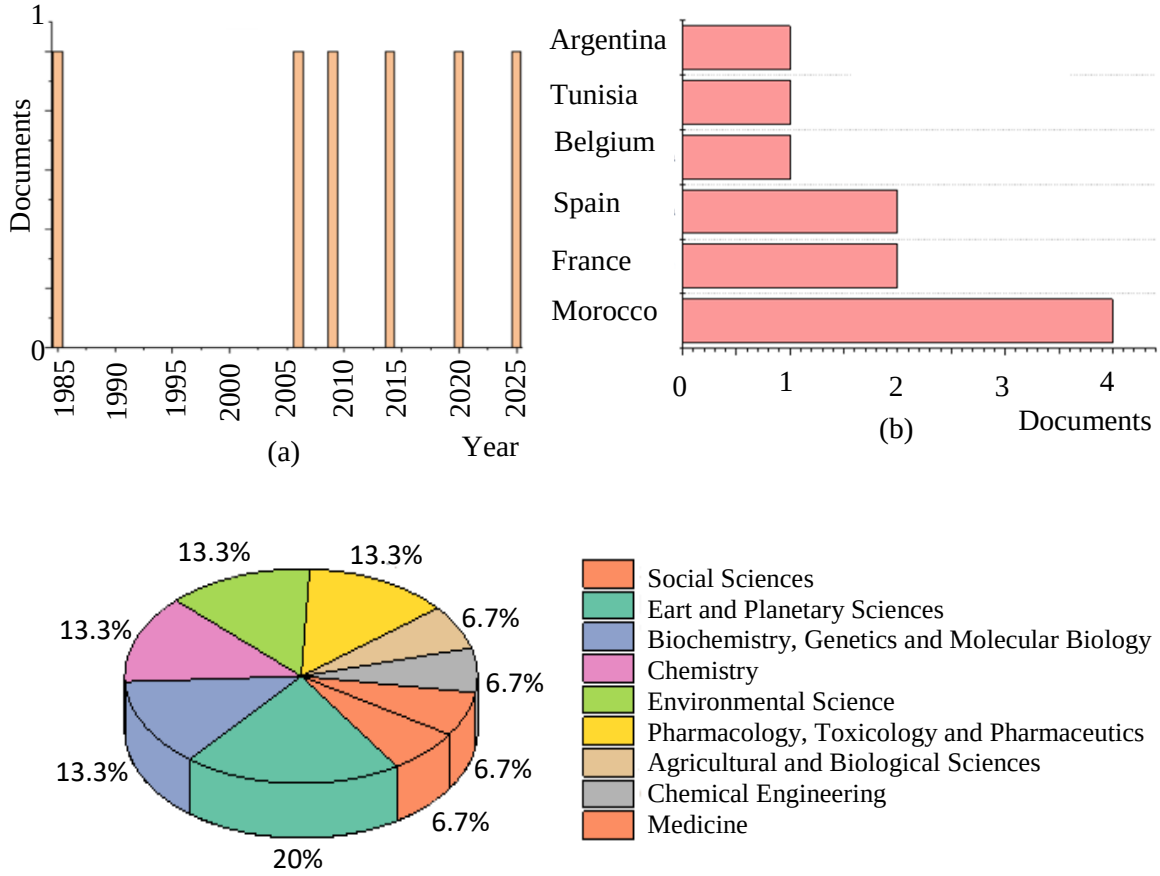

Figure 2. (a) Number of documents on *Eryngium ilicifolium* by year; (b) Geographic distribution of publications by country; (c) Scientific fields associated with *Eryngium ilicifolium* research.

Botanical Description

The information presented in this section is compiled from the book "Révision des *Eryngium* d'Afrique du Nord" by Breton (1962) [25]. *Eryngium ilicifolium* exhibits a period of active growth between April and July. This green annual plant, with a long and slender taproot, has a single stem growing up to three centimeters tall. It has few branches, some of which can be longer than the main stem. The basal leaves form a rosette at the ground level. These soft, glaucous green leaves are rounded at the tip and have seven-nine parallel veins that spread out near the base. The edges are lined with spiny teeth, and the leaves narrow into a well-developed stalk. There are two or three leaves on the stem, near the base of the flower clusters. These leaves can resemble the basal leaves, but some are more triangular in shape with a white, hardened edge and larger spines. The flower clusters themselves are oval-shaped, stalkless, and packed with small flowers. Each cluster has five-six bracts that look like the upper leaves on the stem. The flower bracts are unique. Unlike the other bracts, they protrude from the flowers and have a bumpy texture. They are wide at the base and abruptly narrow into a three-pointed structure with spines. Some of these bracts can be longer and form a tuft at the top of the cluster. The tiny flowers have sepals with a pointed tip and translucent, finely toothed

edges. Four of these sepals have an additional, bumpy, and toothed flap on the side or back. The petals are shorter than the sepals and have a wavy edge. They sit on a base that completely surrounds the base of the flower's style (Fig. 3).

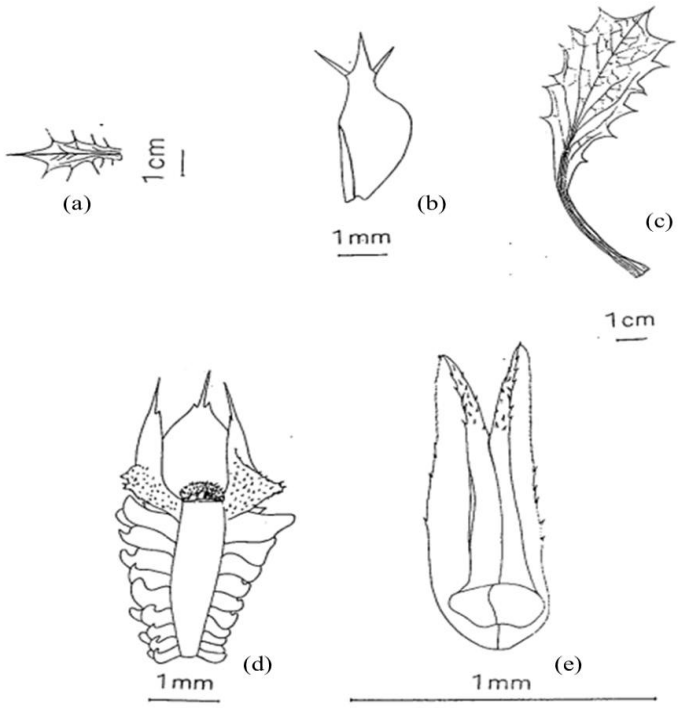

Figure 3. Dimensions of various plant parts in *Eryngium ilicifolium*: (a) Stem leaf, (b) Floral bract, (c) Radical leaf, (d) Mericarps seen from their commissural side, (e) Petals.

Traditional Uses

Traditional use of *Eryngium ilicifolium*, as reported in literature, appears to be concentrated in Morocco. *Eryngium ilicifolium* occupies a significant position within the framework of traditional Moroccan medicine, with diverse application documented across various geographical regions. In the Marrakesh region, the root is traditionally employed to promote weight gain and as a general tonic [26]. The root decoction is widely used throughout Morocco for the treatment of digestive disorders, such as gastritis, and to relieve the symptoms of the common cold [18,20]. In the context of respiratory conditions, the whole plant from the Beni-Mellal area is crushed and combined with honey, with the aim of treating angina [21]. The root decoction is also used throughout the country for the treatment of musculoskeletal and rheumatoid arthritis [18,20,26]. Regarding metabolic disorders, an ethnobotanical survey reported its use in the treatment of diabetes in the regions of Chtouka, Ait Baha and Tiznit [20]. In addition, *Eryngium ilicifolium* has notable veterinary applications, particularly in the northern Rif region, where decoction of the plant's aerial parts is administered to sheep to treat i nternal and external parasites, as well as other health problems [18]. Moreover, the roots of *Eryngium ilicifolium* are employed in the treatment of amenorrhoea [15].

The effectiveness of *Eryngium ilicifolium* can vary, depending on where it grows. This is because the plant's chemical makeup can differ based on its location. Traditional uses are widespread, but scientific studies with human users are needed to confirm the proposed therapeutic benefits of *Eryngium ilicifolium*.

Extraction Methods

Eryngium ilicifolium has been studied using four main extraction methods: Soxhlet extraction, decoction, maceration and ultrasonication.

Soxhlet extraction is a technique which uses continuous solvent reflux to isolate the desired compounds from a solid sample. The solvent circulates repeatedly through the material, dissolving the compounds of interest. These are then collected in a separate flask. In one procedure, 600 g of dried and finely powdered whole plants were extracted with diethyl ether [17]. In another, 50 g of ground plant material were placed in a Soxhlet apparatus with 150 ml of a low-polarity solvent. After recovery of the initial extract, a medium-polarity solvent was added and then a high-polarity solvent to complete the extraction cycle. Two progressively polar solvent systems were used: the first consisting of petroleum ether, diethyl ether and ethanol; the second comprising cyclohexane, ethyl acetate and methanol [23].

The decoction method consists of boiling the plant material in water. This helps to break down the cell walls and release the active constituents. In this study, the dried aerial parts of each plant were extracted using both water decoction and methanol [5]. Maceration is a simple technique in which a plant is soaked in a solvent at room temperature, allowing diffusion and osmosis to extract bioactive compounds. The process was carried out by stirring the material three times for 30 minutes at room temperature. Sequential extraction was used to isolate compounds based on polarity. Petroleum ether, dichloromethane and methanol were used successively at a ratio of 1 g of plant material to 10 ml of solvent [24]. Ultrasonic assisted extraction was performed by mixing 20 g of powdered plant material with 200 ml of different solvents (ethanol, methanol, petroleum ether, diethyl ether, cyclohexane and ethyl acetate) in a beaker. This was followed by sonication at 30°C for 1 hour [23].

These extraction methods are also commonly employed to extract bioactive compounds from other species of the same genus *Eryngium*, such as *Eryngium caucasicum inflorescence* [27], *Eryngium planum*, *Eryngium campestre* and *Eryngium maritimum* [28], *Eryngium creticum* [29] and *Eryngium foetidum* [8,30].

Phytochemicals of bioactive compounds

Despite the identification of diverse bioactive compounds within *Eryngium* species. *Eryngium ilicifolium* has received relatively limited research attention. To date, only three compounds have been isolated and characterized, and a few additional families have been identified.

The first identified compound, kaempferol (1), was detected in 1969 [31]. Sixteen years later, researchers isolated three coumarins (deltoin (2), prantschimgine (3) and (+)-marmesin tiglate (4)) from the roots and aerial parts of *Eryngium ilicifolium* [17]. Leucoanthocyanins, terpenes, sterols, gallic tannins, saponins, quinones, and flavonoids were screened in a methanolic extract [5]. Oxygenated sesquiterpenes like cis-Z-α-bisabolene epoxide (5), ledol (6), aromadendrene oxide 2 (7), and β-bisabolene (8) in a petroleum ether extract by using the GC/MS analysis [24].

Chemical analyses of *Eryngium* plants, including *Eryngium ilicifolium*, have identified various molecules known to possess biological activity (Fig. 4).

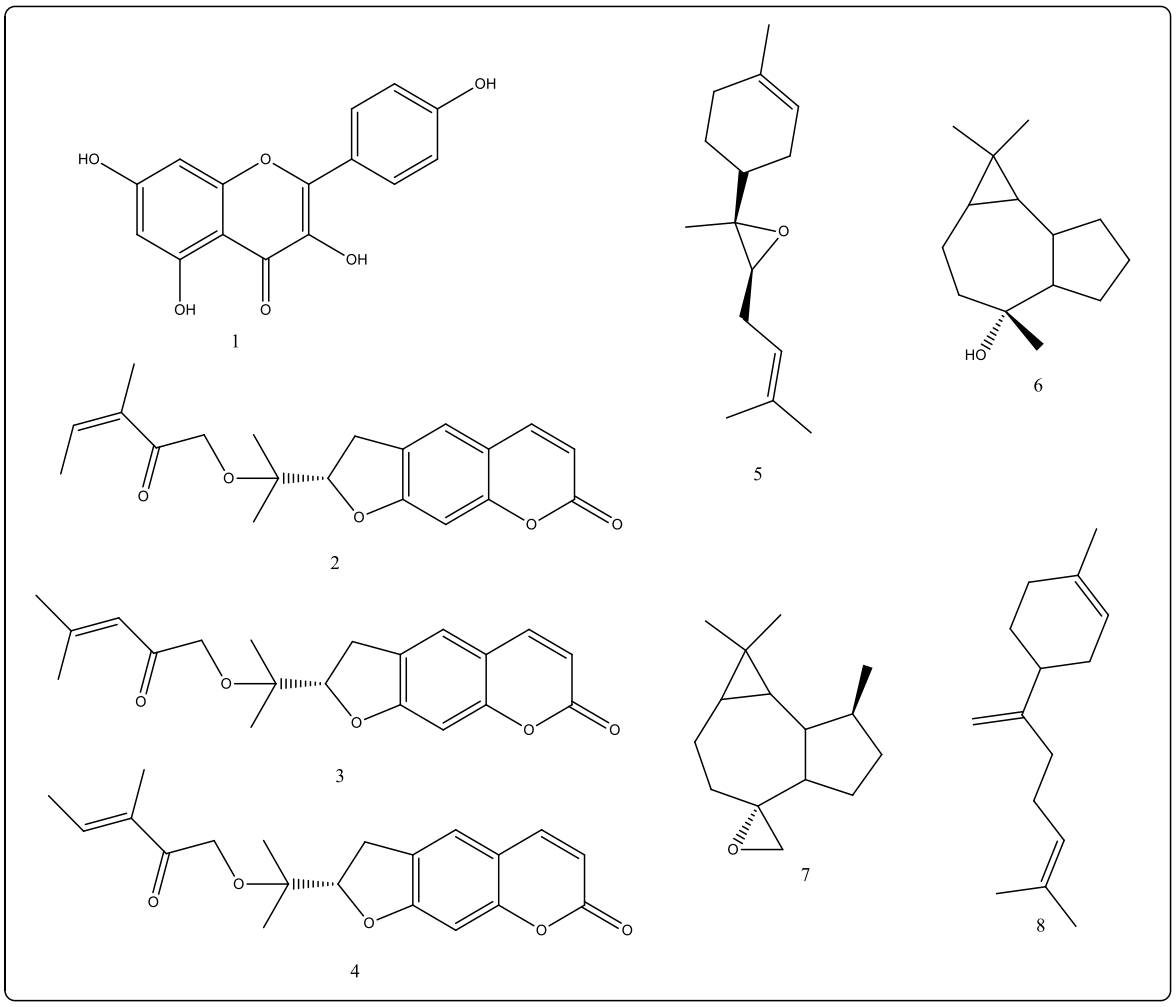

Figure 4. Chemicals structures of bioactive compounds from *Eryngium ilicifolium* ; 1: detected using qualitative phytochemical screening ; 2, 3 et 4 : isolated using column chromatography; 5,6,7 et 8 : detected using the GC/MS analysis.

Biological Activities

Most of the scientific articles related to *Eryngium* species have been limited to studying *Eryngium ilicifolium*. Two papers present the biological activity of organic extracts of this species. This literature review will explore the full range of biological activities exhibited by organic extracts of the plant *Eryngium ilicifolium*.

Antibacterial Activity

Despite advances in understanding pathogens and their life cycles, microbial diseases continue to affect millions of people. In response, researchers are exploring the potential of *Eryngium ilicifolium* extracts to combat a wide range of bacteria.

A study by Warda *et al.* [5] showed that a methanolic extract of *Eryngium ilicifolium* exhibited weak antimicrobial activity against Streptococcus pneumoniae of three origins: Chichaoua (inhibition diameter in mm: 12 ± 0.69; MIC in µg/ml: 256 ± 0.00), Imlil (inhibition diameter in mm: 15 ± 0. 76; MIC in µg/ml: 256 ± 0.00) and Tasseltante (diameter of inhibition in mm: 12 ± 0.41; MIC in µg/ml: 512 ± 0.00), a bacterium responsible for various upper respiratory tract infections such as pharyngitis, rhinitis, otitis and sinusitis [5,32]. This is noteworthy because another study showed antibacterial activity against Streptococcus pneumoniae from *Eryngium foetidum* [33], a close relative of *Eryngium ilicifolium*. It is important to compare the effectiveness of different plant extracts, as the Akroum study [34] suggests that an ethanolic extract of Zingiber may be more effective against this bacterium.

Landoulsi *et al.* [24,35] investigated the antimicrobial properties of *Eryngium ilicifolium*. They tested three organic extracts (petroleum ether, dichloromethane, and methanol) prepared from the root and aerial parts of the plant against 35 bacteria and one yeast at various concentrations (Table 1). The apolar extract (petroleum ether) displayed a strong activity, similar to findings by Meot-Duros et al. in *Eryngium Maritimum* [36]. This suggests that apolar extracts in *Eryngium* species may be richer in antimicrobial compounds. Notably, Landoulsi *et al.* also found that the petroleum ether extract of *Eryngium ilicifolium* was particularly rich in sesquiterpenes, a class of compounds known for their antimicrobial activity [24]. These findings support the potential of *Eryngium ilicifolium* as a source of natural antimicrobials, particularly when using apolar extracts. Landoulsi *et al.* [24] found that UV irradiation significantly increased the antimicrobial activity of the petroleum ether extract of *Eryngium ilicifolium*, suggesting that exposure to light may potentiate the efficacy of this extract.

Elkheloui *et al.* [23] have evaluated the antibacterial activity of *Eryngium ilicifolium* extract against six carbapenem resistant *Acinetobacter baumannii* strains, isolated from the hospital environment. These studies have shown that the Soxhlet diethyl ether extract is efficient against *A. baumannii* with inhibition diameters ranging from 20.7 to 23.3 mm, and minimum inhibitory and bactericidal concentrations between 0.156 and 0.625 mg/ml.

Table 1: Minimum Inhibitory Concentrations (MIC, in mg/mL) of *Eryngium ilicifolium* extracts tested against 35 bacteria and one yeast at various concentrations.

MIC (mg/mL)	*Eryngium ilicifolium*	Petroleum ether	Dichloromethane	Methanolic
0.07	Roots	*S. maltophilia* *S. dysgalactiae*		Inactive
	Aerial parts	S.maltophilia S. dysgalactiae		
0.15	Roots	*S. epidermidis,* *S. lugdunensis,* *S.agalactiae* *Corynebacterium*		
	Aerial parts	*Y. pseudotuberculosis* *S. lugdunensis*	*P. aeruginosa,* *S. maltophilia* *Y. pseudotuberculosis*	
0.3	Roots	*S. aureus, S.warneri,* *M. smegmatis* *C. albicans*		
	Aerial parts	*S.warneri,* *A.baumannii,* *Corynebacterium* *S. epidermidis*	*S. lugdunensis*	
0.6	Roots	*E. faecalis*	*S. lugdunensis* *S. dysgalactiae*	
	Aerial parts	*S. aureus, M. smegmatis* *S. dysgalactiae*	*S. epidermidis* *S. dysgalactiae*	
1.25	Roots			
	Aerial parts	*A. Baumannii*	*A. Baumannii*	

Cytotoxic Effect

In a groundbreaking study, Landoulsi *et al.* [24] investigated the cytotoxic activities of *Eryngium ilicifolium* for the first time. Their research employed a petroleum ether extract of the aerial parts, demonstrating its cytotoxic activity against both cancer and healthy cell lines. Notably, the extract exhibited greater toxicity towards cancer cells (IC50=5.30 µg/ml) than to healthy cells (IC50=13.38 µg/ml), with a Selectivity Index of 2.5. Compared to *Eryngium ilicifolium*, *Eryngium maritimum* and *Eryngium barrelieri* displayed lower cytotoxicity (higher IC50 values). Conversely, *Eryngium glomeratum*, *Eryngium tricuspidatum*, *Eryngium triquetrum*, and *Eryngium dichotomum* exhibited higher cytotoxicity (lower IC50 values).

A study found that extracts of *Eryngium pseudothoriifolium*, *Eryngium thorifolium*, *Eryngium davisii* and *Eryngium falcatum* showed cytotoxic activity against endometrial cancer cells (IC50 ranging

from 10,41 to 23,14 mg/ml) and non-cytotoxic activity (IC50> 30 mg/ml) against prostate cancer cells at the concentrations tested [37]. In addition, research by Kartal *et al.* identified five new triterpene saponins from *Eryngium campestre* with weak cytotoxic activity against human tumour cell lines [38].

Conclusion and future research direction

This study is the first bibliographical work on *Eryngium ilicifolium*. Despite its traditional use in Morocco, the research on this species remains limited. This review compiles information on the traditional uses reported in various Moroccan regions, along with extraction methods, chemical composition, and biological activity.

We conclude that *Eryngium ilicifolium* holds promise as a traditional medicine with potentially active antimicrobial properties. As this plant is believed to have antioxidant, anti-inflammatory, anticancer, diuretic and antiseptic activities, the limited research on this species highlights the need for further investigation. Therefore, we strongly recommend that future studies focus on:

- The preparation of essential oil from different species and the evaluation of their biological activities.
- The separation, isolation, and structural identification of the most antibacterial and antioxidant constituents from organic extracts and essential oil of *Eryngium ilicifolium*.
- Investigating the mechanisms underlying the antibacterial effects of the organic extracts of *Eryngium ilicifolium* and their antibacterial constituents.
- Clinical studies on the safety of extracts of *Eryngium ilicifolium* with demonstrated *in-vivo* activity.
- Exploiting isolated compounds for the synthesis of novel active molecules through organic synthesis routes, followed by the evaluation of their biological proprieties and comparing them with those of extracts in comparison to those of the corresponding extracts.

Code availability: Not applicable

Conflict of interest: All authors declare no conflicts of interest

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Factors Associated with the Use of Specific Diets and Their Impact on the Nutritional Status of Moroccan Adults

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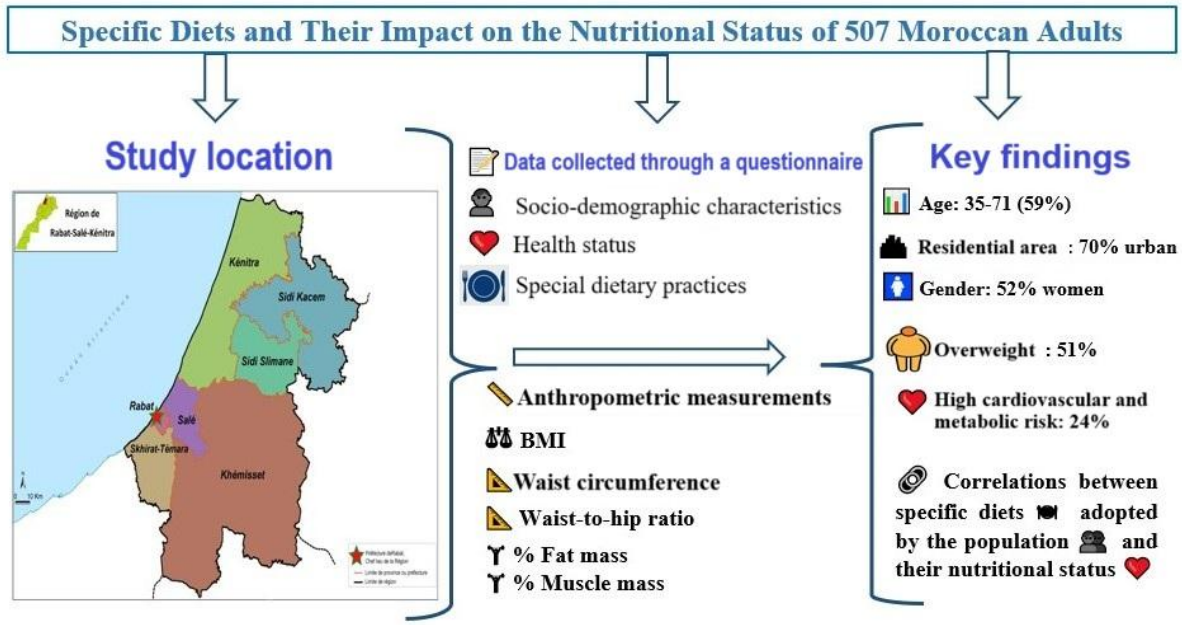
Graphical Abstract

This study examined links between specific dietary practices and nutritional status in 507 Moroccan adults from the Rabat-Salé-Kénitra region. Data were collected using a validated framework, combining questionnaires and anthropometric measurements (BMI, waist circumference, fat and muscle composition). Overweight was observed in 51% of participants, and 24% were at high cardiovascular and metabolic risk. The analysis showed associations between dietary patterns and nutritional indicators, providing a useful basis for targeted health interventions.



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DOI:10.63095/NBSEH.25.402237

Abstract: This research, which used a validated conceptual and methodological framework, examined the factors associated with the adoption of specific diets and their influence on the nutritional status of adults from 507 households in the Rabat-Salé-Kénitra region in Morocco. Data on socio-demographic characteristics, health status, and specific diets were collected using a questionnaire from one member per household. Anthropometric parameters, including body mass index (BMI), waist circumference (WC), waist-to-hip ratio (WHR), body fat composition (%FM), and body muscle composition (%MM), were measured by impedance and metric tape. The majority of the study population was aged 35-71 years (59%), urban (70%), female (52%), and overweight (51%), and 24% were at high risk of cardiovascular and metabolic syndrome. The statistical analysis revealed several associations between the different specific diets adopted by the population and their nutritional status, assessed by various anthropometric indicators. The data obtained can be used as a basis for implementing relevant nutritional interventions.

Keywords: *Diets, Health, Nutrition, Anthropometry, Diseases, Morocco*.

Introduction

Obesity, a risk factor for morbidity and mortality, is associated with the risk of several chronic diseases (CD). Indeed, an increase in BMI, associated with excess body fat, particularly in the abdominal region, increases the risk of developing type 2 diabetes [1]. It has also been reported that the effectiveness of an adapted dietary plan in the prevention and treatment of CD is particularly beneficial for people at risk of non-communicable diseases (NCD), such as being overweight, obesity, diabetes, and metabolic syndrome, when accompanied by physical activity [2-4]. In addition, weight loss is necessary to reduce blood pressure and LDL cholesterol, and to increase HDL cholesterol. It has also been recommended to balance blood sugar in people with obesity associated with diabetes [1]. Scientific evidence has further shown that consuming large portions of food, energy-rich foods, sugary drinks, and adopting a sedentary lifestyle or stopping physical or sporting activity increases the risk of becoming overweight and obesity [5,6]. These risk factors, related to poor eating habits and a sedentary lifestyle, can therefore be avoided by following a specific diet with adequate energy, fat and sugar content, as well as regular physical or sporting activity [7,8]. In type 2 diabetes, it is recommended to favour complex carbohydrates over simple sugars and polyunsaturated fatty acids over saturated fatty acids, to consume foods rich in dietary fibre, and to ensure a balanced distribution of carbohydrates across the three meals of the day [9,10].

In the case of hypertension, weight loss is recommended for those who are overweight, combined with a healthy diet [11,12]. In addition, it is widely recognized and supported by several studies that a close relation exists between hypertension and dietary sodium intake. In fact, reducing dietary sodium decreases blood pressure and the incidence of hypertension, and is therefore associated with a reduction in morbidity and mortality from cardiovascular diseases [13]. In the case of dyslipidaemia, adopting a diet low in fat and saturated fatty acids and rich in mono- and polyunsaturated fatty acids is advisable, in addition to favouring functional foods rich in bioactive substances such as antioxidants and fibre [14]. The present work aims to study the factors associated with the adoption of specific diets and their implication for nutritional status in an adult Moroccan population.

Methods

The data from this work are part of a study conducted in the Rabat-Salé-Kenitra (RSK) region of Morocco, based on a validated conceptual and methodological framework [15].

Data Collection

The data were collected from 507 adult subjects using a questionnaire covering socio-demographic characteristics, health status, and specific diets adopted. Anthropometric parameters were measured using standard techniques (impedancemetry and metric tape).

Low-calorie (LcalDL), low-carbohydrate (LcarbD), low-fat (LfatD) and low-sodium (LNaD) diets were classified as such based on their daily content not exceeding 2000 kcal, 260 g of carbohydrates, 70 g of fat, and 2000 mg of sodium, respectively. These thresholds were established in accordance with the reference nutritional intakes defined by the Official Journal of the European Union [16].

Study Variables

• Socio-demographic characteristics: age, sex, and place of residence.

• Anthropometric parameters:

Body mass index (BMI) (kg/m²), Waist Circumference (WC) (cm), classified according to cardiovascular or metabolic risk (CVMR) [17,18]; Waist-to-Hip Ratio (WHR); Body Fat Composition (%FM); Body Muscle Composition (%MM).

- Body Mass Index (BMI) is categorized in 2 groups : 1) Normal: 18.5 to 24.99 kg/m^2; 2) Overweight/Obese: ≥ 25 kg/m^2
- Waist Circumference (WC), which is an indicator of Cardiovascular or Metabolic Risk (CVMR), is categorized:
  - for men in, 1) WC ≤ 94 cm (No CVMR); 2) 94 cm > WC ≤ 102 cm (Moderate CVMR); 3) WC > 102 cm (High CVMR);
  - for women in, 1) WC ≤ 80 cm (No CVMR); 2) 80 cm > WC ≤ 88 cm (Moderate risk); 3) WC > 88 cm (High CVMR).
- The Waist-to-Hip Ratio (WHR), which is also an indicator of CVMR, is categorized:
  - for men in, 1) WHR ≤1 (Absence of CVMR); 2) WHR > 1 (Presence of CVMR);
  - for women in, 1) WHR ≤ 0.85 (Absence of CVMR); 2) WHR > 0.85 (Presence of CVMR).
- Body Fat Composition (% FM) and Body Muscle Composition (% MM) are categorized in, 1) Deficient; 2) Normal; 3) Excessive; 4) Very excessive.

- Reported diseases: Type 2 diabetes, hypertension, dyslipidaemia.
- Specific diets applied: Low-calorie (LcalD), low-carbohydrate (LcarbD), low- fat (LfatD), and low-sodium (LNaD) diets

Statistical Analysis

Statistical analysis was performed using SPSS for Windows (Statistical Package for the Social Sciences), version 21. Associations between variables were assessed using the chi-square test. The significance threshold is set at P <0.05 and is categorized as follows [19,20]:

- Not significant: P ≥ 0.05
- Not very significant: p < 0.05
- Moderately significant: p < 0.01
- Highly significant: p < 0.001

Results

Socio-demographic Characteristics of the Population

Figure 1 shows that the majority of the study population was aged between 35 and 71 years (59%), female (52%), and lived in urban areas (70%).

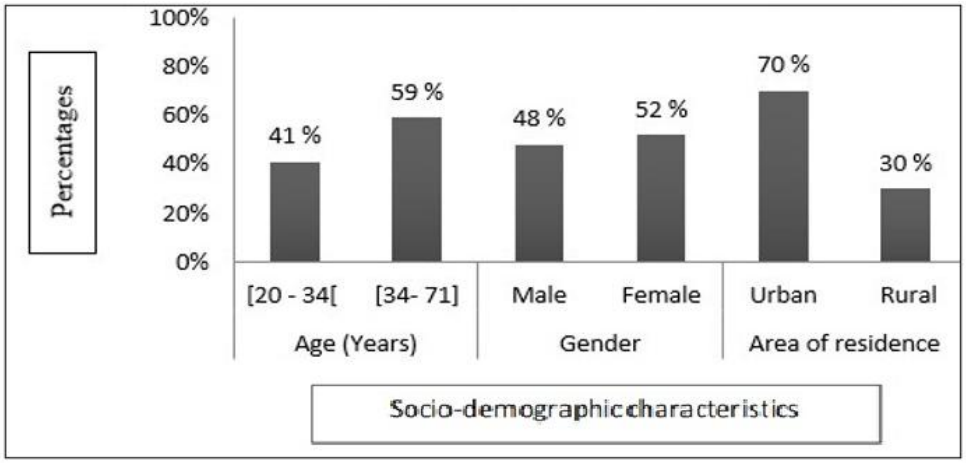

Figure 1. Distribution of the population according to socio-demographic characteristics (n=507).

Nutritional Status, Health Status and Specific Diets Followed

Table 1 shows that 51% of the study population had a BMI ≥25 kg/ m²; 36% a high WHR; 46% had a very excessive % FM; 53% had a deficient % MM; 24% had a high CVMR; 10% reported having hypertension; 7% had type 2 diabetes; 6% had dyslipidaemia; 14% reported adopting a low-calorie diet; 12% followed a low-carbohydrate diet; 11% followed a low-lipid diet; and 15% adopted a low-sodium diet.

Table 1. Distribution of the population according to anthropometric parameters, health status, and adopted specific diets.

Characteristics*	n (%)	[CI 95%]
BMI (kg/m^2)		
- Normal (18.5 to 24.99)	247(49%)	[44-53]
- Overweight/Obese (≥25)	260 (51%)	[47-56]
WC (cm)		
- Without CVMR	297 (59%)	[54-63]
- Moderate CVMR	87 (17%)	[14-21]
- High CVMR	123 (24%)	[21-28]
WHR		
- Normal	326 (64%)	[60-69]
- Increased	181 (36%)	[31-40]
%FM		
- Deficient	2 (2%)	[1-3]
- Normal	151(30%)	[26-40]
- Excessive	113(22%)	[18-26]
- Very excessive	241(46%)	[43-52]
%MM		
- Deficient	269 (53%)	[49-58]
- Normal	170 (34%)	[30-37]
- Excessive	52 (10%)	[8-13]
- Very excessive	16 (3%)	[2-5]
Declared pathologies		
- Hypertension	50 (10%)	[7-13]
- Type 2 Diabetes	34 (7%)	[5-9]
- Dyslipidaemia	31 (6%)	[4-8]
Specific diets		
- LcalD	72 (14%)	[11-17]
- LcarbD	60 (12%)	[9-15]
- LfatD	54 (11%)	[8-14]
- LNaD	77 (15%)	[12-18]

Note: n (%) = sample size and percentage; CI = 95% Confidence Interval; BMI=Body mass index WC=Waist circumference, CVMR = cardiovascular or metabolic risk, WHR=Waist to hip ratio; %FM=body composition in fat mass; %MM=body composition in muscle mass; LcalD: low-calorie diet; LcarbD: low-carbohydrate diet; LowfatD: Low-lipid diet; LNaD: Low_sodium diet.

Characteristics of the Study Population According to the Specific Diet Adopted

Table 2 presents the associations between socio-demographic characteristics and the different specific diets adopted. The table shows significant associations between age ($p<0.001$), sex ($p=0.03$), and place of residence ($p=0.07$) with the adoption of a low-carbohydrate diet; between age and the low-fat diet ($p=0.001$); and between age and the adoption of the low-sodium diet ($p<0.001$). Concerning the associations between the diet adopted and health status, the low-carbohydrate diet is significantly associated with diabetes ($p<0.001$) and dyslipidaemia ($p<0.001$). Additionally, the hypocaloric diet, low-fat diet, and low-sodium diet were associated with diabetes ($p<0.001$), hypertension ($p<0.001$) and dyslipidaemia ($p<0.001$).

Table 3 shows the associations between the diets adopted by the study population and nutritional status. Significant associations were found between the application of the hypocaloric diet and waist circumference ($p = 0.002$); between the low-carbohydrate diet and BMI $p = (0.002)$, waist circumference ($p < 0.001$), WHR ($p = 0.002$), and %MM ($p = 0.04$); and a significant association was found between the adoption of the low-fat diet and BMI ($p = 0.02$), TT ($p < 0.001$), WHR ($p = 0.001$), %FM ($p = 0.03$), and %MM ($p = 0.04$). Finally, a significant association was found between the application of the low-sodium diet and TT ($p = 0.007$) and RTH ($p = 0.03$).

Table 2. Factors Associated with Specific Diet Adoption among Study Participants (n=507).

Characteristics	LcalD		P	LcarbD		P	LfatD		P	LNaD		P
	Yes (n=72)	No (n=435)		Yes (n=60)	No (n=447)		Yes (n=54)	No (n=453)		Yes (n= 77)	No (n =430)	
Age (years)												
[20-34]	23(11%)	187 (89%)	0.07NS	9(4%)	201(96%)	<0.001***	11(5%)	199 (95%)	0.001**	14(7%)	196(93%)	<0.001***
[34-71]	49 (16.5%)	248 (83.5%)		51(17%)	246(83%)		43(14.5%)	254(85.5%)		63(21%)	234(79%)	
Gender												
Male	28(11.5%)	216(88.5%)	0.09 NS	21(9%)	223(91%)	0.03*	20(8%)	224(92%)	0.08 NS	31(13%)	213(87%)	0.1 NS
Female	44(17%)	219(83%)		39(15%)	224(85%)		34(13%)	229(87%)		46(17.5%)	217(82.5%)	
Area of residence												
Urban	57(16%)	298(84%)	0.06 NS	48(13.5%)	307(86.5%)	0.007**	42(12%)	313(88%)	0.2NS	56(16%)	299(84%)	0.6NS
Rural	15(10%)	137(90%)		12(8%)	140(92%)		12(8%)	140(92%)		21(14%)	131(86%)	
Type 2 diabetes												
Yes	20(59%)	14(41%)	<0.001***	34(100%)	0 (0%)	<0.001***	20(59%)	14(41%)	<0.001***	16(47%)	18(53%)	<0.001***
No	52(11%)	421(89%)		26(5.5%)	447(94.5%)		34(7%)	439(93%)		61(13%)	412(87%)	
Hypertension												
Yes	9(18%)	41(82%)	0.4 NS	16(32%)	34(68%)	<0.001***	17(34%)	33(66%)	<0.001***	50(100%)	0 (0%)	<0.001***
No	63(14%)	394(86%)		44(10%)	413(90%)		37(8%)	420 (92%)		27(6%)	430(94%)	
Dyslipidaemia												
Yes	12(39%)	19(61%)	<0.001***	19(61%)	12(39%)	<0.001***	31(100%)	0 (0%)	<0.001***	15(48%)	16(52%)	<0.001***
No	60(13%)	416(87%)		41(9%)	435(91%)		23(5%)	453(95%)		62(13%)	414(87%)	

Note: Characteristics are expressed in sample size and percentage; P= Chi-squared test ; NS= Not Significant ; * = P < 0.05 ; **= P < 0.01 ; ***= p < 0.001 ; LcalD: Low-calorie diet; LcarbD: Low-carbohydrate diet; LowfatD: Low-lipid diet; LNaD: Low-sodium diet.

Table 3. Nutritional Status Indicators in Relation to Specific Diets among Study Participants (n=507).

Characteristics		BMI (kg/m²)		WC (cm)			WHR		%FM				% MM			
		(18.5 to 24.99)	≥25	Absence of CVMR	Moderate CVMR	High CVMR	Normal	Increased	Deficient	Normal	Excessive	Very Excessive	Deficient	Normal	Excessive	Very Excessive
LcalD	Yes n=72	31 (13%)	41 (16%)	41 (14%)	4 (5%)	27 (22%)	41 (13%)	31 (17%)	1 (50%)	20 (13%)	13 (11.5%)	38 (16%)	41 (15%)	23 (13.5%)	7 (13.5%)	1 (6%)
	No n=435	216 (87%)	219 (84%)	256 (86%)	83 (95%)	96 (78%)	285 (87%)	150 (83%)	1 (50%)	131 (87%)	100 (88.5%)	203 (84%)	228 (85%)	147 (86.5%)	45 (86.5%)	15 (94%)
P		0.2 NS		0.002**			0.16 NS		0.3 NS				0.76 NS			
LcarbD	Yes n=60	18 (7%)	42 (16%)	21 (7%)	5 (6%)	34 (28%)	28 (9%)	32 (18%)	0 (0%)	15 (10%)	10 (9%)	35 (14.5%)	41 (15%)	12 (7%)	4 (8%)	3 (19%)
	No n=447	229 (93%)	218 (84%)	276 (93%)	82 (94%)	89 (72%)	298 (91%)	149 (82%)	2 (100%)	136 (90%)	103 (91%)	206 (85.5%)	228 (85%)	158 (93%)	48 (92%)	13 (81%)
P		0.002**		<0.001***			0.002**		0.3 NS				0.04*			
LfatD	Yes n=54	18 (7%)	36 (14%)	20 (7%)	5(6%)	29 (24%)	24 (7%)	30 (17%)	0 (0%)	14 (9%)	5 (4%)	35 (14.5%)	38 (14%)	10 (6%)	4 (8%)	2 (12.5%)
	No n=453	229 (93%)	224 (86%)	277 (93%)	82 (94%)	94 (76%)	302 (93%)	151 (83%)	2 (100%)	137 (91%)	108 (96%)	206 (85.5%)	231 (86%)	160 (94%)	48 (92%)	14 (87.5%)
P		0.02*		<0.001***			0.001**		0.03*				0.04*			
LNaD	Yes n= 77	36 (15%)	41 (16%)	33 (11%)	16 (18%)	28 (23%)	41 (13%)	36 (20%)	0	22 (15%)	24 (21%)	31 (13%)	40 (15%)	27 (16%)	8 (15%)	2 (12.5%)
	No n=430	211 (85%)	219 (84%)	264 (89%)	71 (82%)	95 (77%)	285 (87%)	145 (80%)	2 (100%)	129 (85%)	89 (79%)	210 (87%)	229 (85%)	143 (84%)	44 (85%)	14 (87.5%)
P		0.7 NS		0.007**			0.03*		0.2 NS				0.98 NS			

Note: Characteristics are expressed in sample size and percentage; P= Chi-squared test ; NS= Not Significant ; * = P < 0.05 ; **= P < 0.01 ; ***= p < 0.001 ; BMI=Body mass index WC=Waist circumference, WHR=Waist to hip ratio; %FM=body composition in fat mass; %MM=body composition in muscle mass; LcalD: Low-calorie diet; LcarbD: Low-carbohydrate diet; LowfatD: Low-lipid diet; LNaD: Low-sodium diet.

Discussion

This work reveals associations (a) between the type of diet adopted in terms of composition, and (b) the socio-demographic characteristics, anthropometric measurements, nutritional status, and health status. In addition, according to their declarations concerning the specific diets followed, 14% of the study population adopted a low-calorie diet, 12% a low-carbohydrate diet, 11% a low-fat diet, and 15% a low-sodium diet (15%). It should be noted that these diets are among the therapeutic measures, and their effects on improving health have been validated. However, their prescription is a complex and lengthy technical process, and their effectiveness depends on the precision of the indication and patient compliance. Therapeutic nutrition is based, depending on the case, on *restriction, exclusion, or adjunct diets* to improve the effectiveness of other treatments, assistance, or comfort. Their effectiveness depends on their applicability, which is linked to the relevance of the prescription and the patient's motivation [21,22]. In this context, therapeutic education remains an essential tool in the management of chronic diseases, as it helps patients acquire and/or maintain the knowledge and skills necessary to manage their life with a chronic disease [17].

In the study population, chronic diseases were found to be prevalent, including hypertension, estimated at 10%, type 2 diabetes at 7% and dyslipidaemia at 6%. These results indicate an increase in these diseases when compared to those reported in 2018, with hypertension's prevalence estimated at 6.8% across Morocco and 7.3% in the study region (RSK), and diabetes estimated at 4.8% nationally and 5% in the RSK region. This increase in chronic diseases is also supported by other data previously recorded in Morocco, considering the overall prevalence of these diseases (including diabetes and hypertension), which was 21% in 2018, showing an increase of 2.8% compared to 2011, when a prevalence of 18.2% was reported [23]. An association between socio-demographic characteristics and food consumption in populations has been reported in the literature [24]. In the present study, a significant association between age and the application of low-carbohydrate, low-lipid and low-sodium diets, as well as a significant association between sex and place of residence with the application of the low-carbohydrate diet, were also observed in this population. Furthermore, following a diabetes-specific diet is crucial to maintaining glycaemic, lipid, and lipoprotein profiles at an optimal level to reduce the risk of macrovascular complications [25]. This is in agreement with the data found here, which also revealed a significant association between diabetes and the application of hypocaloric, hypocarbohydrate, and low-fat diets.

No significant association was found between diabetes and the application of the low-sodium diet according to the results of this study. This observation can be explained by the fact that most individuals in the present population do not have hypertension, although it is recommended in the case of diabetes to ensure a reduction in sodium intake, which is favourable for normal blood pressure and reducing the risk of developing cardiovascular diseases [25,26]. Particular attention should also be paid to patients with obesity associated with diabetes. Indeed, management in this case is based on dietary advice, physical activity, and psychological support, which should be sought from a multidisciplinary team composed of nutritionists, dietitians, psychologists, psychiatrists and educators in adapted physical activity [8,27]. A significant association between the adoption of diets low in carbohydrates, lipids, and sodium and hypertension was also revealed by this study. The low-sodium diet is indeed strongly indicated to reduce blood pressure and the risk of cardiovascular disease [28].

In addition, controlled carbohydrate and lipid intake is useful for promoting weight loss and is recommended to improve blood pressure [29,30]. The results revealed a significant association between dyslipidaemia and the application of hypocaloric, low-carbohydrate, low-fat, and low-sodium diets. Weight loss, especially through reducing energy intake, is also reported to be strongly indicated for improving lipid concentrations [31]. Furthermore, reduced consumption of saturated fat and cholesterol can contribute to lowering blood cholesterol levels [32], and limited consumption of sodium [33] and saturated fat contributes to reducing the risk of cardiovascular disease [34].

Reducing energy intake, particularly by cutting down on sugary and fatty products, has also been reported in cases of overweight [8,35]. In addition, moderate and sustained weight loss in overweight or obese individuals is associated with a reduced risk of cardiovascular disease [36]. In line with these observations, the statistical analysis of the data conducted in the present study revealed a significant association between the adoption of a low-calorie, low-carbohydrate, low-fat, and low-sodium diet and anthropometric parameters (BMI, WC, WHR).

Conclusion

This study revealed the factors associated with the adopted diets and their implications for health and nutritional status, as assessed by different anthropometric indicators. The results obtained can be used as a basis for implementing relevant nutritional interventions. They also open up research perspectives, particularly regarding the quantitative and qualitative analysis of specific diets.

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Ethics Approvals: This study was carried out under the auspices of the Department of Higher Education and Scientific Research, particularly with the agreement of the Faculty of Science at Chouaib Doukkali University of El Jadida in Morocco. It has been approved by the Wilaya and the Regional Directorate of Health and Social Protection of the Rabat-Salé-Kénitra region (RSK). Furthermore, the core ethical principles that guide research conduct were upheld, specifically providing participants with information about the study's subject matter, voluntary participation, maintaining participant confidentiality, and obtaining informed consent.

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Code availability: Not applicable

Conflict of interest: The authors declare that they have no conflicts of interest.

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Oil Spills and Ecosystem Threats: Environmental Consequences of the Houthi Operations in the Red Sea

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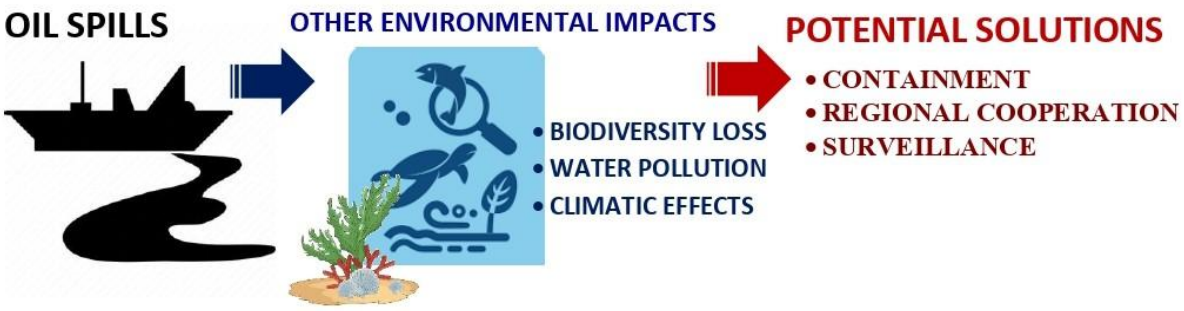
Graphical Abstract

This study examines the environmental consequences of oil spills and discharges related to the Houthis' attacks on ships in the Red Sea, with a focus on their impact on marine ecosystems. Oil spills etc from these activities cause significant biodiversity loss, water pollution, and climatic effects. The study identifies an urgent need for targeted actions, including regional cooperation, and continuous environmental monitoring. Addressing these challenges is essential to protect marine biodiversity and strengthen resilience against these threats.



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Abstract: Attacks by the Houthis on ships in the Red Sea have environmental, economic and political impacts. Even though most of the attacks have been ineffective so far, those that have made an impact have resulted in the sinking of ships loaded with cargo such as fertilizers and bunker oil, which are considered dangerous for the fragile ecosystem of the Red Sea. The paper focuses on the environmental impacts. The necessary rerouting of commercial ships has caused increased carbon emissions. The sunken ships are a concern for the ecosystem of the Red Sea. If the Red Sea continues to be an area of conflict, it is probable that risky development of the Northern Sea Route will become a serious option.

Keywords: *Houthis, Red Sea, Israel, Paris Agreement.*

Introduction

Conflicts have been a major driver of increased environmental degradation owing to the resulting lack of environmental governance and regional environmental cooperation. This degradation has serious ramifications for the future well-being of humanity, especially when it occurs in the context of climate change. Two recent conflicts, namely the Russian-Ukraine conflict and the Israel-Hamas conflict, contribute to threatening human health and destroying the ecosystems on which human communities depend. Although the Russian-Ukraine conflict has largely been confined to the geographical bounds of Russian and Ukrainian territory (mainly the eastern and southern parts of Ukraine) [1], the Israel-Hamas conflict has extended beyond the geographical boundaries of Israel and Gaza to the surrounding seas (the Red Sea) and neighbouring land (Lebanon, Yemen, and Syria) through reactive actions by regional players [2].

What began as retaliatory attacks by Israel to avenge the killing of over 1,200 Israeli citizens gradually escalated into the involvement of the armed religious and political group, the Houthis (or Houthi movement or Ansar Allah), from Yemen, in support of the Palestinians in Gaza [3]. Although the Houthis initially targeted land-based assets of Israel, they soon shifted their focus to predominantly attacking ships in the Red Sea that were deemed to have connections to Israel, These continuous attacks have elevated their status from being merely a ‘local threat’ to one capable of confronting larger nations and disrupting global trade [4]. In addition, these attacks have raised significant environmental concerns, as the Red Sea supports coral ecosystems and unique marine biodiversity, including mangroves that protect the coastline. The region has been forced to endure increased pollution from discharges into the sea caused by damaged ships under attack.

Disrupting international trade by a third party to a conflict (the Houthis in this case) is unprecedented. Some may think that since the Red Sea region has already faced continual environmental pressures, the actions of the Houthis are no different in effect. This view ignores the idea of ecocide and the efforts to apply law to what is regarded as criminal damage to the environment. It is necessary to examine the threats posed by the actions of the Houthis and the risks they create for the maritime environment, especially in the Red Sea. The present paper examines the environmental impact of attacks carried out by the Houthis on ships in the Red Sea since the beginning of their involvement in the Israel-Hamas conflict. Accordingly, the paper will first address the existing maritime pollution in the Red Sea, followed by an analysis of the current Houthi insurgency and its impact on global trade and maritime pollution. This will be followed by a discussion of the events that have occurred, culminating in recommendations for necessary actions before concluding the paper.

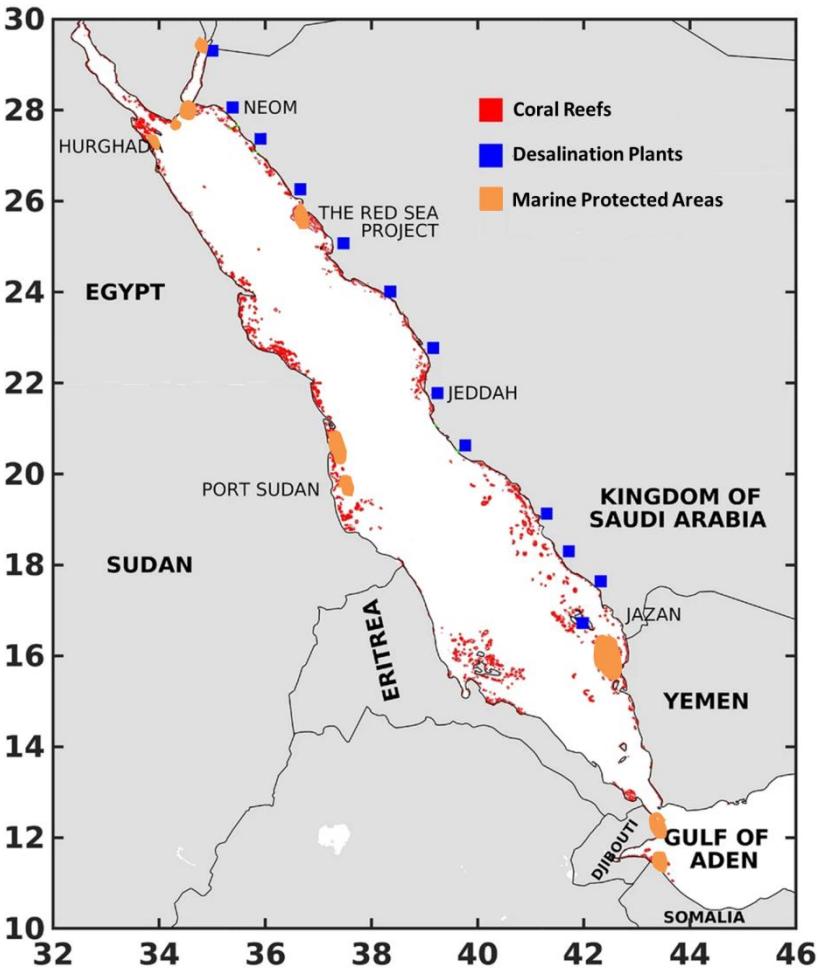

Figure 1. Uniqueness of Red Sea (Source: Author; after Mittal *et al*. [5]).

Maritime Pollution in the Red Sea

The Red Sea, a critical maritime route for global trade, connects the Indian Ocean to the Mediterranean. It was a key section of the Spice Route that allowed trade to move between the Romans, the Egyptians, and the Phoenicians. Today, it is bordered by the coasts of Egypt, Sudan, Eritrea, Djibouti, Yemen, and Saudi Arabia. The Sea is approximately 280 km wide, which reduces to 26 km at Bab-el-Mandeb. The land surrounding the Sea is arid and dry, with no rivers. On the seafloor, two continental shelves meet, which are geologically active even today and present numerous hydrothermal vents [6]. The Sea is considered a natural beauty, with unique marine biodiversity and extensive coral reefs that run parallel to the coastline as barrier reefs. Recognizing this biodiversity, 12 marine protected areas (MPAs) have been identified and demarcated in this region [7], as seen in Figure 1. Being a closed sea, the water renewal here is relatively slow. Water exchange for depth of 200 m above the thermocline takes approximately 6 years, and for the entire Sea it is estimated at 200 years [8].

Even though the marine ecosystem is fragile, it is subjected to numerous threats, including industries (desalination, fishing, manufacturing, tourism, oil, and maritime transport), climate change [9], and human activities leading to pollution through oil [10], plastics [11], industrial discharge [12], overexploitation of marine resources, reduced water quality [13], and destruction of habitat [14]. This has led to identification of organic and inorganic pollutants at many sites in the Red Sea [15].

Attempts to protect the biodiversity of the Red Sea began in the 1980s and resulted in the creation of 12 MPAs, but the efforts to implement, manage, and legally enforce them have been minimal [16]. There is thus a need to create connectivity-informed Large Scale MPAs (LSMPAs) [17] for collective decision-making to meet the desired conservation goals, like those of the Coral Triangle Initiative [18]. Such concerted efforts can come to naught when human actions, such as the intentional attack of cargo-laden ships by the Houthis, are enacted without any concern for the environment. One may argue that conflicts and wars are equally detrimental to the environment, but the discussion here will be limited to pollution in the maritime domain as a result of deliberate attacks by the Houthis in the Red Sea.

Insurgency by The Houthis

The Houthis are an armed religious and political group that has controlled much of northern Yemen and the majority of the population since 2014 [19]. Reports indicate that the Houthis are one of the several armed groups that have received both financial and military support from Iran since 2009 [20], and this support continues to this day [21]. It is believed that Iran supports the Houthis to counter the growth of US influence in the region while avoiding a direct confrontation with the US [4]. This support has allowed the Houthi to acquire missiles (both ballistic and cruise), rockets, and unmanned vehicles (aerial, underwater, and surface) to support their air and ground forces [21]. Although the Iranians support the Houthis, they have a mind of their own and make decisions independently, and they cannot be considered a proxy of Iran [22].

The Attacks

With the intention of diverting the attention of local masses from domestic economic difficulties and the failure to deliver on promises [23], the Houthis attacked land-based targets in Israel in support of Palestine (i.e., Hamas) [24], projecting themselves as true champions of the Palestinians in the Arab world and thereby creating strong pro-Palestinian sentiment among their own people [25]. When land-based attacks proved ineffective because of active involvement of Saudi Arabia [26] and the United States [27], the Houthis shifted focus to targeting ships in the Red Sea [28], with the scope of

these attacks growing over time. The first phase, from 14 November 2023 to 8 December 2023, targeted all Israeli-owned ships. In the second phase, from 9 December 2023 to 17 January 2024, the scope was expanded to include ships with Israel as their destination and all ships protecting Israeli vessels. The third phase, from 18 January 2024 to 2 May 2024, saw the addition of all US- and UK-owned ships, thereby increasing the area of operations to include the Gulf of Aden. In the fourth phase, from 3 May 2024 to 18 July 2024, the scope was further widened to include ships under flags that violated the ban on Israeli shipping or visited Israeli ports from the Mediterranean. Since 19 July 2024, the list of targets has not changed, but there has been an increase in the targeting of Israeli assets, with indications of further escalations until aggression against the Palestinian people in Gaza ends [2].

Although the attack on ships in the Red Sea by the Houthis are our focus, attacks on merchant vessels in the region have been taking place since 2017 and are mainly attributed to the Yemen conflict, Iran sanctions, legal disputes, and Iran-Israel tensions [29]. What makes the current Houthi attacks important are the numbers. The ships involved during attacks from 2017 to November 2023 were limited to 25 (08 in the Red Sea, 04 in the western Arabian Sea, and 13 in the Gulf of Aden). But there were 276 observed attacks from October 2023 to November 2024 (159 in the southern Red Sea, 70 in the Gulf of Aden, 45 in the Bab-el-Mandeb Strait, and two in the western Arabian Sea). A total of 106 merchant vessels were attacked during this period [30]. The naval vessels targeted include those operating under Operation Prosperity Guardian (a US-led multinational coalition established in December 2023 to protect merchant ships in the Red Sea), Operation Poseidon Archer (a campaign of missile and air attacks by the US and UK on Houthi launch pads), and EUNAVFOR Aspides (an EU-led military operation established in February 2024 in the Red Sea to protect merchant ships).

Most of the attacks have not caused significant damage, but some ships have been lost by fire or flooding resulting from these attacks. The incidents have led to the loss of life of three sailors (from *True Confidence*), one sailor remains missing (from MV *Tutor*), and many others have been reported injured but safe. Additionally, the crews of the *Galaxy Leader* and *MSC Aries* remain captive with the Houthis.

Impact

The attacks on ships by the Houthis have resulted in a number of economic, environmental, and security challenges [31]. The economic impacts include delays caused by rerouting ships around the Cape of Good Hope, increased fuel consumption because of longer routes, and higher insurance cost of vessels as a result of the attacks. The environmental damages stem from increased carbon

emissions because of rerouting, oil spills, sunken ships, and fires onboard caused by the attacks. The security concerns include the need for naval ships to ensure the safe passage of transiting vessels while also maintaining their own safety.

The cumulative effect has been an increase in product costs caused by longer travel times and higher operating expenses from rerouting. Since the onset of the attacks, various researchers have studied, discussed, and analysed their impacts, often presenting a mixed picture. Although most studies have focused on the security and economic aspects, the environmental impact, though mentioned, is often treated superficially.

To appreciate the *entire* spectrum of impacts that these attacks on ships in the Red Sea, both naval and commercial, have had on humanity, it is essential to analyse the environmental impacts in greater detail. This understanding is crucial given the current awareness of marine environmental degradation and the undeniable impact of climate change. Accordingly, this paper aims to focus on the 'environmental impacts' of the attacks by the Houthis in the Red Sea.

Environmental Impact

The attack on merchant ships passing through the Red Sea has had a two-fold environmental impact on shipping. The first and the most natural one is *physical damage* to the ship. This could result in loss of watertight integrity making a ship susceptible to loss of stability and eventually sinking in the Red Sea or becoming unserviceable to remain adrift and become a threat for other vessels and marine infrastructure. In some attacks injury or loss of life could also occur if a sailor is hit by splinters of the projectile or is trapped in a damaged space of the ship. In all these cases, the cargo in the ship, which could vary from chemicals to crude oil, would leach into the Sea causing pollution of the marine environment. In the short term this would result in added cost of cleanup and/ or loss of livelihood for coastal communities that depend on the oceans [32]. In the long term it could mean destruction of habitats resulting in reduced availability of seafood and irreversible damage to the food chain caused by continual presence of pollutants [33] thereby causing loss of available food and economic gains for the coastal communities.

The second impact is *increased carbon emissions*. These increased carbon emissions will occur from the firing of rockets and missiles for attack, the counter measures employed to nullify these attacks, and the longer distance ships will need to cover to maintain supply chains. The focus in this paper concerns increased carbon emissions by merchant vessels as a result of rerouting of ships around the Cape of Good Hope. To appreciate the true environmental damage done by the Houtis through their deliberate attacks on ships in the Red Sea, let us look at each of these components independently.

Physical damage

The Houthis have employed a variety of projectiles, including anti-ship ballistic missiles, cruise missiles, rockets, RPGs, and other unidentified airborne projectiles. These have been delivered to targets using UAVs, USVs, and land-based launchers. In some cases, the Houthis have resorted to small arms and manually placed explosives to carry out these attacks [34]. Most of the projectiles have missed their targets; some have caused damage (see Table 1). No reports of significant structural damage resulting from these attacks have been documented. Most ships have reported fires on board following these attacks, which have been brought under control without causing serious damage to the ship's ability to continue its voyage. In some instances, flooding has also been reported, with only a few cases proving difficult to control.

Since the primary aim of the coalition forces is to ensure freedom of navigation and safe passage for commercial vessels in the Red Sea [35], in cases where the crew has abandoned a vessel because of uncontrollable fires or flooding the coalition forces have towed the affected vessel away from the main shipping lanes for repairs [36]. Despite these efforts, there have been instances where vessels have been lost to sinking [37]. Table 1 lists vessels, which have sustained extensive damage and have either already sunk or are likely to sink in due course because of the damage. These sunken vessels, along with their cargo, pose significant environmental concerns for the fragile marine ecosystem of the Red Sea. Additionally, these sunken vessels also called ‘potentially polluting wrecks’ [38] present hazards such as leakage of hazardous material, heavy fuel oil, and threatening safe passage of other ships in the region if they have sunk in relatively shallow waters. With no standards available to assess and deal with these wrecks [39] major environmental pollution is in the waiting. Although one may say that these wrecks act as Underwater Cultural Heritage (UCN) and are a means of revenue generation [40], their cargo and fuel continue to be potent environmental threats.

The greatest threat posed by these sunken ships is the eventual release of their hazardous cargo, heavy bunker oil, and chemicals into the water. Removal of these would be governed by their hazardous nature and the likely damage they would cause. Once that has been defined, cost effectiveness between costs of removal vis-à-vis costs of damage caused will define if these materials will be removed [49]. Routine oil exploration and transportation activities make oil slicks in the Red Sea common. They are a significant concern for the region [50].

Table 1. Ships severely damaged by attack of the Houthis in the Red Sea (Source: Author's compilation from Lloyd's List [30]).

Date of Attack	Name of ship	Attacks by	Type of ship	Cargo carried	Damaged Sustained
18-Feb-24	Rubymar	Missile	General cargo ship	22,000 metric tons of ammonium phosphate sulphate fertilizer [41]	Hit. Vessel **sunk** after two weeks [37]
12-Jun-24	Tutor	USV and airborne projectile	Bulk carrier	80,000 t of coal	12 June 2024 - Stuck on stern Caused severe flooding and damage to Engine room 15 June 2024 – Reported having **sunk** [42]
13-Jun-24	Verbena	Two missiles and unknown projectile	General cargo ship	Wood construction material [43]	Fire on board, brought under control Vessel unlit, on fire, drifting and sinking 15 June 2024 - Ship abandoned 09 July 2024 – Towed away from threat area [44] Reported by Houthis as having **sunk** [45]
15-Jul-24	Chios Lion	USV	Crude oil tanker	90, 000 t Crude Oil	Hit but underway **Oil spill** during passage observed [46]
21-Aug-24	Sounion	Missiles, small arms	Crude oil tanker	150,000 t Crude Oil	21 Aug 2024 - approached by two small craft. Brief exchange of small arms fire. Vessel struck by projectiles Fire on board. Out of control, Vessel not under command Ship abandoned. 23 August 2024 - Houthis boarded vessel. Planted explosives. 02 September 2024 – Potential oil spill [47] 16 September 2024 - Vessel towed away but **remained ablaze** [36]. Took three weeks to fight the fire. 14 January 2025 - Salvage completed after vessel declared safe [48].

Studies indicate that water circulation in the central and northern parts of the Red Sea facilitates faster transportation and dispersal of oil slicks, whereas the rate of dispersal is slower in the southern basin. The spread of oil is also influenced by seasonal changes, so that the coastlines of Eritrea, Yemen, Sudan, and Saudi Arabia are relatively unaffected by oil spills for approximately five months each year. In contrast, the western coastline (Sudan and Egypt) and the border beaches of Saudi Arabia and Yemen face a high risk of pollution throughout the year [5]. These studies show that oil spills in the Red Sea severely impact coastal ecosystems and coastal industries, but there is limited satellite oil pollution monitoring of the Red Sea [51]. Research indicates that the area covered by the slicks before and after the Houthi attacks has nearly doubled [52]. In addition to oil, cargo such as coal (MV *Tutor*), fertilizers (MV *Rubymar*), and oil products (MV *Lavant*), pose risks of environmental degradation, the specifics of which will be discussed in the subsequent section.

Increased carbon emissions

With passage for merchant ships through the Red Sea becoming unsafe, many ship operators have been forced to reconsider the longer but safer route around the Cape of Good Hope as an alternative for moving cargo from Europe to Asia and beyond or from Asia to any part of Europe [53]. This rerouting demands additional travel and hence additional days to reach the destination. As a result, the carbon emission from the ship (extra distance) and from personnel (extra time) will increase the overall carbon footprint of delivery of the same goods when compared to a route through the Red Sea.

To maintain uninterrupted cargo movement, three to four additional container ships would need to be deployed weekly [54], further increasing carbon emissions. If these additional ships are not employed, existing ships would need to increase their speed, moving them out of their economical operating range, thereby further increasing carbon emissions as the engines operate less efficiently [55]. With no clear arrival pattern, ships may reach ports earlier than expected and be required to wait at anchorage for a berth, contributing further to emissions. All of these scenarios go against efforts aimed at optimizing shipping operations for maximum efficiency and minimal carbon emissions [56].

Another factor contributing to increased carbon emissions due to rerouting is carbon leakage.[1] Since the EU enforces a carbon pricing policy for ships entering the European Economic Area (EEA), operators may conduct transhipment activities at intermediate ports to obscure actual maritime emissions [57]. Such additional stops increase emissions both from the ship and the transhipment process.

A longer sea route around the Cape of Good Hope stimulates a push towards the opening of the Northern Sea Route (NSR) through the Arctic. Even though the opening of the NSR is imminent because of increased melting of Arctic ice as a result of global heating, the opening is still considered to be some years away [58]. But, attacks in the Red Sea may hasten the process [59] forcing unsustainable means to prepare the route and infrastructure to support the route causing irreparable damage to the fragile and unexplored environment of the Arctic [60]. This route would be nearly 40% shorter than the route from Hamburg to Shanghai through the Suez Canal, but the associated environmental issues are numerous especially on water bodies, air emissions and animal survival; unfortunately, they have not been researched in detail [61].

In addition, the Red Sea crisis has shifted focus from sea based transportation to land based transportation. This will effectively increase the carbon emissions emitted as land based

[1] A spillover effect that quantifies increase in GHG emissions in one country owing to emission reduction by a second country with stricter climate change mitigation policies

transportation is considered to be costlier and not environment-friendly when compared to the sea based transportation [62, 63].

Expected environmental damage

The broad contours of the environmental damage as a result of the attacks by the Houthis on shipping in the Red Sea have been discussed in the previous section. Let us now examine the details of the expected environmental damage.

Pollution due to cargo

Cargo on ships that have sustained damage poses a serious threat to the environment. The cargo and other liquids present on the ships damaged by the Houthis in the Red Sea that can cause a serious environmental concern are seen in Table 2.

Table 2. Cargo and liquids present on ships damaged by Houthi attacks in Red Sea (Source: Author compilation).

Date of Attack	Name of ship	Type of ship	Impact on ship	Cargo carried	Other liquids	
18-Feb-24	Rubymar	General cargo	Sunk – 100 m of water	22,000 metric tons of ammonium phosphate sulphate fertilizer	200 t of ULSFO (Ultra-Low Sulphur Fuel Oil) or heavy fuel oil 80 t of LSMGO (Low Sulphur Marine Gas Oil) or marine diesel	29 km oil slick on sinking
12-Jun-24	Tutor	Bulk carrier	Sunk in position 14’19’N 41’14’E	80,000 tons of coal		Debris and oil slick sighted on sinking
13-Jun-24	Verbena	General cargo	Sunk	Wood construction material		
15-Jul-24	Chios Lion	Crude oil tanker	Oil Spill	Crude Oil		125 mile oil slick
21-Aug-24	Sounion	Crude oil tanker	Oil Spill	Crude Oil		4 km oil slick

Oil Slick

Oil slick is one of the most common pollutants emanating from a ship either when it is operating at sea or when it meets with an accident/ attack. Even with ships attacked and distressed by the Houthis in the Red Sea, oil slick figures prominently as a pollutant of concern (see Table 2) which raises concerns over environmental impact on fragile ecosystem (coral reefs and marine biota), air quality, fishing areas and desalination plants through physical smothering and toxic effects. Satellite images show that the number of oil slicks has surged by 113.8% and the area covering these slicks has increased by 115.4% during the Red Sea crisis. Although all these events are not directly linked to the crisis, they are surprising especially when the transit through the Suez Canal and Bab-el-Mandeb

have decreased by 46% and 56%, respectively, during this period [64]. For such disasters, the cleanup cost is high and difficult to ascertain as it varies with nature of oil spilt, location and current where the spill occurs, and the topography of the area to be cleaned [65].

For sea creatures, the juvenile fishes are susceptible to presence of oil in water but adult fishes are not. But, if marine life is oil-tainted, it is less marketable. If concentration of oil is high, mass mortality may occur; it is otherwise rare. Seabirds that move on the surface of water are at risk because insulation of their feathers is disrupted. Marine mammals (whales, dolphins, and others) are at risk only if they come to the surface for breathing. Marine reptiles (turtles, sea snakes and marine iguanas) are at risk during nesting season as they visit the beach and are likely to come in direct contact with the oil slick.

In shallow waters this oil slick will cause mortality of benthic animals living in sediments. Dispersed oil in water will damage coral reefs and the communities dependent on the corals. Flora and fauna of coastline (mangroves, saltmarshes, sand beaches and rocky sediment shores) are resilient by varying capacity as they withstand varying tides and hence have the ability to clean oil spills naturally when they occur with the time required for cleaning varying from days to years. But, high oil content can cause smothering, and hence loss of habitat resulting in impacting organisms living in these ecosystems [66]. The overall public health impact of such oil spills is disrupted supplies of food and water, with increased cardio-vascular hospitalisation over duration of spill [10].

Studies show that an oil spill increases the concentration of Chlorophyll-a (Chl-a) and sea surface temperature (SST) [67]. With increase of Chl-a, surface stratification will increase disallowing vertical mixing of nutrient rich waters, and increase of SST would increase phytoplankton growth leading to harmful algal blooms that can produce toxic compounds that are harmful to mammals, fish, shellfish and even people [68].

In the Red Sea, with currents, this spill is likely to move both southeast and north ensuring that it will spread along the coast of Yemen and then towards the Gulf of Aden thereby increasing the area of impact. During this movement, the oil will affect ports and desalination plants disrupting normal life along with economic gains lost from tourism because of destroyed beaches and foul smell emanating from oil residues. In most cases the most impacted will be planktons, sand beaches, exposed and sheltered rocky shores, salt marshes and mangroves [66]. All these environmental impacts would be visible sooner or later in the region especially with the Red Sea being the only unique and diverse marine environment in a warm, saline and bio-diverse ecosystem [69]. This becomes even more critical as the Red Sea is known for its heat-resistant coral reefs which can sustain temperature rise of 5-6° C and are expected to survive future global heating.

Impact of fertilizers

One of the hazardous cargoes on MV *Rubymar* was 21,000 metric tonnes of ammonium phosphate sulphate, a fertilizer that can easily dissolve in water and can cause soil acidification, water pollution and harm to aquatic life. When dissolved in water, this substance promotes growth of algae and macrophytes that lower dissolved oxygen, which is detrimental to aquatic life. MV *Rubymar* sank near the Hanish Islands of the Republic of Yemen which is a biologically rich area [41]. Since the fertilizer can trigger algal blooms, it can result in low-oxygen dead zones that devastate fishing and shellfish collection in the region. If inhaled by human beings, the poisonous gases can develop hepatic failure, autoimmune diseases, pulmonary disorders, and other health problems [70]. The overall impact on the marine environment would be a disruption of balance in the marine ecosystem that could have a cascading effect on the food web and bring about a serious economic crisis to the communities that depend on the ocean for their livelihood.

Impact of coal

Studies of a sunken coal ship show that polycyclic aromatic hydrocarbons (PAH) and other pollutants continue to pollute the water even though the ship sank in 1891 [71]. This impact is lower than that of sewage entering water. In a coal spill nearly 15% of the coal would be dispersed by ocean current which reduces the size of the problem, as the spill contributes to the coastal sediments. Once again, these coal sediments have not been found toxic to marine life. When coal particles collect on the sea floor over a prolonged period of time, they can impact the flora and fauna of the region, reducing oxygen, with sea creatures becoming darker in colour [72]. Studies appear to be inconclusive [73].

What is conclusive is that coal in the marine environment impacts eggs and larvae of fishes and reduces the diversity of marine creatures when present in the marine environment [74]. Coal contains thorium, uranium, arsenic and mercury but these do not leach into seawater and even if they do, their concentration is minimal. The impact of coal on corals shows that fertilization, embryo survival, and larva settlement are significantly inhibited by exposure to coal particles [75]. In the Red Sea, a coal spill is likely to impact coral and sea creature growth in the long term and would decolour sea creatures reducing their acceptance as food thus causing economic stress to the fishing communities. In addition, the sea beaches would find coal sediments in due course of time to make the beaches look unappealing to tourists.

Impact of timber

Wood debris in water bodies is considered natural as it provides habitat for aquatic species, provides nutrients, and traps sediments, to name a few positive points. This debris is degraded by insects, bacteria and fungus [76]. But, large quantities, such as in wood spill, can overwhelm the natural cycle

of degradation. Since most of this debris reaches the shore, wood can impact the productive habitat of fish species. With time, as the debris decays and mixes with the sediment, it will impact benthic communities [77]. The metal (arsenic) concentration found in wood can sometimes be lethal to fishes and invertebrates. Similarly, decaying wood can be toxic to aquatic life, impacting oxygen exchange and endangering survival rates of fish eggs and juvenile fishes. Increased total organic carbon from wood deposits can impact growth and survival of seagrass thereby impacting the fish community structure [78]. For the Red Sea, the sinking of a timber ship would increase the available wood debris in the region and impact aquatic life especially on the shore thereby causing a serious ecological impact in years to come.

Impact of ULSFO and LSMGO

Both ULSFO and LSMGO are types of marine fuel that are used to reduce air pollution from ships. They are a basic necessity for a ship to be underway irrespective of the nature of cargo being carried by the ship. Hence, such fuel will be available on every ship with the quantity of the fuel depending on the size of the ship and the distance of travel planned. Pollution by these fuels is of concern for ships that sink because these fuels are available in the ship, irrespective of the cargo, when the ship sinks. If not salvaged, this oil will leak into the ocean causing an oil slick once the watertight integrity of the tank holding the oil is compromised. But, since these fuels are refined forms, their viscosity is much lower than crude oil and will have a much greater tendency to disperse naturally than crude oil. In addition, through heat, these oils will evaporate more than crude oils thereby reducing the overall impact seen from an oil slick. They will, however, continue to cause the same environmental impact an oil slick would cause and as discussed earlier. As MV *Rubymar* carrying about 280 t of fuel oil sank near the biologically rich Hanish Islands of the Republic of Yemen it is expected that the spill when it happens will cause environmental impact on fish stocks and coral reefs of the island.

Carbon emissions

In compliance with the Paris Agreement to limit climate change / reduce global heating, IMO agreed to address GHG emission from ships in 2016. Events such as the Red Sea crisis have forced the shipping industry to emit greater carbon emissions than envisaged to ensure that the global supply chains are not impacted. This increased carbon emission would not have occurred otherwise.

Around the Cape of Good Hope

As an alternative to the Red Sea, one of the options being used by shippers is travelling around the Cape of Good Hope. This route adds approximately 8,500 nautical miles and approximately 20 days of operation (at cruising speed of 15-16 knots) to a round trip [79]. Accordingly, the associated carbon

emissions from the additional fuel consumed increase by 38% (equivalent to 4.32 million kg) for a single leg [80]; not including the carbon footprint of the resources consumed by the crew during these additional days. In addition, with the need of additional 3 to 4 containers being required to maintain the supply chains, the net carbon emission from this rerouting will be approximately 12.96 to 17.28 million kg of carbon emission per round trip. Assuming that the ship operates for about 260 days at sea per year, this additional carbon emission would amount to an additional 56.16 million kg of carbon emission per ship per year. In addition, for anchorage, crew, manoeuvring, and cruising another 10% (5.6 million kg) can be added [81]. For operating additional ships to ensure the required global supply chains, this figure will increase accordingly. With IMO pushing for reduction of carbon emissions to meet the Paris Agreement, the challenge for the shipping industry is high.

Carbon leakage

With an intention to reduce GHG emissions from ships, IMO agreed to price emissions from 2030 [82] which has started in phases. Hereafter shipping companies are financially responsible for all emissions caused by transportation. Reducing the travel distance from a region where this emission trading system (ETS) is used can offset the additional cost which is called ‘carbon leakage’. This is done by transhipping containers in ports of Africa that are not currently part of ETS. But, since transhipment adds to the carbon emissions, carbon leakage caused by rerouting is an added environmental impact of the Houthi attacks in the Red Sea. With studies showing 16-19 kg of carbon emission per TEU [83], and the average TEU movement between EU and Asia being at 16.58 million TEU for 2023 [84], the contribution of carbon leakage can be assumed to be approximately 260 million kg of carbon emission per year. This cannot be ignored.

Alternative routes

Since the Suez Canal and Bab-el-Mandeb act as choke points, alternative trade routes have been considered essential for some time. The efforts began with the Belt and Road Initiative (BRI), followed by the proposed International North-South Trade Corridor (INSTC) and now the India-Middle East-Europe Economic Corridor (IMEC). These alternatives will cause higher carbon emissions as sea-route is considered the most environment-friendly option, including inter-modal transportation. Yet another maritime trade route being explored is through the Arctic which too raises environmental issues. Let us discuss each of these alternatives in greater detail.

Rail transportation

Rail transportation is an alternative for transporting goods from the Mediterranean to the Strait of Hormuz and bypassing the Red Sea. Owing to the growing geopolitical pressures and the growing

concerns against the Belt and Road Initiative (BRI), the India-Middle East-Europe Economic Corridor (IMEC) was proposed: an alternative that uses the land rail-route from Jebel Ali in UAE to Haifa in Israel, with the two ends being sea routes. Unfortunately, because of the Israel-Hamas crisis this route has not been developed to date. But, if this route were used, the net carbon footprint would be larger (by nearly 1.5 times) than the conventional sea route as rail transportation is considered more polluting than sea transportation [85], unless the rail route runs on clean energy as proposed under IMEC, when the overall carbon footprint would be less.

Arctic sea route

The shipping industry has not shown much interest in the maritime trade route through the Arctic. There are problems of lack of demand, unforgiving climatic conditions, lack of icebreakers, lack of pilots and many more. Events such as the Red Sea crisis are likely to force the industry to reconsider. This route is considered environmentally a disaster but it is being pushed to create alternatives to the existing maritime trade routes. With the melting of the Arctic this route would open safely, but the Red Sea crisis is only forcing the route to become operational much earlier than recommended. This is likely to cause serious global environmental damage. Too little is known [61].

Discussion and Way Ahead

The Red Sea is a critical navigational trade route for the movement of global trade, especially between Europe and the Far East. The region is environmentally fragile and considered a global hotspot for biodiversity, as it is home to coral reefs and unique marine species [86]. Since only 12 to 15% of global trade flows through the Red Sea [79], it may not disrupt the world economy on its own. Nevertheless, the recent geopolitical tensions created by the attacks on commercial shipping by the Houthis, and the coalition of various nations to ensure freedom of navigation, have made the Red Sea a focal point for numerous discussions. What began as attacks on Israel bound ships in the Red Sea slowly saw other ships including military ships being targeted. Of the commercial ships attacked 33% were container ships, 31% tankers, 24% bulk-carriers and 12% other ship types. For most of these attacks drones, missiles or a combination of both were used. In some cases the Houthis boarded the ship using skiffs, small boats or helicopters. The ships suffered minor damages with no injuries to personnel reported. But, the resulting economic, environmental, and security challenges have been numerous. There are many studies on the economic and security matters; those related to the environment are scarce and scattered. Accordingly, the focus here has been to address the environmental impact of the Houthis' attacks on commercial ships in the Red Sea.

One realizes that the Houthis, in an effort to present themselves as true supporters of the Palestinian cause in the Arab world, decided to join the Israel-Hamas conflict. Although they initially attacked land-based targets, they soon realised their limited success and shifted to attacking marine targets moving through the Red Sea. Since the targets to be attacked have increased over time, it is expected that this list will continue to grow. One also notices the shift in strategy by the Houthis over the months. What began with hijacking and kidnapping, slowly evolved into the use of technology to achieve the desired goals. When it was observed that the technology was not yielding the desired results, small arms battles and the physical positioning of explosives were chosen, which clearly indicates the Houthis' intentions. It is also an indication that the Houthis will stop at nothing.

As in any war, where environmental concerns are often disregarded, here too, environmental degradation has been ignored. This has been done not only by the Houthis but by all others in the Israel-Hamas conflict. It is ironic that on the one hand, nations are struggling to meet their Nationally Determined Contributions (NDCs) to achieve the targets set in the Paris Agreement on climate change [87] while on the other hand they are generating huge levels of pollution on land, in the air, and in the water.

Of the numerous attacks conducted by the Houthis in the past 13 months, only a few have raised environmental concerns, thanks to the active involvement of coalition forces in intercepting the missiles and drones launched by the Houthis. The negative environmental impact that has resulted from these attacks has been discussed here and considered concerning. If left unchecked, it could lead to widespread ecological destruction. Some impacts, such as increased carbon emissions and oil slicks, are visible, others, such as the forced opening of the Northern Sea Route and the cascading environmental degradation, are yet to be fully understood, as they have not received the necessary scholarly attention.

Many scholars and analysts had predicted that the Russia-Ukraine conflict would end in a few weeks, but it continues even today, well beyond 1,000 days. Similarly, to discount the idea that the Israel-Hamas conflict, which has already lasted more than 450 days, will end soon may be a mistake. In such a scenario, disregarding the environmental impacts caused by the Houthis may be improper and should be viewed as an obstacle to achieving the goals of the Paris Agreement.

The need of the hour is to address the problem at a global level, rather than a local one. The efforts of the Houthis are largely an offshoot of the Israel-Hamas conflict, which needs to be addressed. Alongside it, the Russia-Ukraine conflict also requires resolution. For both, the United Nations, which was established to resolve such issues but is now limited in its actions, must play a much larger role.

Humanity has no Planet 'B' for its survival and must ensure that Earth is saved from the detrimental effects of climate change. Such acts of war, with no visible end in sight, will only make things more difficult for future generations, and the very efforts toward sustainability and climate change targets will come to nothing. It is time for the global community to come together and ensure that issues are resolved at the negotiating table rather than on battlefields.

Conclusion

The paper discusses the attacks by the Houthis on vessels in the Red Sea and the ensuing impact on the environment. It is evident that most of the attacks have been limited in causing serious damage to the ships or the environment. These attacks have forced commercial ships to reroute around the Cape of Good Hope, thereby increasing carbon emissions on the route through the Red Sea. The few attacks that have resulted in actual damage to the ships are a matter of concern because of the potential negative impact on the environmentally fragile and globally significant hotspot for biodiversity, the Red Sea. Since these attacks have brought to the fore economic and security concerns for commercial ships at a time when even the Panama Canal is being restricted because of drought, it will not be long before ship operators push for the opening of the Northern Sea Route (NSR) much earlier than anticipated, should the Red Sea crisis persist. The ensuing environmental disasters from the opening of the NSR would be a nightmare that humanity would prefer to avoid but may have to face if positive efforts to resolve the Israel-Hamas conflict are not made at an early date.

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BOOK REVIEW

Nile Basin Politics: From Coordination to Cooperation, edited by *Steven C. Roach, Derrick K. Hudson, and Kaleb Demerew, Cheltenham, Edward Elgar Publishing, 2025, 180 pp., £90 (hardback), ISBN: 978-1-80392-716-9; eISBN: 978-1-80392-717-6.*

The three main riparian countries of the longest river in the world have not created a regime for their shared waters in regard to each one's needs and climate change variations. This failure can be attributed to internal politics in these countries, economic and social dynamics, as well as their international relations. One must examine the situation through different perspectives. This is what Nile Basin Politics has to offer.

The book establishes that since the 1990s, a new era has begun in the Nile Basin, where new actors have challenged the colonial-inherited paradigm, bringing about a new reality that demands a new understanding, and joint actions to make cooperation over the Nile possible (p. 76). The book examines the challenges of long-term cooperation among the three main riparian states of the Lower Nile Basin, viz., Egypt, Ethiopia, and Sudan, dubbed the 'Big Three', by focusing on domestic nationalist forces and hydro-hegemonic factors (p. 2). It also discusses the importance of the role of other riparian states located in the Lake Victoria Basin and foreign powers such as the United States in the overall management of the Nile and in maintaining peace and stability in the area.

The contributors to the book maintain that the power of the nationalist forces in these countries has not been recognized in designing or hindering cooperation between the Big Three, nor has intervention by foreign powers (p. 13). (Some observers would see the United States as acting with imperial self-interest.) The book argues that successful agreements and frameworks for cooperation require understanding the changes and dynamics of power in those countries (p. 79) and taking a gradual multi-micro-macro approach to resolve the issue of sharing the Nile waters. Such an approach seems to be inherently difficult. States of the federal Commonwealth of Australia fail to work together on allocating the waters of the Murray-Darling river system.

Thus, for cooperation to succeed, there needs to be coordination. The book defines coordination as 'a process in which two sides learn to work with one another to forge commitments to cooperate with new rules of agreement.' It describes it as less regularized than cooperation, occurring in small and practical steps based on common understanding. Coordination can enhance trust and create goodwill. It lays the groundwork for long-term cooperation as it comes from within, i.e., not imposed by outside

actors, and is less prone to politicization since it occurs on a small scale in gradual and practical steps. Coordination and cooperation must be voluntary, not forced or imposed, so that trust is built between the parties (pp. 3-5,125-126). Some may find this obvious and banal. Others may consider that it requires an almost mystical imagination. Some may think coordination is more about 'regularization' and cooperation is more about goodwill.

There are factors to consider regarding the lack of cooperation and how cooperation can occur in the future between the Nile Basin riparian states: internal politics, political changes and upheavals, nationalism, socio-economic situations, and international relations. Sudan's internal instabilities, for instance, have always influenced its foreign policy towards the Nile; they have improved relations with Egypt but worsened those with Ethiopia. Nationalism in the Big Three, particularly in Egypt and Ethiopia, pushes toward non-cooperation over the Nile. Domestic politics in Egypt and Ethiopia have been the most important factors in explaining variations in foreign policy toward the Nile over the past three decades (pp. 24-33).

The politics of the Nile River have also been affected by external stakeholders: governments, organizations, and influential individuals. The British colonial power established Egypt as the master of the Nile Basin through a diplomatic Note, i.e., the 1929 Agreement, which allocated Egypt 48 BCM of the Nile waters (out of the river's total 84 BCM annual flow) and granted it the authority to inspect and veto upstream Nile water projects. This was reinforced by the 1959 Agreement between Egypt and Sudan, which increased Egypt's share of the Nile waters to 55.5 BCM and allocated 18.5 BCM to Sudan. Together, these two allocations constituted 90 percent of the total Nile flow in a year. The result was that the countries at the Nile's origins have no water for agriculture, urban use, etc. The agreements do not embody the spirit of equitable use of the shared waters, a principle upheld by many countries around the world (pp. 41,91).

Nevertheless, many changes in the region over the past decades have led to the decline of Egypt's hydro-hegemonic power in the Nile Basin: the rise of nationalism in Ethiopia; the availability of outside expertise and funds for water development projects in the upper riparian countries; the presence of (neo-imperial) China as an economic and political power in the area; political instability in Egypt in recent decades; general instability in the region. The unfair arrangements of 1929 and 1959 disregard the interests of upper riparian countries and counter the spirit of the principles of equitable sharing of watercourses without harm to downstream countries. These changes have created a new reality that requires cooperation. According to Demerew and Hudson, the world has changed; so should the Nile Basin riparian countries' policies, approaches, and perceptions.

This would mean increasing water resources and reducing reliance on the Nile, especially in Egypt, which depends on Nile waters for all its human and industrial needs – 98 percent of Egypt's total renewable water supply is provided by the Nile (p. 67). This reliance has led Egypt to maintain the

claim of having a legal hydro-hegemonic power in the basin (which nowadays seems questionable); and it has made the country very vulnerable to changes in water flow because of the increasing influence and power of upstream countries and the variability of climate change. Egypt, as the last downriver country of the Nile waters, exerts power because of the 1929 and 1959 arrangements.

The international relations of the Big Three have affected the politics of the Nile waters. Sudan, for example, signed the 1959 Agreement with Egypt, which favoured Egypt to a great extent because a pro-Egyptian government was in power in Sudan. Similarly, for Egypt to maintain its hydro-hegemony over the Nile, it continued to support governments in Sudan and promised economic aid to the Democratic Republic of Congo, Burundi, and other riparian countries (pp. 29,97-103). Egypt had been dominated by Britain until Gamal Abdel Nasser deposed King Farouk. In 1956, Britain with France and Israel attempted to regain authority by taking back control of the Suez Canal. Eisenhower threatened to bankrupt Britain, failed to support the Hungarian Uprising of 1956, and later invaded Lebanon with a spurious argument (a non-existent communist threat).

The United States became an influential power in the region, especially after Egypt, under President Anwar Sadat, signed a peace treaty with Israel in 1977. Egypt's strong ties with the US led a riparian country like Uganda to support Egypt's Nile policy, fearing that if it did not, it would negatively affect millions of dollars in aid it was receiving from the US (pp. 105-106). An exception to the US support for Egypt occurred when Sadat's predecessor, Nasser, drew Egypt closer to the Soviet camp, which provided for the Aswan High Dam (AHD), a structure which has produced many problems of its own. In reply, the US offered some support to Ethiopia in its ambition to gain some control over the Nile.

The US support for Egypt became very evident during Donald Trump's first term (2017-2021), jeopardizing future negotiations for an agreement. The US administration under Trump bolstered Egypt's hydro-hegemonic position at the expense of all the other riparian states. It sided with Egypt on many occasions and used 'coercive diplomacy' to subjugate Ethiopia when it tried to mediate among the Big Three (p. 122). Trump exacerbated the situation by stating that Egypt would blow up the Grand Ethiopian Renaissance Dam (GERD) if Ethiopia continued with its Nile policy (p. 111). The Biden administration attempted to correct Trump's policy but did not achieve much since it largely left the matter to the African Union to resolve (p. 127).

Ethiopia and other upper-Nile states attempted to gain legitimacy for their current and future developmental projects on the shared watercourses. They signed the Nile Basin Initiative (NBI), which resulted in the Cooperative Framework Agreement (CFA), in which Egypt is not a member (p. 78). The CFA did not succeed because, according to Udobong, it was based 'on ideal notions of equitable and shared use of the river [Nile] among all riparian states' (p. 133). Why should nation states exempt themselves from international law?

One major practical step that has changed the dynamics of Nile politics and calls for a new approach to the issue is the GERD on the Blue Nile in Ethiopia. GERD resulted from growing nationalism and internal state-building efforts in Ethiopia after the appalling years of Mengistu's revolution against Emperor Haile Selaissie. The Ethiopian government was able to collect US$ 350 million through domestic taxation and bonds. Demerew argues that the commencement of GERD's construction in 2011 brought about a dramatic change to Egypt's longstanding monopoly over the Nile, because it repudiated the arrangements of 1929 and 1959. An upper riparian state opposed Egypt and Sudan (pp. 21,27,28). The Big Three had split.

The Blue Nile flows through Ethiopia and supplies 86 percent of the Nile's total waters. The White Nile, which flows from Lake Victoria, provides the remainder of the Nile's waters. The Nile is about 6,700 km long, the longest river in the world (p. 41). The GERD's storage capacity peaks at 74 BCM; its annual average flow is estimated at 49 BCM. The GERD is highly contentious; it challenges Egypt's long-held hydro-hegemony over the Nile. Egypt views the GERD as a threat to its water security, national security, and dominance over the Nile (p. 10). This perception often leads to military preparedness and renders coordination and cooperation a distant possibility **[1]**. Egypt does not appear to think that its extraordinarily large population and its claim to receive so large a volume of the Nile threaten itself and other countries.

Similarly threatening to a future agreement on the operation of the GERD is the parties' reluctance to treat each other on an equal footing; to share information about water in their dams and canals; or take responsibility equally during droughts (pp. 47-49). The situation is related to national development and water security, which are inherently linked; therefore, the countries in the Big Three are unwilling to relinquish their historical rights, as in the case of Egypt, or territorial sovereignty rights, as in the case of Ethiopia, to the Nile waters (pp. 91-92).

This approach is political and security-derived, but it does not have to be. GERD can be 'what states make of it,' in line with social constructivism's view of international relations in an anarchical world that 'Anarchy is what states make of it' **[2]**. GERD can be very beneficial for all the riparian countries, except perhaps during the filling and re-filling stages. Among its benefits are redistributing water, especially now that climate change increasingly affects our planet, and reducing the evaporation of Nile waters. Other dams on the Nile have a higher evaporation rate than GERD; for example, the AHD in Egypt 'has 250 percent more evaporation loss than the GERD' (p. 56).

Ghebremichael and Asefa mention additional benefits of GERD. The dam reduces flood risks, minimizes sediments and silt that accumulate in millions of tonnes yearly and settle at the bottom of downstream dams – something that gradually reduces the storage capacity of the dam and incurs significant costs for cleaning and maintaining the canals. It creates a stable flow of water by decreasing peak flow during flood seasons and increasing low flow during drought seasons. It

generates clean and affordable electricity that can benefit both Ethiopia and Sudan, reducing the demand for wood fuel in Ethiopia, thereby improving the environment and increasing the likelihood of more precipitation.

GERD can help reduce current and future uncertainties owing to the impact of climate change. It can benefit the entire region more than it can harm it. This requires the parties to develop a positive view toward the dams in general and GERD in particular, treating GERD as a positive-sum game, not a zero-sum game or a zero-sum competition, as has so far been the case. Ethiopia's gain is not necessarily Egypt's loss. 'Egypt's water security can be achieved through cooperation and the efficient use of the Nile waters' (p. 12). The GERD can be the turning point for cooperation and reconciliation between the parties and become the basis of a new legal framework that accommodates existing international laws and treaties on sharing transboundary rivers, such as the United Nations 1997 Non-Navigational Uses of International Watercourses (p. 15).

It is imperative to develop this understanding. From 1947 to 2010, Egypt has transitioned from 'water abundance' through 'water adequacy' to 'water scarcity'. It faces a water deficit of 21 BCM, which is expected to rise to 51 BCM by 2050 (p. 67). This means that Egypt will encounter significant challenges in producing food for its growing population, which stands at 118 million **[3]** and is projected to rise to 175 million by 2050 (p. 74), along with many other developmental issues.

Disagreements among the Big Three about the GERD initially focused on the construction of the dam; later, they centred on filling the dam, and now they concern the amount of water to be released during normal times and drought (p. 142). The construction of the dam is nearing completion **[4]**, and the final phase of filling its reservoir has been achieved **[5]**. These developments occurred without a prior agreement, and irrespective of 1929 and 1959 arrangements (pp. 77,78). The release of water during both normal times and drought is the most contentious issue between the parties, and this will persist unless an agreement is reached. The book indicates that a temporary solution can be found, and a short-term plan can consolidate the foundation of a long-term agreement.

GERD is not the only dam on the Nile River; but, it is one of the largest. There are many dams on the river, including AHD, which can store 160 BCM, twice as much as the storage capacity of GERD. AHD was constructed without prior agreement with the upper riparian states. AHD and GERD can store more than 250 BCM of water combined. This water-saving capacity in the Nile basin increases if other dams and artificial ponds are added. The saved water can be used for the best interest of all parties.

An interdependent relationship among the Big Three through joint projects, investment, and trade can make the above dream a reality. Liberal International Relations theorists maintain that economic interdependence, which signifies mutual dependence, and a higher level of transnational relations

between states, is a necessity of modern times. It brings countries closer, fostering cooperation and promoting peace **[6]**.

A shift in perception and a change in position are necessary for any coordination and cooperation over the Nile waters. The GERD and other dams need not be viewed in a negative light, and the regional watercourses can be understood as a common property owned by all, which should be used for the benefit of all. The principle of Absolute Sovereignty over the waters should be abandoned in favour of Limited Sovereignty, which should be incorporated into their negotiations and used as a principle for future agreements. There needs to be a water management protocol that promotes equitable and reasonable use while minimizing significant harm to Egypt and Sudan, the two downstream countries (pp. 79,82).

Udobong suggests that the 'notions of equitable and shared use of the river [Nile] among all riparian states' are very idealistic and were the reason behind the failure of previous attempts to resolve the issue. Instead, he proposes 'functionalism,' which is in the spirit of 'coordination': 'iterative, project-specific, cross-country working groups would work better at enhancing global cooperation than broad ideals and supra-governance structures.' Broad universal commitments may not be effective; 'functional experiences of trust-building, policy sharing, and joint investments' (interdependency) may prove successful (p. 135). Perhaps there is no real difference of meaning. Being functional with goodwill can produce coordinated actions which manifest cooperation.

As applied to water governance, this functionalist theory encompasses three tenets: (i) identification of well-defined working areas and common policy directions; (ii) pooling rather than encroachment of sovereignty toward joint and coordinated action on specific issues; and (iii) the possibility of building on selective agreements rather than only comprehensive ones (p. 135).

Perhaps as important as an agreement over the sharing of waters in the GERD and Nile is improving and expanding water resources and the efficient use of the available water, especially in Egypt. These include desalination, reuse of treated wastewater, rainwater harvesting, and more. The efficiency of water use includes conservation of water at all levels: irrigation, industrial, and domestic. Irrigation of agricultural land in general consumes approximately 85 percent of the water supply; hence, the improvement of irrigation by introducing and developing new methods such as drip and sprinkler irrigation, as well as planting crops that do not require much water, is a very necessary step, especially in Egypt and Sudan, where 97 percent of the irrigated land in the Lower Nile Basin is situated. 'Recent studies indicate that a total of 40 BCM of water [in a year] can be saved in Egypt through the implementation of various water-saving measures.' By moving away from water-intensive crops such as rice, Egypt can save about 12.4 BCM of water in a year (pp. 54,55). This may require Egypt to seek advice from Israel, which has practised such economy, looking back to Nabatean examples.

The election of Donald Trump as President of the United States (2025-2029), after four years of Joe Biden's presidency, might not be beneficial for the Nile Basin water-sharing problem. The US, during Trump's first term, did not act as a stabilizing power in the Nile Basin. The region needed the US to serve as a mediator but also as a superpower to bring the Big Three to an agreement over sharing the Nile waters. Instead, the Trump administration sided with Egypt regarding the Nile waters. Trump did not have a coherent policy for the Nile Basin, and his approach to the issue exacerbated the situation. It created uncertainties and made an agreement a remote possibility (pp. 118-122). It is up to the Nile riparian states to change the situation. The basin belongs to all of them, and they need to act with coordination.

The final chapter of Nile Basin Politics sees a future for the Nile Basin where political leaders and nations collaborate for the benefit of all. Verhoeven and Tawfik believe that there is hope for change: a couple of decades ago, observers speculated about 'water wars' and 'climate conflicts,' yet these did not happen. The imperatives of climate change and future uncertainties must drive regional integration in the Nile Basin among Egypt, Ethiopia, and Sudan (pp. 150-170).

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BOOK REVIEW

Into the Great Wide Ocean: Life in the Least Known Habitat on Earth, **by** Sönke Johnsen, Princeton University Press, 2024, 248 pp., $24.95/£20.00 (hardback), ISBN: 978-0-6911-8174-5.

Sönke Johnsen, a biologist, offers in this book a work of rare elegance, weaving together meticulous observation and lyrical narrative to reveal the mysterious world of the open ocean. The narrative brings readers into the vast midwater column, miles above the seafloor and far from the coast, a realm that houses the planet's most abundant and least understood life. Johnsen's treatment is not just a broad survey but also a meditation on what it means to study, witness, and belong to a world governed by unfamiliar laws. The book is at once a poetic field guide, a memoir of life at sea, and a call to scientific wonder and ecological responsibility.

From the outset, Johnsen redefines how scientific storytelling might operate. In the first chapter, "I Never Knew the Ocean," he begins not with taxonomy or data, but with vulnerability, admitting his earlier ignorance of the ocean's profundity. He describes the sea as "an unsuspected cosmos just beneath our feet", immediately inviting readers to reconsider their own assumptions. This chapter captures his first descent in a submersible (pp. 10–14), where the gradual extinction of sunlight is rendered not only visually but philosophically, mirroring the descent into the unknown. It sets the emotional and intellectual tone for the journey that follows. The writing also reflects Johnsen's belief that scientific language need not be sterile. Instead, it should resonate with imagination, using metaphors and poetic flourishes not to obscure facts, but to clarify them. He invites the reader to navigate not only the depths of the sea but also the language we use to describe it.

What distinguishes this book is Johnsen's ability to use scientific phenomena as thematic gateways. In Chapter 2, "Gravity," he reveals how deep-sea life evolves in near weightlessness. He writes, "gravity loses its grip, not through defiance but through diffusion", reimagining gravity not as a constant but as a relational force. Diagrams on pages 27–33 comparing skeletal structures in surface versus abyssal species show how life dissolves into suspension rather than resisting it. Chapter 3, "Pressure," transforms an abstract physical condition into a sensory metaphor, describing pressure as "a silence so heavy it folds sound inward". Through detailed explanation, he unpacks the molecular mechanisms, membrane fluidity, enzyme stability, protein folding, that allow organisms to survive

where pressure would crush a truck. These mechanisms, often reduced to textbook diagrams, are presented here in a vivid, relatable context, how a molecule bends, flexes, and breathes differently when it is five miles beneath the waves.

In Chapter 4, "Light," Johnsen explores the paradoxical importance of bioluminescence in a place where sunlight never reaches. His metaphor of "fireworks in slow motion, launched by creatures who have never seen the sun" captures both the beauty and evolutionary utility of light in darkness. His textual descriptions guide the reader through luciferin, luciferase reactions and light organ structures without compromising narrative flow. These biochemical reactions, often perceived as arcane or purely functional, are elevated into storytelling devices, each flash of light, each luminous trail, becoming a message in the otherwise silent dark. In Chapter 5, "Motion," Johnsen explores propulsion and orientation in a medium with no fixed directions. The barreleye fish, with a transparent head that allows it to peer upwards through its own skull, and the squid's jet propulsion, exemplify adaptations to a three-dimensional wilderness. His metaphor of the siphonophore as "a living chandelier descending through ink" stands among the most evocative in the book. He illustrates how movement is not only a question of physics but of perception: how organisms navigate a world where "up" and "down" are fluid concepts.

The discussion of food in Chapter 6 challenges terrestrial norms. The ecological arc of a whale fall, from "feast to fossil", is told with reverence for the temporal rhythms of decomposition. Marine snow is poetically described as "the slowest blizzard on Earth" (p. 137), a continuous drift of organic detritus that nourishes the unseen. One of the book's most haunting metaphors: tubeworm colonies at hydrothermal vents, "a red-tipped garden in hell," highlight the contrast between the vibrancy of life with the toxicity of its surroundings. Johnsen shows us the ecological richness of environments we might otherwise deem barren. He challenges us to consider the ocean not as a void, but as a reservoir of complex, finely tuned survival strategies shaped by millennia of adaptation. The food web is not linear but particulate, not sequential but simultaneous, particles descending from above while chemical riches erupt from below.

Johnsen also infuses the chapters on reproduction and kinship with emotional and ethical resonance. Chapter 7, "Family," highlights the anglerfish's extreme reproductive strategy, wherein the male fuses permanently with the female's body, calling into question biological individuality. The maternal sacrifice of deep-sea octopuses, which go without nourishment for years while brooding, is described with quiet dignity. The image of the dumbo octopus "ballooning in the water like a cautious umbrella" (p. 164) shows tenderness without anthropomorphism. In Chapter 8, "Community," Johnsen rebuts the notion that the deep sea is a place of solitude. Symbiotic relationships, such as those between shrimp and bioluminescent bacteria or tube worms and chemoautotrophic microbes, are reframed as

essential systems of mutual survival. The metaphor of a vent city as "a furnace-fed metropolis" evokes the density and interdependence of abyssal life. By rejecting the outdated idea of the deep as lonely and lifeless, he makes a compelling case for a re-evaluation of what constitutes community, one that includes the microbial and the unlit, the unfamiliar and the interdependent.

These scientific portraits are enriched by Johnsen's accounts of life aboard research vessels. His reflections on the camaraderie, isolation, and humour of seagoing scientists bring warmth and humanity to the narrative. The fieldwork anecdotes are not decorative but integral: they reveal how science is not merely conducted but lived. His personal voice, combined with Marlin Peterson's delicate illustrations, allows the reader to appreciate not only the facts but the aesthetic of discovery. The ocean emerges not as an object of study but as a participant in the narrative, a presence that shapes the mood, methods, and meaning of scientific inquiry.

The Epilogue brings the book full circle, from curiosity to responsibility. The declaration that "we know more about the surface of Mars than our own seabed" is both a lament and a call to action. Marine biology becomes, in his words, "detective work in a liquid cathedral," a metaphor that marries reverence with empiricism. The urgency of conservation is clear in the final lines: "the deep sea is not empty, it is full of secrets, and many are already vanishing," signalling that to ignore this habitat is not only a scientific failure, but a moral one. The final message is both humble and haunting: exploration must be paired with protection, curiosity with care.

Into the Great Wide Ocean is far more than a book about oceanography; it is a profound reflection on life's adaptability, vulnerability, and inventiveness. With prose that balances scientific precision and a deep sense of wonder, Johnsen portrays the open ocean as both unfamiliar and fundamental. The book challenges our surface-bound assumptions and reveals that the seemingly strange ways of life in the deep sea are, in fact, the oldest and most enduring on Earth. By blending biological insight with philosophical reflection, it not only deepens our understanding of marine life but also reshapes how we perceive knowledge itself. This is a masterful work of marine literature, one that will linger in the reader's imagination long after the final page is turned.

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BOOK REVIEW

Genfortryllet, Vejen til Mere Biodiversitet på Din Landejendom, by *Anne Erland Eskildsen and Heidi Buur Holbeck, Aarhus, Aarhus Universitetsforlag, 2024, 190 pp., DKK 299 (hbk), ISBN: 978-87-7597-117-6.*

In recent years there has been a plethora of books on designing a 'wild' or 'natural' garden, but (at least in Denmark) no guide to establishing a wilder and more natural farm. 'Re-enchanted. The road to more biodiversity on your farm' should set that right, and it could serve as a model for such publications elsewhere, covering so many matters in a very readable style, on most pages supplemented by illustrations. But keeping in mind that important parts of such a book must be country-specific, with its details of the local types of nature as well as its in-depth covering of public laws and regulations to follow when modifying a property,

The book is made more appealing to the hesitant beginner in that it presents five families who are interviewed with regard to the biodiversity projects on their farms. In an honest and modest way they describe their journeys with the unavoidable mistakes, hardships, disappointments, contacts with the authorities etc. It should be said that the stories are mostly positive, such as the farmer who after just 12-15 years has 50,000 flowering orchids on his former agricultural fields. Nature often seems to have surprising regenerative powers. To read about the experiences of real persons surely would make it less frightening for the readers to start on their own. In a modern society, perhaps in densely populated Denmark more than in most countries, there is certainly a frightening amount of laws to be followed when tinkering with the environment! But so it should be.

The book begins by presenting the sorry present state of Denmark's biodiversity. Among the birds, during the last 50 years the common starling has been reduced by 60 percent, and the Northern lapwing by 70 percent. 12 species or 20 percent of Danish butterflies have disappeared from Denmark since the 1950s. More than 340 species of animals and plants have disappeared from the country since 1850, no doubt further unknowns in addition to these. Denmark is one of the most intensely cultivated countries, and at present only about two percent of the territory are exclusively devoted to the preservation of biodiversity. It has been decided, now, that 12 percent (75,000 hectares) of the Danish forests should become 'untouched' by human beings (though still with public access).

The largest adjustment needed is perhaps not of the environment itself, but of the ideas inside the heads of people. Danes have the historical instinct that land should be 'used', be productive and provide a harvest; it is really shameful just to have disorderly wilderness on your property! The authors admit that most species really are quite useless to human beings, but they should be regarded as of value in themselves. Most of the 300 species of bees in Denmark could disappear without significant loss of pollinators, but bees in all their diversity are becoming popular among the Danes. It will be entirely up to their value-based decision whether these and other species enrich the modern world! The honey bee is certainly the most useful of the bees. Many people regard it as a service to biodiversity to support that species, but in fact it should be regarded as a farm animal like cattle and sheep. It outcompetes the indigenous bees. Such mistakes are common. Many Danes would consider it standing in the middle of 'nature' when they stand in a field of rapeseed.

An important part of the rewilding of larger properties is to take care of the cattle or horses preventing the open grassland from becoming dense growth. Some benign neglect of the land will not damage the prospects of the livestock. The book also provides the basic instructions for such tasks, but much necessary knowledge must be found elsewhere, and for this the authors not only give a traditional list of references, but also for many subjects QR-codes in the relevant chapters as paths to further information. Of course the citations of public laws etc given in the book are up to date, such as the widening from 2 to 3 m of the agricultural-free zone along water courses in 2023. Online links to further information anticipate that those links may have longer lives than the printed page! But an impressive amount of information of more permanent value is found in the book itself, such as detailed instructions for veteranisation of trees. Let us hope that it will stimulate new growth of good possibilities!

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BOOK REVIEW

Research Handbook on Plastics Regulation: Law, Policy and the Environment, edited by *Elizabeth A. Kirk, Naporn Popattanachai, Richard Barnes, and Eva R. van der Marel, Edward Elgar Publishing, 2024, 480 pp., £190.00 (hardback), ISBN: 978-1-80220-151-2; eISBN: 978-1-80220-152-9.*

The editors open the debate in this work, with a compelling preface that raises an uncomfortable question: how have plastics—almost magical materials, widely praised for their versatility, lightness, and durability—become a global socio-economic threat? Far more than mere waste, as traditional regulatory frameworks (e.g., UNCLOS, the Basel Convention, and MARPOL) have historically classified them (pp. 88, 130), plastics are now regarded as a geological marker of the Anthropocene, bearing witness to the indelible footprint of human activities on the planet (pp. 84, 85).

By deconstructing conventional theoretical frameworks, Hamley, Switzer, Kirk, and Hunter examine this contradiction through a systemic approach, intertwining history, science, and law. They highlight the concept of the Anthropocene and the critical ecological thresholds that society is either approaching or surpassing—particularly in terms of chemical pollution, disruption of phosphorus and nitrogen cycles, and biodiversity loss—all of which align with the nine planetary boundaries defined by the Stockholm Resilience Centre ([1], pp. 82-85).

The authors first trace the evolution of these materials and justify the need for effective plastic regulation under key strategic principles. They argue that such regulation is essential for governing the use, production, and management of plastics on a global scale, insisting that hope must not be lost. The Montreal Protocol (1987) serves as an instructive precedent—offering both a lesson and a beacon of hope—demonstrating that global action can yield tangible results, as seen in the successful recovery of the ozone layer [2].

The first key approach advocates a cross-cutting and systemic strategy to limit legislative fragmentation and strengthen institutional and international coordination through the creation of enforcement mechanisms and sanctions for non-compliance. Yes, this may be an effective solution—provided we keep in mind that this is a global issue affecting everyone (*erga omnes*, p. 10).

It would also be relevant to simplify the application of laws to ensure a more coherent and effective regulatory framework. Furthermore, regulatory intervention should be shifted upstream; but, as the authors highlight, existing policies often favour a downstream approach, focusing on recycling and waste reduction rather than effectively limiting plastic production at its source (p. 126).

Although a science-based, evidence-driven approach is present, the authors stress the importance of continuous monitoring of the latest scientific developments. There are instances where action must be taken as a precautionary measure, an alternative principle that sometimes overrides our judgment, eve n in the absence of conclusive scientific proof (pp. 29, 56, 105).

The book truly surprises us with its rigorous exposition of how these ubiquitous materials, which permeate our daily lives, nano-fragment, dispersing into the air, water, and soil, thereby affecting both wildlife and human health. Like invisible parasites, they surround us, infiltrating cells undetected, evading filters, and silently invading the living world, wreaking havoc at every stage of their cycle—from production to disposal (pp. 19-23).

Silent stranglers of marine life (turtles, fish, birds) (cover page, p. 123), they poison entire ecosystems, lay ering their toxicity over time. A ghostly plague, multi-toxic and endocrine-disrupting. An invisible agent, causing neurological damage, cardiovascular diseases, cancer, and reproductive disorders. Plastic invades our clothing, packaging, food and drink, and indeed our bodies. Moreover, simply eating a meal outdoors exposes us to as many microplastics as drinking from a plastic water bottle [3]. This contamination extends to seafood and table salt, which are additional vectors of microplastic ingestion [4].

Furthermore, there are numerous pathways through which these particles reach our plates (pp. 38-58). A study on honey harvested in Switzerland revealed that the presence of microplastics is mainly linked to beekeeping practices and environmental contamination [5]. Similarly, another study found microplastics in edible root vegetables, released through the degradation of plastic waste, including traces of polystyrene and PVC [6]. Plasticulture materials and pesticides further exacerbate the situation, serving as major sources of microplastic exposure. These particles persist in the soil for decades, altering its structure and threatening biodiversity (pp. 101-106).

The water we consume is not spared: microplastics found in tap water and bottled water originate from the degradation of plastic pipes, reservoirs, and even the bottles themselves, as fragments break off over time [7].

But beyond consumers—and beyond us—it is the workers in plastic production factories who suffer the most severe exposure, experiencing a double impact (p. 20). The risk is spreading everywhere. We can no longer ignore this reality: the impact of plastics on human health and the environment demands a stronger response. This issue must be placed within a broader framework of social justice and the right to health.

A legal framework does exist, but it is insufficient! International treaties, such as the Convention on Biological Diversity (CBD) and the Bonn Convention, focus on preserving wildlife and ecosystems from plastic waste, but they do not directly address food contamination. Others, like the Codex Alimentarius, remain incomplete. Meanwhile, the FAO and the WHO have mandates that are too broad to regulate plastic contamination in food specifically. These laws contain significant gaps in addressing the issue as a whole, and fail to emphasize the critical need to act at source (p. 46)!

In international trade, countries cannot freely ban certain plastics in food products, as they must comply with World Trade Organization (WTO) rules, which require a scientific justification proving that such a ban is necessary to protect health or the environment. Otherwise, the ban could be challenged at the WTO as an illegal trade barrier!

Paradoxically, some plastic exports remain entirely legal and are even regulated under agreements such as the Basel Convention. Yet, many Global South countries are turned into dumping grounds, without the necessary infrastructure to recycle or manage these wastes sustainably (pp. 89, 97) ... A clear example of environmental injustice—an unacceptable scandal!

The petrochemical industry refines and cracks oil to obtain essential monomers (ethylene, propylene, styrene, etc.) required for plastic production. The environmental impact of this activity is immense. Its inherently polluting nature often leads to the depletion of fossil resources, the destruction of forests, mangroves, and natural habitats [8], as well as significant greenhouse gas emissions and other pollutants that heavily contribute to climate change.

Its chemical processes, which rely on solvents, additives, and toxic catalysts, also result in harmful emissions into the air and water (pp. 59-78). Given the severe consequences of this impact, urgent and effective regulation is imperative.

Currently, each country adopts a distinct—often contradictory—approach to the environmental and industrial challenges posed by the petrochemical industry. Hunter illustrates this by comparing risk and impact management plans, based on regulatory frameworks, as applied in Australia, the United Kingdom, and Canada. The findings reveal significant disparities in the strategies implemented, making the fight against plastic pollution an increasingly complex task—one that must navigate environmental restrictions, economic incentives, and the regulation of natural resource exploitation (pp. 60-75). It is strange that Australia, Canada and the United Kingdom do not work in the same way on this problem.

The authors piece together the complex puzzle of scattered global regulatory frameworks (pp. 80-186). du Toit, Goodwin, Scott, van der Marel, Ballardini, and Vesala decipher the clues and follow the narrative thread, leading to a rigorous descriptive and comparative analysis of current regulations against plastic pollution—shedding light on "Where do we stand today?" across various national and regional contexts.

Their investigations extend across a wide range of legal frameworks, from European regulations to specific strategies adopted in geopolitically and ecologically sensitive areas, such as the Northeast Atlantic and the Arctic, where plastic management is a major environmental challenge. In Oceania, a region particularly vulnerable to marine pollution, they examine how island nations strive to balance ecosystem protection with economic development.

On the African continent, plastic regulation is explored at two levels: first, at the continental scale, where collective initiatives are emerging, and second, in Kenya, often cited as a model for its strict ban on plastic bags.

In Asia, China, the world’s largest producer and consumer of plastics, is scrutinised through the evolution of its policies, particularly regarding restrictions on plastic waste imports. In the Philippines, where plastic pollution is of critical concern, the analysis focuses on legal responses to this crisis, illustrating the specific challenges faced by developing island states.

Finally, in Europe, the study examines the European Union, a global leader in environmental regulations, and the United Kingdom, where plastic policies have evolved distinctly post-Brexit, revealing differentiated approaches to environmental governance.

In line with ecosystem-focused legal frameworks and human-centred regulatory approaches, the authors highlight the need for a systemic approach, referred to as "Earth System Law", which considers the complex interconnections within the Earth's system. They argue that it is time to recognise the rights of nature as an entity with intrinsic value, granting legal rights to its elements (forests, rivers, oceans, animals, etc.). This means an adaptive and dynamic legal framework, capable

of responding to the rapid and chaotic evolution of ecosystems, which are increasingly threatened by collapse and climate change (pp. 83-85, 93-94, 98, 99).

The self-assessment conducted by Paloniitty, Ala-Lahti, Tanaka, Mackie, Hossain, Raubenheimer, Strydom, Opondo, Eisma-Osorio, Chang, Sun, Wang, and Besco was crucial in developing an improvement plan and anticipating future regulatory and innovation developments. Their forward-looking approach offers insights into improving current policies and developing alternative solutions that emphasize innovation and sustainability (pp. 187-374).

As the final highlight, Richard Barnes dedicates a comprehensive section to the circular economy (pp. 375-397), demonstrating how it could reduce plastic pollution by promoting recycling, reuse, and waste reduction. Current laws remain insufficient to support this transition effectively. More global and better-coordinated regulations are needed, covering all stages of the plastic life cycle, rather than focusing solely on waste management.

Barnes' work is immediately complemented by the well-established analysis of Malcolm and Mikheeva-Ashe (pp. 398-420), who examine the European Union's case. The EU stands out as one of the few economic blocs to have fully integrated Life-Cycle Thinking (LCT) into its regulations. Unlike other regions that prioritise recycling or end-of-life waste management, the EU takes a more systemic and preventive approach, relying on ambitious policies such as the Ecodesign Directive and the Sustainable Products Regulation (ESPR).

By rethinking plastic production and usage before manufacturing even begins, the EU seeks to abolish the linear "take-make-dispose" model in favour of a sustainable and regenerative system. With a critical perspective, Malcolm and Mikheeva-Ashe highlight that this transition remains incomplete. Th ough a pioneer, the EU must still overcome regulatory and industrial challenges to make the circular economy the global standard. A powerful conclusion to a decisive challenge.

Edward Elgar Publishing, renowned for its expertise in economics, law, political science, environmental studies, and innovation, once again delivers an essential reference with this book. A true "legal codex" and "academic and regulatory benchmark" on plastic governance, this volume meticulously examines global legislative frameworks, highlighting both the limitations of current approaches and the opportunities for more effective regulation. Through a comparative and systemic analysis, it underscores the urgent need for coordinated and proactive action, offering concrete pathways towards more coherent and sustainable plastic governance.

Ending with a section on the circular economy is no coincidence—*it is a necessity*. This is where the future of responsible plastic management lies, moving beyond the partial solutions of recycling. More than just an assessment of the status quo, this indispensable handbook provides a vision and practical tools to rethink the regulation of these omnipresent materials.

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