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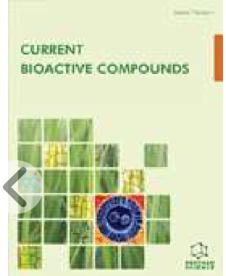

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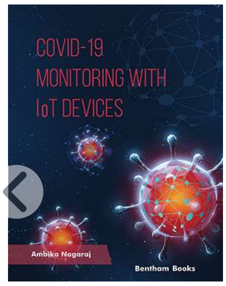

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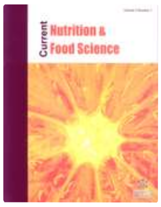

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Review Article

Food Contamination with Micro-plastics: Occurrences, Bioavailability, Human Vulnerability, and Prevention

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Author(s): NSV Lakshmayya, Ashoutosh Panday, Rajasri Yadavalli, C Nagenrdanatha Reddy, Sanjeeb Kumar Mandal, Dinesh Chand Agrawal and Bishwambhar Mishra*

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Abstract

Microplastics (MPs) are emergent environmental contaminants that are designated as either primary or secondary dependent on their origins. Formulation, morphology, dimensions, and colour scheme, along with other features, are connected with their propensity to reach the food webs and their dangers. Whilst ecological adversities of MPs have drawn considerable interest, the hazards to individuals from dietary exposure have yet to be determined. The aim of this review is to gauge existing understanding concerning MPs in foodstuffs and to explore the problems and inadequacies for threat assessment. The prevalence of MPs in foodstuffs and sugary drinks has been detected all over the world, but most researchers judged the existing information to be not only inadequate but also of dubious value, owing to the notable lack of agreement on a regulated quantification methods and a consistent appellation. Most published papers have highlighted potable water and condiments such as sugars, salts, and nectar as significant food components of MPs for humans. The threat assessment reveals significant discrepancies in our understanding of MP toxicity for human consumption, which hinders the estimate of risk-based regulations regarding food safety. The lack of comparators for evaluating MPs food consumption prohibits dietary MPs risk description and risk mitigation. Researchers and Food Safety Administrators confer various obstacles along with possibilities linked to the appearance of MPs in foodstuffs. Further investigation on the MPs categorization and exposures is essential considering that any subsequent threat evaluation record can contain a comprehensive dietary viewpoint.

Keywords: Food contamination, Food Safety, Mircoplastics, ToxicityFood contamination, Toxicity

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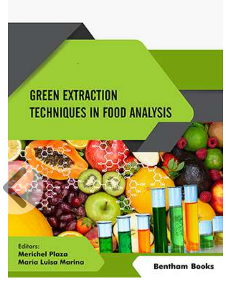

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Volume 183, March 2024, Pages 708-725

Valorisation of agro-industrial wastes: Circular bioeconomy and biorefinery process – A sustainable symphony

Mrunal S. Wagh [a] [1], Sowjanya S [a] [1], Pinku Chandra Nath [b] [1], Arnab Chakraborty [a], Rajshree Amrit [a], Bishwambhar Mishra [c], Awdhesh Kumar Mishra [d], Yugal Kishore Mohanta [e] [f]

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Abstract

In the quest for a sustainable future, the bio-economy and biorefineries have emerged as pivotal agents of transformation. This review paper offers an accessible and comprehensive exploration of the multifaceted bio-economy landscape.Environmental concerns, resource scarcity, and the demand for renewable and bio-based products are the key drivers shaping this sustainable paradigm.Agriculture and agro-industry play an indispensable role, acting as the primary suppliers of the essential feedstock for biorefineries. They not only fuel the bio-economy but also foster sustainable farming practices and rural development, forming a mutually beneficial relationship.Biorefineries, the workhorses of the bio-economy, optimize resource usage, minimize waste, and produce a diverse range of bio-based products. Innovative biorefinery techniques are at the forefront, revolutionizing efficiency and expanding the array of feedstock's, thereby creating higher value-added derivatives.These value-added products, spanning biofuels, bio-plastics, and more, drive the market towards a greener and circular economy. The bio-economy's commitment to sustainability is evident through waste reduction and the promotion of circular economy principles. Policy, regulation, and market developments shape the bio-economy by promoting bio-based industries while favouring eco-friendly alternatives, creating a competitive and healthy ecosystem.While the bio-economy shows promise, it faces challenges. Optimizing conversion efficiency, discovering new feedstocks, and solving biorefinery environmental issues need technological breakthroughs and research.In summary, the bio-economy and biorefineries orchestrate a sustainable symphony, driven by environmental consciousness, rooted in agriculture, refined by innovative techniques, and harmonized by the production of bio-based products. The stage is set for a greener, more sustainable future.

Bio-economy and biorefineries have become crucial drivers of transformation in the pursuit of a sustainable future. The review paper provides a thorough and easily understandable examination of the diverse bio-economy landscape. Environmental concerns, limited resources, and the need for biodegradable and renewable products are some of the main things that are shaping the sustainable paradigm. Agriculture and the agro-industry play a big role in this because they provide biorefineries with the feedstock they need. The bio-economy is not only fuelled by them, but they also contribute to sustainable farming practices and rural development, creating a mutually beneficial relationship. Biorefineries are the backbone of the bio-economy as they effectively utilize resources, minimize waste, and generate a wide array of bio-based products. At the forefront of innovation, biorefinery techniques are revolutionizing efficiency and expanding the range of feedstock's available. This, in turn, leads to the creation of higher-value derivatives and value-added products, such as biofuels and bioplastics, promoting a greener and more circular economy. The commitment of the bio-economy to sustainability is demonstrated through its efforts to reduce waste and promote the principles of a circular economy. Policy, regulation, and market developments impact the bio-economy by working together to support bio-based industries and encourage the use of eco-friendly alternatives. As a result, a competitive and healthy ecosystem is created. Although the bio-economy holds promise, it also encounters various challenges. Technological breakthroughs and research are necessary for optimizing conversion efficiency, discovering new feedstock's, and solving biorefinery environmental issues. In essence, a commitment to the environment guides how the bio-economy and biorefineries collaborate in a sustainable manner by utilizing innovative methods to refine and produce bio-based products. This harmonious process creates a symphony of sustainability, paving the way for the dream of a greener, more sustainable future.

Introduction

In the relentless pursuit of sustainable solutions to the global challenges of resource scarcity, environmental degradation, and climate change, the concept of the bio-economy has emerged as a beacon of promise (Gawel et al., 2019). In the tapestry of modern agriculture and agro-industry, encompassing the domains of agriculture, forestry, fisheries, and biotechnology, the bio-economy is an intricate thread that weaves together innovation, conservation, and economic growth (Kircher, 2021). It is a concept that not only defines a novel economic paradigm but also encapsulates the essence of human ingenuity in harmonizing with the natural world. The Duan, bio-economy, as a multifaceted construct, defies a single definition (Bauer et al., 2018). However, at its core, it represents a transformative shift from a traditional fossil fuel-based economy to one that hinges upon the sustainable utilization of biological resources and processes (Donner and de Vries, 2021). In the context of agriculture, it involves the judicious management of crops and livestock, harnessing genetic advancements, precision farming techniques, and eco-friendly practices to maximize productivity while minimizing environmental impact (Solis et al., 2020). Waste management is s significant problem in the agro based industrial sector which are accountable for air pollution, waste water contamination along with negative impact on the public health. The biological conversion of plant products has received more attention at present. Manufacturing of biofuels from the organic waste is a viable solution to the waste water treatment crisis (Naik et al., 2019). In forestry, it invokes the responsible stewardship of forests, recognizing them not merely as sources of timber but as reservoirs of biodiversity, carbon sequestration, and renewable energy. In fisheries, it emphasizes the sustainable harvesting of aquatic resources to safeguard both marine ecosystems and livelihoods. In biotechnology, it encompasses the relentless exploration of bio-prospecting, genetic engineering, and bioinformatics to create innovative products, fuels, and medicines derived from living organisms (Kircher, 2021). To appreciate the bio-economy's significance in our modern world, we must delve into its historical evolution, tracing its roots from the dawn of agriculture to the present-day confluence of science, industry, and environmentalism (Gawel et al., 2019). This journey reveals how societies have progressively recognized the finite nature of fossil fuels, the fragility of ecosystems, and the imperative of sustainable living. It underscores the bio-economy's evolution from a passive reliance on nature's bounty to an active commitment to shaping it for the betterment of humanity. Moreover, the urgency of transitioning from a fossil fuel-based economy to a bio-based one looms large on the horizon. Fossil fuels, once the lifeblood of industrial progress, now cast a shadow of peril over our planet (Solis et al., 2020). Climate change, air pollution, and resource depletion are the harbingers of a reckoning that compels us to shift our allegiance to bio-based alternatives. The bio-economy offers a lifeline-an opportunity to recalibrate our relationship with the environment, reduce greenhouse gas emissions, and foster economic growth through the sustainable utilization of biological resources (Gawel et al., 2019). However, issues arise due to the emission of hazardous byproducts from agricultural and industrial practices, such as pesticides, herbicides, and chemical fertilizers, into the environment. When these substances are discarded, they have the potential to leach into the soil and water, resulting in detrimental effects on ecosystems (Mosa et al., 2016). This can impact the well-being of plants, animals, and even human health if these contaminants penetrate the food chain. Further worry pertains to the presence of organic matter in these waste materials. Although organic matter might be advantageous in certain situations, an excessive accumulation of it from agro-industrial waste can give rise to complications. Eutrophication occurs when the decomposition of organic materials depletes the oxygen levels in water bodies. This process results in the reduction of oxygen levels, leading to the asphyxiation of aquatic organisms and causing disturbances in the equilibrium of ecosystems (Freitas et al., 2021). Furthermore, the inappropriate disposal of agro-industrial waste can lead to the deterioration of soil quality. These waste materials may contain substances that can alter the pH balance of the soil or introduce harmful ions. Over a period of time, this process can make the soil incapable of supporting plant growth, which in turn has a negative impact on agricultural output and the variety of living organisms in the area. Moreover, the substantial amount of agro-industrial waste produced poses significant difficulties, like the accumulation of toxic degradation products and the multiplication of pathogenic bacteria and fungi (Sadhukhan et al., 2016). Improper handling or disposal practices, such as open burning, can emit greenhouse gases into the environment, hence exacerbating global warming and climate change. Adopting sustainable waste management strategies is essential for mitigating these environmental challenges (Al et al., 2023).

This review paper systematically discusses the drivers of the bioeconomy, emphasizing the role of agriculture and agro-industry within this paradigm. It explores biorefinery concepts and principles, particularly focusing on innovative biorefinery techniques. The paper investigates the production of bio-based products and value-added derivatives and scrutinizes sustainability considerations, emphasizing waste reduction and circular economy practices. Additionally, it delves into policy, regulation, and market trends, while also addressing the technological challenges and research frontiers associated with the bio-economy. This comprehensive analysis endeavours to provide a scientific understanding of the bio-economy, its potential for reshaping industries, and its vision of sustainability and innovation.

Section snippets

Factors influencing the growth and development of the bio-economy

The bio-economy, a transformative economic paradigm, is shaped by a complex interplay of factors that drive its growth and development. This scientific elaboration provides a comprehensive examination of these drivers, encompassing environmental concerns, resource scarcity, and technological advancements. Additionally, it underscores the indispensable role of policy, regulation, and international agreements in moulding the landscape of the bio-economy, illustrated through relevant case studies (…

Environmental concerns

One of the primary catalysts behind the bio-economy is the mounting concern for the environment. As global climate change escalates, biodiversity dwindles, and pollution proliferates, the imperative for a sustainable alternative to the traditional fossil fuel-dependent economy becomes increasingly evident (Solis et al., 2020). The bio-economy offers a compelling solution by prioritizing practices that are in harmony with the natural world. The bio-economy strives to reduce greenhouse gas…

Challenges and opportunities in integrating bio-economy principles in agro-industry sectors

Integrating bio-economy principles into agro-industry sectors comes with its share of challenges (Gawel et al., 2019). Resource competition, for instance, involves the complex task of balancing the use of limited land and essential resources between food production and bio-based feedstock cultivation. Sustainable practices are required to prevent the overexploitation of resources and degradation of the environment(Solarte-Toro and Cardona Alzate, 2021). High initial investments for…

Biorefinery as a concept

The concept of biorefinery represents (Fig. 1) a pioneering approach in resource utilization, aligning closely with the principles of sustainability and environmental responsibility (Sillanpää and Ncibi, 2017). Biorefineries are dynamic facilities that transform various forms of biomass, such as agricultural residues, forestry by-products, and algae, into a spectrum of valuable products, including biofuels, bioplastics, bio-chemicals, and biomaterials (Solarte-Toro and Cardona Alzate, 2021).…

Biorefinery types

Sustainable resource utilization is a pivotal theme in the modern world, primarily driven by concerns of resource scarcity and environmental degradation. Biorefineries are positioned at the forefront of addressing these challenges through their intrinsic relationship with sustainable resource utilization (Table 2).…

Innovative biorefinery techniques

The quest for sustainable resource utilization and the transition towards a circular bioeconomy has prompted the development of innovative biorefinery techniques (Maina et al., 2017). These pioneering approaches capitalize on the inherent complexity of biomass, unlocking its full potential through enzymatic and microbial conversion processes, advanced separation and purification techniques, and the transformative power of biotechnology (Kircher, 2021). Here, we explore the dynamic landscape of…

Products from agro-industrial wastes

Sugarcane bagasse, wheat bran, rice bran, green gram, wheat straw, rice husk, soy hull, sago hampas, debris from grapevine trimmings, sawdust, corncobs, coir pith from coconut, banana waste, aspen pulp, palm oil waste, sugar beet pulp, apple, peanut meal, rapeseed cake, coconut oil cake, mustard oil cake, cassava flour, wheat flour, steamed rice, steam treated willow, starch, etc are some examples of agro-industrial wastes. On the other hand, wheat bran is the most frequently utilized in…

Bio-based product development and commercialisation

In the current times countries are working on the employing food wastes as fuels. Countries like Denmark, Finland and Sweden are utilizing agricultural and food wastes like bakery waste, fruit and vegetable wastes, household biowaste, animal waste, agricultural waste to investigate into new technologies and convert them to biofuels (Food Waste to Biofuels – Nordic Energy Research, 2019).

Several studies have been carried out for the recovery of enzymes from food waste and by products according…

Assessment of environmental and economic benefits

The common practice in most of the developing countries is the burning of the crop residues especially in Asia. A study conducted states that ethanol from corn degrade water quality rapidly. However cellulosic ethanol has a less impact than on corn whereas it relies on fertilizers for its growth (Dey et al., 2021). Regarding the cost benefit analysis using nanoparticle based fertilizers there aren't many research in the literature. Although current nano formulations have an abundance of…

Sustainability considerations of biorefinery

The bio-revolution represents a profound paradigm shift in the fields of industry and technology, where the conventional sources of fuels, plastics, and chemicals are supplanted by plant-based alternatives. This visionary transition signifies a transformative relationship with nature, driven by the sustainable utilization of agricultural feedstock's (Konwar et al., 2018). At its core, the bio-revolution entails the conversion of these feedstock's into a diverse range of biofuels (Tsegaye et…

Waste reduction and circular economy

Imagine a biorefinery equipped with cutting-edge enzymatic technologies (Conteratto et al., 2021). Scientifically designed enzymes break down agricultural residues, such as corn stover and wheat straw, into sugars and biofuels (Tsegaye et al., 2021). These processes, grounded in scientific understanding, efficiently convert waste into valuable resources, supporting a circular economy (Kircher, 2021, Maina et al., 2017). The scientific foundation of this approach not only minimizes waste but…

Global transition towards a sustainable bioeconomy

The global transition towards a sustainable bioeconomy (Donner and de Vries, 2021) has gained immense momentum in recent years, driven by the pressing need to address climate change, resource scarcity, and environmental degradation (Gawel et al., 2019). This paradigm shift represents a holistic approach to harnessing the potential of biological resources to create value-added products while simultaneously mitigating the negative impacts of traditional industries. At both international and…

Analysis of market trends and consumer demand for bio-based products

The global landscape for bio-based products has witnessed significant shifts in recent years, driven by evolving market trends and changing consumer demands (Ronzon et al., 2020). This analysis delves into these dynamics, highlighting the challenges and opportunities inherent in scaling up biorefinery processes for commercial production (Conteratto et al., 2021)....

Exploring uncharted territories: research frontiers of bioeconomy

In the realm of biorefinery processes (Conteratto et al., 2021), there exists a pressing need to overcome substantial technological challenges while simultaneously exploring exciting research frontiers to realize the full potential of sustainable resource utilization (Donner and de Vries, 2021). These challenges are multifaceted, starting with the diverse array of feedstocks, each bearing unique characteristics. Tackling this issue requires the development of effective pretreatment methods,...

Conclusions and future perspectives

The bioeconomy is a dynamic and progressive domain that integrates scientific advancements, policy frameworks, and innovative practices with the aim of fostering a sustainable trajectory for the future. The bioeconomy is propelled by significant factors, including heightened environmental consciousness and economic prospects. Within this context, agriculture and agro-industry assume a crucial function by supplying raw materials and transforming them into valuable commodities. Biorefineries,...

CRediT authorship contribution statement

Conceptualization, B.M., Y.K.M. and A.K.M.; Data curation: M.S.W, S.S., and P. C.N,; writing-original draft preparation, M.S.W, S.S., and P. C.N; writing-review and editing, A.C., R.A.B.M., A.K.M. and Y.K.M.; visualization, Y.K.M. and A.K.M; image preparation, S.S., resources and software, B.M. and Y.K.M. All authors have read and agreed to the published version of the manuscript....

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper....

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Renew. Sustain. Energy Rev. (2019)

J.R. Banu *et al.*
Impervious and influence in the liquid fuel production from municipal plastic waste through thermo-chemical biomass conversion technologies - a review
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Organic recycling of post-consumer / industrial bio-based plastics through industrial aerobic composting and anaerobic digestion - techno-economic sustainability criteria and indicators
Polym. Degrad. Stab. (2021)

F. Cherubini
The biorefinery concept: using biomass instead of oil for producing energy and chemicals
Energy Convers. Manag (2010)

K.W. Chew *et al.*
Microalgae biorefinery: high value products perspectives
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A review of biochemical and thermochemical energy conversion routes of wastewater grown algal biomass
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Review

Recent advances in cellulose-based sustainable materials for wastewater treatment: An overview

Ramesh Sharma [a][1], Pinku Chandra Nath [a][b][1], Yugal Kishore Mohanta [b][c][1], Biswanath Bhunia [a], Bishwambhar Mishra [d], Minaxi Sharma [b], Shweta Suri [e], Maharshi Bhaswant [f], Prakash Kumar Nayak [g], Kandi Sridhar [h]

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Highlights

- Cellulose hydrophobicity promotes the interaction with water molecules for wastewater treatment
- Appropriate cellulose processing methods are crucial aspects of wastewater treatment
- Cellulose derivatives are effective in removing of pathogens & pollutants

Abstract

Water pollution presents a significant challenge, impacting ecosystems and human health. The necessity for solutions to address water pollution arises from the critical need to preserve and protect the quality of water resources. Effective solutions are crucial to safeguarding ecosystems, human health, and ensuring sustainable access to clean water for current and future generations. Generally, cellulose and its derivatives are considered potential substrates for wastewater treatment. The various cellulose processing methods including acid, alkali, organic & inorganic components treatment, chemical treatment and spinning methods are highlighted. Additionally, we reviewed effective use of the cellulose derivatives (CD), including cellulose nanocrystals (CNCs), cellulose nano-fibrils (CNFs), CNPs, and bacterial nano-cellulose (BNC) on waste water (WW) treatment. The various cellulose processing methods, including spinning, mechanical, chemical, and biological approaches are also highlighted. Additionally, cellulose-based materials, including adsorbents, membranes and hydrogels are critically discussed. The review also highlighted the mechanism of adsorption, kinetics, thermodynamics, and sorption isotherm studies of adsorbents. The review concluded that the cellulose-derived materials are effective substrates for removing heavy metals, dyes, pathogenic microorganisms, and other pollutants from WW. Similarly, cellulose based materials are used for flocculants and water filtration membranes. Cellulose composites are widely used in the separation of oil and water emulsions as well as in removing dyes from wastewater. Cellulose's natural hydrophilicity makes it easier for it to interact with water molecules, making it appropriate for use in water treatment processes. Furthermore, the materials derived from cellulose have wider application in WW treatment due to their inexhaustible sources, low energy consumption, cost-effectiveness, sustainability, and renewable nature.

Graphical abstract

Introduction

Water is essential for human beings and is necessary for all other forms of life to survive. However, during the past 20years, as a result of the rise of the economy, quick industrial development, urbanization, and agricultural development have led to water pollutions which is considered a serious global issue [1]. Water pollution occurs in many different ways, but one particularly terrible form is oil-water pollution, which occurs when wastewater containing oil is dumped into natural water bodies from various sources, including the food and petrochemical industries, daily living, and sewage treatment plants. Due to heavy metal ions' inability to degrade, tendency to cause cancer, and high toxicity, the pollution of water with heavy metal ions has been also a burning issue in recent years [2]. Another unpleasant form of pollution that comes from various industrial sectors, including the textiles, plastics, paint, cosmetics, and paper manufacturing industries is mainly caused by dyes [3]. By the end of 2010, >700,000 tons of dyes had been manufactured, and there are currently about 100,000 commercial dyes known to exist [4]. Sewage treatment poses a significant environmental and economic challenge today.

Although some materials with thorough study can be utilized to purify water quickly and effectively, not all materials are affordable and environmentally friendly. They have not been successfully used in the treatment of huge amounts of wastewater. Therefore, there is a pressing need to create some eco-friendly and effective water treatment materials. These materials must also be simple to use, highly active or efficient, and environmentally benign. Although their uses need more research, biodegradable biomass materials can be viewed in this light as viable candidates for use in practical water treatment systems. A rapidly expanding field of study called biodegradable biomass as a raw material offers wider applications for wastewater treatment. The biomass materials obtained from plants include forest derive waste, agricultural wastes, aquatic weeds, etc. [5]. It offers a potential option for practical water treatment due to its repeatability and degradability. Pollutants that harm both the environment and humans include textile dyes, heavy metal ions, and oil stains which are present in wastewater discharges [6]. For instance, heavy metal ions have been linked to a number of illnesses, including cancer. Dye-containing wastewater can make water bodies less clear and deplete the O_2 in the water, which stunts the survival of aquatic flora and microbes. Because of their diversity and simplicity of modification, optimal biomass concentrations are therefore particularly suitable for the elimination of these toxic pollutants. The biomass material can be altered which is a contribution from numerous researchers who also contribute to the creation of cutting-edge water treatment techniques that can be customized to meet particular requirements for the efficient removal of toxins from the wastewater. In the current situation, there is a lot of interest in finding a sustainable approach for the remediation of water contaminants [7].

A common macromolecule found in biomass is cellulose, a polymer of linear polysaccharide made up of β-1, 4-linked glucose units. Organic and inorganic pollutants are removed from wastewater using naturally obtained and modified groups of cellulose substances. However, in order to compete with competing materials for the WW treatment, the characteristics of this biopolymer must be improved. The characteristics of cellulose can frequently be modified to fit specific demands by utilizing appropriate chemical alteration in conjunction with appropriate mechanical treatments.

Adsorption, on the other hand, is a quick, simple, and cost-effective approach for treatment of wastewater with lower concentration of pollutants [8]. Activated carbon is a popular adsorbent at the moment, but its production costs are high, with higher regeneration conditions under harsh conditions [8]. Natural biopolymer are slowly gaining popularity due to their low cost, repeatability, and high efficiency of adsorption [9]. Among the biopolymers, cellulose has the higher isolation yield (1011–1012 t/y), being nontoxic, and having a high amount of hydroxyl groups, which are amenable for extended modification [8]. Examples include heavy metal removal employing cellulose-fabricated adsorbents and membranes for the purification of water [10]. A Physical and chemical approach, including chemical precipitation, membrane microfiltration, evaporation, adsorption, flocculation, and chemical oxidation, can be used to remove pollutants from effluent from the oil industry. All of the aforementioned techniques are expensive with high-energy consumption. Thus, using cellulose-based WW treatment methods are regarded as an alternative energy efficient and low-cost method. Therefore, this review focused on the effective utilization of cellulose derivatives (CD), including cellulose nanocrystals (CNCs), cellulose nano-fibrils (CNFs), cellulose nanoparticles (CNPs), and bacterial nano-cellulose (BNC) for the wastewater treatment. Moreover, we examined diverse cellulose processing methodologies to derive the CD for WW treatment. Additionally, the review highlighted the incorporation of these derivatives to other polymers/nanoparticles, with improving their performance on WW treatment is discussed.

Section snippets

Synthesis and characterization of cellulose and its derivatives for wastewater treatment

Anselme Payen, a French scientist, originally extracted cellulose from plants in 1839; since then, it has been the subject of several variations [10]. The global production of cellulose is around 1000 tons per year and is derived from plants, bacteria, wood, algae, and tunicates [10]. People then began extracting cellulose from bacteria, algae, and tunicates, and systematic research on extraction techniques increased [11]. A long-chain linear polysaccharide called cellulose is composed of…

Modification of cellulose

These cellulosic materials are transformed into CNCs, CNFs, CNPs, and BNC, which is naturally obtained for wastewater treatment, through the application of chemical or mechanical pre-treatments. Cellulose is chemically modified with the process of esterification, grafting modification, etherification, oxidation and cross-linking to obtain the CD. Similarly, acid, alkali and organic/inorganic treatment are performed to obtain the CD. Nano-cellulose is typically divided into four groups based on…

Cellulose based nano-composites for wastewater treatment

Applications of nanoparticles and nanocomposites (NC) for wastewater treatment are reported in some of the current evaluations [[123], [124], [125], [126]] or of cellulose-derived materials in the treatment of WW [127]. Researchers are concentrating on cellulose or inorganic nanoparticles composite materials due to their special qualities and functions [128]. Because cellulose has more hydroxyl groups with a hydrophilic nature on the surface, it has several fascinating qualities, including…

Cellulose-based adsorbents

A rapidly expanding field of study that offers a variety of enticing choices for wastewater treatment is biodegradable biomass as a raw material. For practical water treatment, its repeatability and degradability offer a viable option. Textile dyes, heavy metal ions, oil stains, and personal care items are just a few of the pollutants found in wastewater discharges that are hazardous to both environmental and human health [6]. Cellulose is naturally hydrophilic and is modified with hydrophobic…

Removing heavy metals, dye, and other pollutants

Due to heavy metal ions' non-degradability, carcinogenicity, and high toxicity, heavy metal ion contamination of water has also grown to be a severe issue in recent years [192,193]. Another unpleasant form of pollution that comes from various industrial sectors, including the cosmetics, textiles, paint, plastics, and paper industries, is pollution caused by dyes [194]. By the end of 2010, >700,000 tons of dyes had been manufactured, and there are currently about 100,000 commercial dyes known to …

Conclusions and future trends

This paper provides a brief overview of several CD, including CA, cellulose triacetate, CMC with a focus on hydrogel's, cellulose/nanoparticles composites, CNCs, CNFs, and CNPs. Additionally, this paper highlights several cellulose processing techniques, such as spinning, mechanical, biological, and chemical approaches. The spinning methods included electro-spinning, dry spinning, wet spinning, hybrid dry jet-wet spinning and solution blow spinning. The cellulose-based materials including…

CRediT authorship contribution statement

Ramesh Sharma: Conceptualization, Data curation, Formal analysis, Methodology, Software, Writing – original draft. **Pinku Chandra Nath:** Conceptualization, Data curation, Formal analysis, Methodology, Software, Writing – original draft. **Yugal Kishore Mohanta:** Conceptualization, Data curation, Formal analysis, Methodology, Software, Writing – original draft. **Biswanath Bhunia:** Formal analysis, Software, Visualization, Writing – review & editing. **Bishwambhar Mishra:** Formal analysis, Software,…

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.…

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Recommended articles

References (264)

A. Scheuhammer *et al.*
Recent progress on our understanding of the biological effects of mercury in fish and wildlife in the Canadian Arctic
Sci. Total Environ. (2015)

N.M. Mahmoodi *et al.*
Activated carbon/metal-organic framework nanocomposite: preparation and photocatalytic dye degradation mathematical modeling from wastewater by least squares support vector machine
J. Environ. Manag. (2019)

A. Demirbaş
Biomass resource facilities and biomass conversion processing for fuels and chemicals
Energy Convers. Manag. (2001)

P. Rudnicki *et al.*
Evaluation of heavy metal ions removal from acidic waste water streams
Chem. Eng. J. (2014)

K.G. Satyanarayana *et al.*
Biodegradable composites based on lignocellulosic fibers—an overview
Prog. Polym. Sci. (2009)

A. Bhatnagar *et al.*
Agricultural waste peels as versatile biomass for water purification–a review
Chem. Eng. J. (2015)

B. Peng *et al.*
Cellulose-based materials in wastewater treatment of petroleum industry
Green Energy Environ. (2020)

S. Olivera *et al.*
Potential applications of cellulose and chitosan nanoparticles/composites in wastewater treatment: a review
Carbohydr. Polym. (2016)

S.F. Kabir *et al.*
Occurrence, distribution, and structure of natural polysaccharides

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[1] Authors contributed equally and treated as joint first authors.

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Essential oils-based nano-emulsion system for food safety and preservation: Current status and future prospects

N.S.V. Lakshmayya [a] [1], Awdhesh Kumar Mishra [b] [1], Yugal Kishore Mohanta [c] [d] [1], Jibanjyoti Panda [c], Bindu Naik [e], Bishwambhar Mishra [a], Rajender S. Varma [f]

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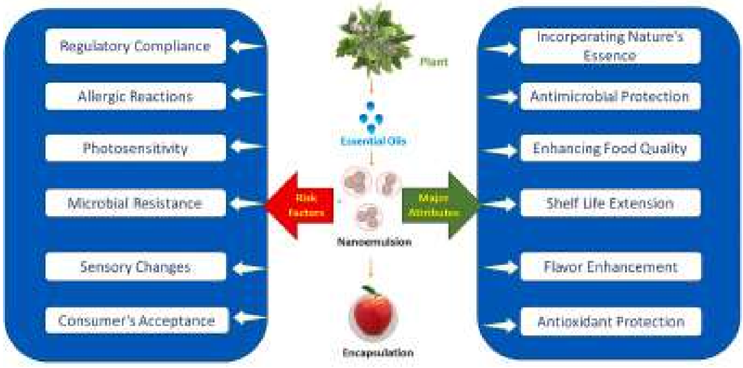
Highlights

- Studying edible coatings with essential oils to enhance food quality.
- Enhancing the food nutrition, shelf life, and quality deploying nanoemulsion coatings.
- Essential oil nanoemulsions for improved food safety and quality assessment.
- Shifting focus from synthetic to natural agents in food for safety and quality.

Abstract

The growing public desire for healthy eating has prompted researchers to develop newer methods for incorporating less processed foods without using preservatives in daily diet. Edible coatings based on emulsions contrived from constituents of essential oils (EOs) are thought to be a good way of improving the quality of food in a variety of ways. Nanoemulsion compositions with active ingredients can be utilized to create biodegradable coatings and packaging films that improve functional qualities of the food, its nutritional value, and shelf life. Various studies have scrutinized the deployment of essential oil-based nanoemulsion formulations for efficient food processing and enhancing the distribution of active substances such as colorants, flavoring agents, nutraceuticals, preservatives, and antibacterial agents in foods. Safety considerations such as ingredient security, allergen concerns, proper storage conditions, and compatibility with the food matrix must be carefully considered while utilizing nanoemulsions for food preservation. Herein, current breakthroughs in the use of nano-emulsion-based edible coatings are deliberated as carriers of functional elements such as antibacterial agents, antioxidants, and texture boosters for the retention of the product safety of fruit and vegetables. Besides discussion on the synthesis and evaluation of essential oil-based nanoemulsions, the strategy emphasizes using bioactive components as a replacement for synthetic agents in food preservation.

Graphical abstract



Introduction

In recent years, the usage of essential oils in nano-emulsion systems has emerged as a promising frontier in food safety and preservation. Essential oils have garnered recognition for their natural antimicrobial properties and capability to combat foodborne pathogens as the global food industry continuously seeks innovative strategies to increase the shelf life of perishable products while ensuring consumer health (Maurya et al., 2021b; da Silva et al., 2022; Omar et al., 2022). This innovative strategy of combining essential oils with nano-emulsions has the potential to revolutionize food preservation techniques. Currently, there's been tremendous progress achieved in the marketplace for healthier dietary alternatives, like enhanced consumption of freshly cut fruits and vegetables. Users evaluate and gravitate to the next most agreeable elements among all these items, namely originality, nutritious qualities, flavoring, and innovative tastes that maintain the aesthetic over extended time periods (Bodirsky et al., 2020; Jadhav et al., 2021).

Essential oils, which are produced from plant sources, exhibit significant antibacterial and antioxidant characteristics. However, the utilization of these compounds in the field of food preservation has been constrained as a result of their inadequate solubility in aqueous solutions (He et al., 2020; Álvarez-Martínez et al., 2021). The difficulty is effectively addressed by nano-emulsion technology, which involves the reduction of oil droplets to nanoscale dimensions. This process enhances the solubility of the oil droplets and facilitates their dispersion in aqueous solutions (Suhag et al., 2020; Yaashikaa et al., 2023). Essential oils possess bioactive constituents that have the capacity to impede the proliferation of harmful microorganisms, encompassing bacteria, fungus, and viruses, within food items (Tripathi et al., 2021). Nano-emulsions have been found to augment the antibacterial effectiveness of essential oils by the amplification of their surface area and subsequent interaction with foodborne microorganisms. The aforementioned findings carry substantial ramifications in the realm of food safety, as well as in the mitigation of foodborne infections (Mushtaq et al., 2023; Zhang et al., 2023). These coatings and films perform specific functions such as moisture retention, oxygen absorption, and element leakage mitigation besides serving as aids in the preservation of food's nutritional value and its external characteristics (Blancas-Benitez et al., 2022). The nature of coatings can be selected based on the ingredients in the food and their intended use, as edible coatings offer certain unique uses and significant benefits in preventing deterioration in quality (Nunes et al., 2023).

In terms of active ingredients, essential oils along with additional extracts from plants have been considered in the fabrication of edible coatings due to their proven ability to prevent microbial growth, which harms the products and shortens their duration of storage. Such coatings can also capture free radicals, slow down degradation, and arrest oxidative damage occurrences by utilizing the antioxidant properties of herbal extracts and essential oils (Mushtaq et al., 2023). Today, the development of transporters that carry certain active compounds, like polyphenols and carotenoids, with antibacterial and antioxidant capabilities, offer promising option for nanotechnology. With no negative impacts on human health or the natural world, the preservation of food and packing is now achievable by virtue of the development of nanotechnology in the culinary and farming sectors (De Bruno et al., 2023). It is envisioned that in not-too-distant future, engineered containerization will be substituted with edible coatings as they are considered a superior alternative in combating quality degradation; they meet all the prerequisites such as decay safeguarding, high-quality upkeep, conserving, longevity implications, eco-friendliness, and economical practicality (Suput et al., 2015). Once the tender fruit gets sliced, it becomes highly susceptible to decomposition as the slicing affects the inner cells of the fruit's flesh resulting in pathological exertion (González-Aguilar et al., 2009).

The growing inclination of consumers towards natural and clean-label components has led to a corresponding demand for essential oil-based nano-emulsions, which are in line with this prevailing trend. They provide a natural substitute for synthetic preservatives, which are frequently regarded as less preferable by consumers who prioritize their health. This has the potential to facilitate the advancement of food items that are both safer and more commercially viable (Zamuz et al., 2021). Nano-emulsions have been demonstrated to be highly successful in inhibiting the oxidation process of lipids and proteins in food, thereby leading to a significant extension of the products' shelf-life. This is especially advantageous for perishable commodities such as oils, dairy goods, and meat, as they are prone to spoiling and rancidity. Despite the potential that essential oil-based nano-emulsions hold, there exist certain limitations pertaining to their formulation and stability (Raghav et al., 2016; Bodirsky et al., 2020; Jadhav et al., 2021). The stability of these systems can be influenced by various factors such as pH, temperature, and the selection of emulsifiers. In order to maintain consistent performance in practical settings, it is imperative for researchers and food technologists to confront and tackle these challenges. As the advancement of this technology progresses, regulatory agencies are applying greater scrutiny to nano-emulsions derived from essential oils (Ravera et al., 2021). The legislation and labeling requirements pertaining to food safety are undergoing continuous development. It is imperative for the food businesses to adhere to these standards, while simultaneously providing evidence of the safety and effectiveness of their goods. The potential of essential oil-based nano-emulsions in the realm of food safety and preservation shows considerable promise. Current research endeavors are aimed to optimize formulations, improve stability, and investigate innovative sources of essential oils. Furthermore, the establishment of partnerships among scientists, food producers, and regulatory authorities will play a pivotal role in the progression of this discipline (Campolo et al., 2020; Taban et al., 2020; Zamuz et al., 2021; Mushtaq et al., 2023).

This review's main objective is to acknowledge, assess, and assign the remarkable impact of botanical extracts (Essential Oil; EO) on the shelf life of food in multiple variations, like immediate absorption in films that are edible or through the use of nanoemulsions. Throughout this paper, the essential oils' most recent advancements, advantages, and function as an edible coating for food products have been comprehensively discussed with emphasis on significance, purposes, formulation techniques, impacts on longevity, various functional attributes, and possible futures of edible coatings. Fig. 1 highlightes the aspects of preservation and extension of food shelf-life by essential oil-based nanoemulsions.

Section snippets

Formulation and characterization of nanoemulsions

Nanoemulsions comprise colloidal dispersions of droplets of oil containing tiny fragments (usually 10–200nm in dimension) in an aqueous solution. Nanoemulsions, in contrast to clear, opaque, and thermally stable microemulsions, are merely stable under kinetic conditions; nanoemulsification concept is centred on emerging nanotechnologies that have the potential to transform the food sector. The prolonged mechanical durability of a nanoemulsion (with no evident flotation or agglomeration) is…

Essential oils with antimicrobial properties

The potency of EOs and their vital constituents over a variety of yeast, bacteria, and molds has been frequently mentioned and is determined to be influenced by EO substance profile and architecture, as well as the sort and form of intended microbes (Mahdi et al., 2021a; Kalagatur et al., 2018). The antimicrobial efficacy of EOs does not rely on any particular process, and the effect varies depending on the constituents of the essential oil. Membrane disruption is the most prevalent route of…

Advantages of nanoemulsions in food system

There has been quite a lot of speculation about using nanotechnology-based innovative techniques to enhance the benchmarks for foodstuffs, usage of nanoemulsions in the food-related collateral sector being one of the key prospects. Significantly, microbial development and deterioration are two variables that affect the freshness and preservation of foodstuffs, vegetables, and fruits. According to the application, nanoemulsion-based methods of administration may additionally encompass pigments,…

Applications of nanoemulsions in food industries

Nanoemulsions are widely recognized as exceptionally popular tactic deployed in food enterprises. Food-grade nanoemulsion technologies have been discovered to enhance the appearance, durability, sensory, and nutritional attributes of a variety of food-related goods. The deployment of nanoemulsions in food preparation improves the thermodynamic rigidity, visual candor, and homogeneous dispersibility. The prospective utilization of nanoemulsions in the flavoring, coloring, nutraceutical, and food …

Disadvantages and sustainability aspects of nanoemulsions

The drawbacks associated with the deployment of nanoemulsions include the expensive nature of manufacturing processes and the difficulty in locating an edible surfactant, as well as the reality that they are almost thermodynamically unsettling owing to a variety of variables. They comprise environmental and inherent variables, which entails amalgamation, creaming, maturation, flocculation, etc., instantaneous biologically active ingredient expulsion, and preservation uncertainty (Peng et al.,…

Future perspective and conclusion

Essential oils offer antimicrobial effect aimed at microorganisms found in foodstuffs. Nevertheless, their extreme hydrophobicity and powerful influence on the taste and texture of food items, the risk of allergic reactions, and to a large extent the development of microbial resistance, render their inclusion within culinary systems to be a significant challenge. Consequently, encapsulating these oils might provide potential remedies for the aforementioned problems. In broad terms, only a few…

CRediT authorship contribution statement

Conceptualization, L.N.S.V., B.M., Y.K.M. and A.K.M.; original draft preparation, B.M., L.N.S.V. and Y.K.M.; writing—review and editing, R.S.V.; visualization, B.M., B.N., and R.S.V.; supervision, R.S.V. All authors have read and agreed to the published version of the manuscript.…

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.…

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Recommended articles

References (181)

A. Abdullahi *et al.*
Phytochemical profiling and antimicrobial activity of ginger (Zingiber officinale) essential oils against important phytopathogens
Arab. J. Chem. (2020)

J.A. Aguirre-Joya *et al.*
Basic and applied concepts of edible packaging for foods

O. Alliod *et al.*

Comparison of three processes for parenteral nanoemulsion production: ultrasounds, microfluidizer, and premix membrane emulsification

J. Pharmaceut. Sci. (2019)

H. Almasi *et al.*

Development and characterization of pectin films activated by nanoemulsion and Pickering emulsion stabilized marjoram (Origanum majorana L.) essential oil

Food Hydrocolloids (2020)

F.J. Álvarez-Martínez *et al.*

Antibacterial plant compounds, extracts and essential oils: an updated review on their effects and putative mechanisms of action

Phytomedicine (2021)

B. Arabpoor *et al.*

Multifunctional coating composed of Eryngium campestre L. essential oil encapsulated in nano-chitosan to prolong the shelf-life of fresh cherry fruits

Food Hydrocolloids (2021)

N. Baig *et al.*

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Mater Adv (2021)

Z. Ban *et al.*

Ginger essential oil-based microencapsulation as an efficient delivery system for the improvement of Jujube (Ziziphus jujuba Mill.) fruit quality

Food Chem. (2020)

M.M. Bazargani *et al.*

Antibiofilm activity of essential oils and plant extracts against Staphylococcus aureus and Escherichia coli biofilms

Food Control (2016)

F.J. Blancas-Benitez *et al.*

Impact of edible coatings on quality of fruits: a review

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[1] Authors are contributed equally and treated as joint first authors.

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Effect of semi batch and fed batch addition of glucose on alkaline protease production: a multi-objective optimisation approach

by Anitha Mogilicharla; V. Swapna; Rajasri Yadavalli

International Journal of Engineering Systems Modelling and Simulation (IJESMS), Vol. 14, No. 4, 2023

Abstract: Alkaline protease is one of the important enzymes in many industries. In this effort, semi batch addition and fed batch addition of glucose have been considered for maximisation of protease concentration in minimum fermentation time. The kinetic model of the process is validated with the experimental batch and fed batch addition of glucose from the open literature. A theoretical study has been conducted with such a validated model to check the effect of protease concentration on the semi batch addition of glucose. Based on this, multi-objective optimisation studies have been done for the simultaneous minimisation of fermentation time and maximisation of protease concentration with the relevant constraints. The elitist non-dominated sorting genetic algorithm (NSGA II) has been utilised for this purpose. The additions of glucose in semi batch mode show the potential increasing of protease concentration in at a less fermentation time as compared to the batch experimental data.

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Polymer Testing

Volume 128, November 2023, 108223

Review of microplastic degradation: Understanding metagenomic approaches for microplastic degrading organisms

C. Nagendranatha Reddy [a], Parashuram Kallem [b c], K.V.S.S.N. Mounika [a], Abdul Muqeet [a], J Caleb Joel Raj [a], C.V.S. Aishwarya [a], Rakesh Kumar Gupta [d], Veerababu Polisetti [e], Bishwambhar Mishra [a], Rajasri Yadavalli [a], Sanjeeb Kumar Mandal [a], Mikael S. Hedenqvist [e], Fawzi Banat [b]

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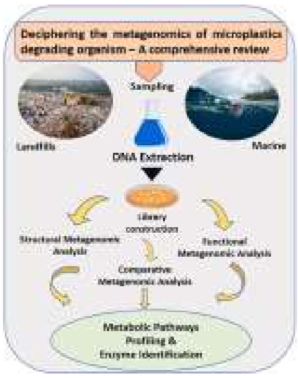
Highlights

- Metagenomics helps understand microbial communities in plastic biodegradation.
- Research on microplastic biodegradation could lead to new pollution-fighting technology.
- Comparative studies on enzymes suited for microplastic degradation are important for large volumes of micropollutants.
- Interdisciplinary approaches like metagenomics said in understanding factors for microplastic biodegradation.
- More research will provide insights for effective strategies to reduce plastic pollution.

Abstract

Environmental problems caused by plastic pollution are among the most pressing issues of our time. In recent years, metagenomics has become a powerful tool for understanding the microbial communities responsible for plastic biodegradation. In this review, recent developments and trends in metagenomics are discussed, and a comprehensive overview of the metagenomic methodology, analysis, and comparison of plastic-degrading bacteria is provided. In addition, the environmental consequences of plastic degradation are discussed, such as the impact on soil, water, and air quality, as well as the potential health risks posed by ingesting and inhaling microplastics. Possible solutions to the plastic degradation problem, such as using biodegradable materials and implementing recycling programs, are also explained. This review highlights the potential impact of metagenomics on the development of sustainable solutions to plastic pollution.

Graphical abstract



Previous

Next

Keywords

Microplastics; Toxicity; Metagenomic analysis; Microorganisms; Enzymatic degradation; Polyethylene terephthalate (PET) degradation mechanism; Macroplastics; Polyesters

1. Introduction

Plastic waste, especially microplastics, has become one of the biggest contributors to environmental and health hazards in the last decade. They are found dispersed throughout the planet, contaminating all natural environments, including marine, terrestrial, and water bodies, from the deepest part of the sea, the Mariana trench, to the highest Himalayan mountains [[1], [109]]. These contaminations have led to significant microplastic accumulation and distribution of plastic to a higher level in the food chain, eventually making its way into the human body [2]. The United Nations has classified plastic pollution as one of the ten emerging environmental problems [3]. In 2015, more than six thousand metric tons of plastics were manufactured globally, of which 79% were accumulated in our environment, most notably in landfills. The growing worry surrounding the rise of plastic waste in ecosystems and its effects on organisms has prompted the development of biodegradable alternatives. Nonetheless, the extended degradation periods of these biodegradable plastics in natural environments indicate that they may still pose risks of ecological consequences. The precise impact of microplastics on organisms remains uncertain, particularly due to the utilization of particle concentrations in experimental exposures that greatly exceed those typically observed in natural ecosystems [116]. When this increasing rate of plastic production is paired with the current waste management system, by 2050, there will be about twice the amount of plastic waste in our environment [4]. To address this problem, an emphasis has been placed on using microorganisms and microbial enzymes to manage plastic waste sustainably. However, approximately 98% of microorganisms in microbial communities cannot be cultured under laboratory conditions, making the selection and characterization of countless plastic-degrading enzymes of microbial species arduous. With tremendous technological development and the collaboration of great minds in the field of bioinformatics and genome sequencing technologies, a new field has emerged, an amalgamation of the best of both worlds, metagenomics.

Metagenomics offers the solution to this microplastic crisis through next-generation sequencing (NGS), high throughput sequencing methods, shotgun metagenomics, and an array of modern omics, such as genomics, proteomics, and bioinformatics tools and software [110]. Analyzing metabolic pathways and microbial, phylogenetic, and functional diversity of uncultivable microbes using metagenomics provides crucial insights. The application of molecular biology and metagenomics has expanded our understanding and knowledge of the microbiome and its biological systems in polluted environments, allowing us to study microbial communities from highly contaminated sites [5,6]. This review article discusses the latest discoveries and trends in metagenomics, a comprehensive study on metagenomic methodology, analysis, and comparison of plastic-degrading microbes and their enzymes.

2. Elucidation of microplastics and their characteristics

2.1. Sources of microplastics

Plastics come in two varieties: large and small plastic waste less than 5 mm in size, known as microplastics. According to recent research, 8.3 billion tons of plastic have been generated worldwide since its created. An estimated 9% of this has been recycled, but the annual amount of plastic waste entering the ocean is between 4.8 and 12.7 million megatons. Considering these current estimations and efforts to quantify the issue, it is crucial to comprehend the connection between macro and microplastics [7]. Based on the annual garbage production per person, the proportion of plastic waste in that pollution and the proportion of poorly managed plastic waste that could end up in the ocean as plastic pollution indicate that there are more microplastics and larger plastics in the sea than the frequently stated average of 8 million metric tonnes [8]. The sources of microplastics considered here come from the roughly 300 million tons of plastics consumed worldwide. The primary uses are for plastic goods that start as pellets (85%), synthetic fabrics (11%), and synthetic rubber in tires (2%). The only losses that can be considered purposeful losses are losses from personal care products. Primary and secondary microplastics are the two types of microplastics that pollute the world's oceans. Primary microplastics are defined as plastics released directly into the environment as minute particles (Fig. 1). The first category of microplastics is purposefully added to water bodies. Whereas some secondary microplastics are the result of accidents during the synthesis, transportation, use, maintenance, or recycling of objects containing plastic through abrasion, weathering, or unintentional spills [[9], [10], [11]]. These fibers obtained through abrasion and fiber shedding, washing, etc., end up in the oceans. Significant numbers of these textile fibers have been discovered in both open-water and marine sediments through numerous in situ sampling studies [12]. The microplastics resulting from tires degradation are then dispersed by the wind or removed by rain into water bodies [108]. Marine coatings viz., Solid coatings, anticorrosive paint, and antifouling paint made from various plastics release microplastics during construction, maintenance, repair, and use (wear and tear) [13].

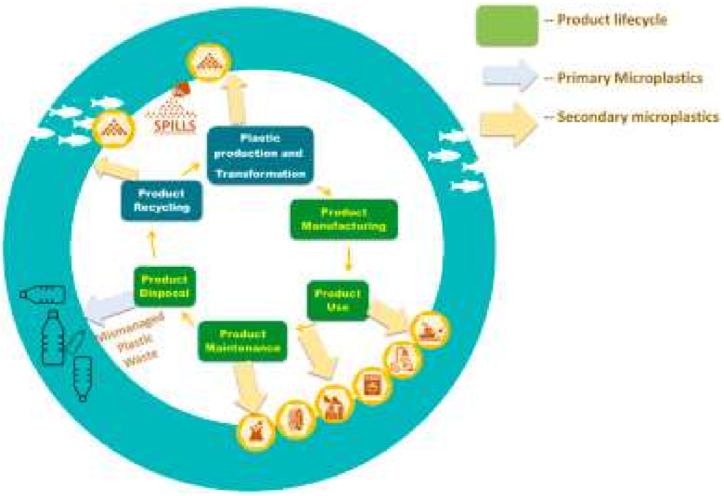


Fig. 1. Sources and distribution of various microplastics in the world's oceans.

In personal care and cosmetic products, plastic microbeads cause plastic particles to be directly introduced into wastewater streams from residences, hotels, hospitals, and sporting venues such as beaches [14]. (Fig. 2). City Dust is a catch-all name for a collection of nine causes recently identified in national assessments and most frequently seen in urban settings. City Dust includes losses from abrasion of infrastructure (home dust, city dust, artificial turfs, ports, and marinas, building coating), abrasion of objects (synthetic cooking utensils, synthetic shoe bottoms), abrasion of things, abrasive blasting, and deliberate pouring (detergents). These sources are combined because their separate contributions are negligible [15]. They eventually gather in gyres created by ocean currents. Estimates suggest that 93–268 kilotons of these microplastics floats in the waters [16]. Many microplastics will eventually accumulate in the deep sea and ultimately in food chains, as other types of microplastics, such as acrylic, are denser than saltwater and will most likely get deposited on the ocean bottom [17].

Fig. 2. Release of plastics, specifically primary microplastics, into the oceans by various parts of the world.

2.2. Types of microplastics

Microplastics are distinguished from larger plastic wastes, such as plastic bottles, containers, sheets, and waste plastic, by their size. Microplastics are currently classified into two types (Fig. 3). Any plastic pieces or particles that are 5.0 mm or smaller before entering the environment are considered the primary category of microplastics. Microfibers, beads, and plastic pellets used in clothing are a few examples (also known as nurdles). Secondary microplastics are created when larger plastic goods deteriorate in the environment due to normal weathering [18]. Secondary microplastics can come from various sources, including tea bags, fishing nets, water and soda bottles, plastic bags, microwave containers, and tire wear. Both types of contaminants are known to remain in the environment at high concentrations, especially in aquatic and marine ecosystems where they pollute the water. 35% of all ocean microplastics are made of textiles and apparel, mainly due to the normal evaporation of polyester, acrylic, or nylon garments. However, microplastics accumulate in the atmosphere and terrestrial ecosystems [19].

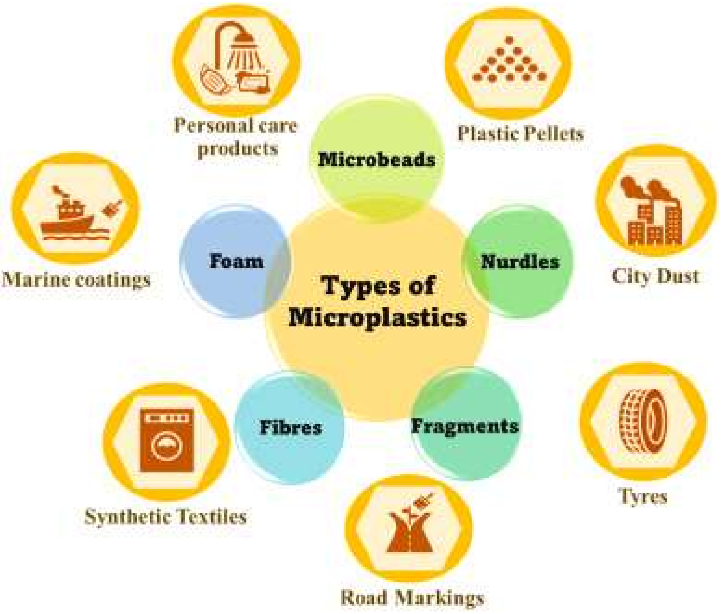


Fig. 3. Types of microplastics and where they are usually sourced from.

2.2.1. Primary microplastics

Small bits of plastic produced on purpose are known as primary microplastics. They are frequently discovered in cosmetics, facial cleaning products, and air-blasting technology. Their use as drug vectors in medicine has been described in some cases [20]. In exfoliating hand cleaners and facial scrubs, microplastic “scrubbers” have taken the role of naturally occurring substances such as powdered nut shells, oats, and pumice. For use in air blasting technology, primary microplastics have also been produced. Acrylic, melamine, or polyester microplastic scrubbers are fired at machinery, motors, and boat hulls to remove paint and rust (Gilbert, 2022). They are used repeatedly until their size decreases, and their cutting effectiveness is lost. These scrubbers usually contain heavy metals, such as cadmium, chromium, and lead [21]. Although many businesses have pledged to cut back on microbead production, there are still plenty of bioplastic microbeads that degrade slowly, much like regular plastic [22].

2.2.2. Secondary microplastics

Secondary plastics are tiny fragments created as bigger pieces of plastic debris, both on land and at sea, break down [23]. A mixture of physical and biological means can gradually erode the structural integrity of plastic debris, and chemo-photodegradation processes, including photooxidation, are caused by sunlight exposure. Eventually, this can make the debris too small to be seen by the human eye. Fragmentation technique involves reducing large amounts of plastic material into significantly tiny pieces [24]. Although microplastics are believed to continue to break down and shrink in size, the smallest microplastic currently considered to have been found in the oceans has a diameter of 1.6 μm (6.31 in). The prevalence of microplastics in irregular forms indicates fragmentation is a significant source [25]. Some of them include Fibers [26,27], microbeads [[28], [29], [30]], polymer blends [113], Fragments [31], Nurdles [[32], [33], [34], [35], [36]], styrofoam [[37], [38], [39]]

2.3. Toxicity caused by microplastics

Microplastics, mainly in the range of 5 μm, are worldwide contaminants that are widely disseminated in the environment. They are constantly prevalent within human ecosystems. The scale of pollution, it is widespread and its long-term durability raises significant concerns about its impact on ecosystems, animals, and human health [40]. Microplastics have fatal impacts on the environment as they are abundantly distributed in the soil and aquatic ecosystems due to their minuscule particle size. They indirectly or directly affect plant life by clogging in plant parts such as roots, stems, or leaves, thus affecting their nutrient uptake. Toxic and hazardous chemicals are used during the process as additives to improve the properties of polymers and increase their useful life, thus transporting toxic chemicals across ecosystems [[41], [107]]. The ecotoxicity of microplastics is seen not only in plants but also in animals. Microplastics are quickly taken up by the aquatic creatures and are transferred in the food chain to higher organisms, such as humans, thus becoming a source of concern for human health. Fish serve as one of the most integral biological models for assessing the toxicity of microplastics. Microplastic contamination of the aquatic ecosystem is one of the major concerns since they are easily ingested by the fauna in the waters and usually accumulate in their intestines. Several studies have proven the potential for microplastics to hinder reproduction capacity and cause fish organ failure [42,43].

At the apex of the food chain, humans are more vulnerable to microplastic contamination. Microplastics derived from the exhaust of gas and oil products tend to settle in household dust. They can be breathed due to their tiny size, and depending on individual sensitivity and particle qualities, they cause respiratory system lesions. Synthetic fibers of microplastics have been detected in human lungs by biopsies. Such airborne microplastics can cause injury or even death from chronic exposure due to their carcinogenic or mutagenic properties, potentially leading to cancer [44]. Microplastics have also been found to have a considerable influence on several regulatory enzymes, such as catalase, glutathione-*s*-transferase, and acetylcholinesterase [45]. Due to their ability to inhibit acetylcholinesterase, which results in an inflammatory reaction that may aid in the development of cancer, microplastics have also been shown to have neurotoxic effects. The interaction between humans and microplastics has been shown to affect cell function at the molecular level [46,47]. The inappropriate disposal of face masks worn during the COVID-19 pandemic contributes to the considerable amount of fibrous polypropylene microplastics found in non-woven fabrics. Again, this is another major factor responsible for the build-up of microplastics in air and water. Proper treatment of industrial effluents such as those of cosmetics, textiles, manufacturing, or other industries is also crucial, as they tend to contain a high concentration of microplastics [48]. The impact of microplastics on living things may be broadly categorized into physical and chemical impacts. Physical effects include the size, structure, and concentration of microplastics, while chemical effects include their toxic traits [49].

3. Characterization of microplastic degrading microbes

3.1. Microbes and their enzyme action

The significance of microorganisms in plastic degradation in the natural environment is unclear. However, abiotic environmental degradation plays a significant role in the fragmentation of large plastic waste, leading to micro- and nano-plastic contamination. Recent reports suggest that several microorganisms can depolymerize artificial polymers in a laboratory environment [50,51]. Microbial biotechnology has frequently been suggested as a viable solution for sustainable plastic waste disposal, even if the actuality and potential of biotechnological recycling technologies are not yet clearly understood by scientific communities, plastic end users, and policymakers [[52], [111]]. Microbial communities engaged in synthetic polymer degrading activities are a valuable source of enzymes. Biofilms that foul polyethylene terephthalate were reported to have undergone shotgun metagenomic sequencing by using ceramic, polyhydroxyalkanoate (PHA) and polyethylene terephthalate (PET) as the substrates at the sediment-water interface of a coastal lagoon [53]. PET plastic biofilms could not be distinguished from ceramic biofilm control. However, bioplastic biofilms of PHA could be identified because they were significantly enriched in phylogenetically diverse polyhydroxy butyrate (PHB) depolymerase and sulfate-reducing microorganisms (SRM). Here, it is seen how crucial the SRM of the plastisphere is to PHA biodegradation [53].

Numerous research studies have focused on the enzymatic breakdown of PET in the past ten years. The genome of the marine bacteria *Pseudomonas aestusnigri* included a unique PET hydrolyzing enzyme type IIa (PE-H), which was physically and functionally characterized. Amorphous PET was discovered to decompose at 30°C via PE-H [54]. By rearranging the active site conformation in a Y250S variation, structural modeling and mutagenesis were used to gain new knowledge about the structural elements necessary for the effective degradation of polyester. This variant exhibit enhanced PET hydrolytic activity [105]. Although UV treatment significantly enhanced chain scissions at the surface layer of amorphous PET films, the resulting increase in surface crystallinity significantly decreased the effectiveness of enzymatic degradation [55]. The microbial metabolism of plastic monomers and additives will be a research focus on environmental degradation of plastic pollution and biotechnological plastic upcycling, i.e., the utilization of plastic hydrolysates as feedstocks for the microbial production of high-value chemicals. Engineered whole-cell catalysts have recently been identified to have a high potential for plastic degradation [56]. Depolymerases, which convert long-chain polymers into low molecular weight oligomers or monomers that can be taken up by microbial cells or broken down into CO_2, are secreted as the initial stage of the microbial degradation process. These depolymerization products could be utilized to manufacture high-value compounds via specific metabolic pathways, which align with the circular economy principle and could valorize plastic trash [57].

However, little is known about the depolymerase that aids in the decomposition of plastics. Therefore, future studies should focus on discovering additional depolymerase from microbes that degrade plastic. The efficiency of enzymatic breakdown must also be increased, which is a difficult task. On the one hand, the crystalline structures and cross-linking networks seen in the macromolecular aggregate structures of plastics prevent enzymatic breakdown [58]. These macromolecular aggregation formations may be disorganized and more amenable to enzymatic breakdown using physical pre-treatments like mechanical grinding and irradiation. However, directed evolution and rational protein engineering are needed to increase depolymerization activity and stability, increasing the efficiency of enzymatic degradation [59]. Although depolymerases could break down long-chain polymer molecules into smaller pieces (monomers or oligomers), cells would have utilized these tiny depolymerization by-products as metabolic feedstocks [60]. The comparative list of plastic-degrading enzymes and microbes is given in Table 1.

Table 1. List of plastic degrading microbes and enzymes.

Enzyme	Types of plastic	E.C number	Microorganism/s	Mechanism	Sample collection location	Reference
poly(3-hydroxyoctanoate) depolymerase	Polythene (PE)	EC 3.1.1.76	*Pseudomonas* sp., *Comamonas* sp	Hydrolysis	Gujrat, India	[5,6]
poly (ethylene terephthalate) hydrolase	Polyethylene Terephthalate (PET)	EC 3.1.1.101	*Fusarium oxysporum*	Hydrolysis	Gujrat, India	[5,6]
The cutinase-like enzyme (CLE)	PET	EC 3.1.1.74 (cutinase)	*Pseudozyma and Cryptococcus*	acid/base mechanism - acylation and deacylation processes	-	[61]
MHETase	PET	EC 3.1.1.102	*Ideonella sakaiensis*	Hydrolase	Sakai City, Japan	[62]
PET hydrolases	PET	EC 3.1.1.101	*Ideonella sakaiensis*	cleave internal ester bonds	Sakai City, Japan	[62]
Cut 190	PET	-	*Thermophilic actinomycetes*	Hydrolyze	-	[63]
T manganese peroxidase (MnP)	PE	EC 1.11.1.13	*Irpex lacteus*	Degradation of Polyethylene membrane	-	[64]
-	Polythene and other plastic	-	**Bacteria:** Pseudomonas sp., *Staphylococcus* sp., *Moraxella* sp., *Micrococcus* sp., *Streptococcus* sp. **Fungi:** *Aspergillus glaucus, Aspergillus niger*	-	Mangrove soil	[65]
-	Low-Density Polyethylene (LDPE)		**Bacteria:** *Bacillus* sp. *Pseudomonas* sp. *Streptococcus* sp. **Fungi:** *Aspergillus* sp. *Fusarium* sp		dumped soil, Chennai	[66]

3.2. Mechanism of plastic degradation

3.2.1. Ideonella sakaiensis

A novel strain of bacteria called *Ideonella sakaiensis* 201-F6 can use PET as its main source of carbon. Two hydrolytic enzymes, namely mono (2-hydroxyethyl) terephthalate hydrolase (MHETase) and PET hydrolase (PETase) produced by *I. sakaiensis*, can break down PET into its monomeric components [67]. PET is transformed into mono-(2-hydroxyethyl) terephthalate (MHET) by the enzyme PETase, a consensus α/β hydrolase enzyme with a well-characterized structural fold. The second most necessary enzyme, MHETase, hydrolyzes MHET to produce PET byproducts of terephthalate (TPA) and ethylene glycol. Together, PETase and MHETase break down PET through MHET in two stages, producing simpler components required for a new cycle of PET synthesis (Fig. 4). While MHETase is necessary to destroy PET, its exact function is unclear. PETase effectively acts on PET in its crystalline state and at the optimal temperature [68].

Fig. 4. PET degradation involving 2 different enzymes.

3.2.2. Pseudomonas sp.

Pseudomonas sp. is a widespread and diverse microorganism genus with a total of 191 distinct species. As a result, they have a wide variety of properties, including plant growth factors, electroactivity, pathogenic activity, etc. Apart from these, the significant uses of *pseudomonas sps*. are bioremediation and plastic biodegradation. They produce simple enzymes to break down several types of polymers and aid in the degradation of PE, polystyrene (PS), polyurethane (PUR), and PET by employing primary enzymes such as hydrolase, alkene monooxygenase, esterase, lipase, and protease. The breakdown mechanism consists of two significant steps: the breakdown of macro-plastic into micro-plastic by extracellular enzymes such as depolymerase. This initial stage employs two distinct approaches, depending on the type of plastic: exo-attack (chain-terminal) for breaking smaller subunits and endo-attack (along the polymer chain) for molecular weight reduction. The tiny fragments of plastic traverse intracellular metabolic cycles such as the tricarboxylic acid (TCA) cycle and metabolic pathways, such as the catabolism pathway, in the second stage. Therefore, macroplastics would be completely decomposed into simpler compounds without toxicity [5,6].

PET is broken down into ethylene glycol (EG) and terephthalic acid (TPA) during the enzymatic degradation of polyethylene by Pseudomonas. Both products also gain new functional groups at the site of lysis. During hydrolysis, bis-(2-hydroxyethyl) terephthalate (BHET) and MHET are formed as intermediates that are converted into TPA and EG. The TPA is transported to the microbial cell by a TPA transporter, where it undergoes metabolic processes and is transformed into protocatechuic acid (PCA). PCA is metabolized in the TCA cycle. Likewise, EG is merged into the TCA cycle and biosynthesis process and metabolized. Enzymes such as hydrolase and polyethylene terephthalate are degraded by alkane hydroxylase (PET). The metabolic pathway consists of various phases, including oxidation, dehydrogenation, and breakage of carbon-carbon bonds, in the enzymatic degradation of PE. The PE is broken down into acetic acid, a new functional group, and then it is integrated into the TCA cycle. Metabolic hydrocarbon products of about 20 carbon atoms are transported directly into the microbial cell for the final breakdown. Hydrocarbons larger than 20 carbon atoms are metabolized outside the cell until through they can pass the microbial cell wall. And enzymes such as esterase and alkene monooxygenase will help in the degradation of polystyrene [69].

3.3. Recent discoveries

Due to the possible risk, they pose to aquatic life and human health, as previously indicated, and their link with invasive microorganisms, microplastics in the ecosystem are currently a significant source of environmental concern [70]. Microplastics are ubiquitous in many environments, particularly aquatic and soil biomes [[70], [71], [72]]. Recent studies have revealed that microplastics are essential vectors for microorganisms that could form fully developed biofilms on this artificial substrate [71,72]. Microorganisms play a vital role in the breakdown of microplastics because they control nutrient cycling in the immediate environment, which links biotic and abiotic processes [73]. They have evolved enzymes to digest plastic particles into assimilable carbon sources, as they have unfortunately become prevalent in the environment [74]. The breakdown of microplastic particles is significantly influenced by abiotic environmental deterioration. However, research on the effects of bacteria on biotic circumstances is ongoing [[6], [75], [76]]. Environmental conditions like pH, temperature, etc., should also go hand in hand with the available microplastic-degrading microbes in the immediate circle [77].

Microplastic-associated biofilms are a prominent microplastic aggregation observed in the aquatic environment. Specific bacterial communities play an important role in the production of these biofilms. Microplastic biofilms selectively enhance certain pathogenic bacteria [70]. As we dig deeper into the processes, one fact is that biofilms have pros and cons. Both merge at the point where biofilms play an influential role in the development of microbial biocommunities [73]. In the absence of microbial activity, plastics slowly degrade, with half-lives ranging from hundreds to eons, depending on the polymeric material and the characteristics of the environment [74]. As mentioned above, microbial populations provide a rich source of enzymes that break down plastics. One such organism is pseudomonas, whose enzymes are extensively studied because of their ability, especially in the upcycling process [6,75]. The researchers found that a bacterial consortium significantly altered the surface topography and rheological properties of the degraded polyethylene surface by forming a biofilm. These findings showed that, like pure fungal cultures, bacterial consortia could accumulate as harmful biofilms on the surface of microplastics [77].

The degradation of plastic polymers is one of the most studied effects of microbial communities on microplastics. Recent research has identified primary bacterial genera capable of dissolving poly (3-hydroxybutyrate-*co*-3-hydroxyhexanoate (PHBH) biofilms such as Alteromonadaceae and Burkholderiales. *Alcanivorax borkumensis* that grows in microplastic biofilms appeared significant in the degradation process of low-density polyethylene. Furthermore, it has been shown that Erythrobacter species in microplastic biofilms break down hydrocarbons [70]. According to a recent study, aquatic bacteria have adapted to plastics as a surface for colonization and may even break them down. For instance, numerous types of plastic, including macro- and microplastics, have been found to contain Erythrobacteraceae, a common aquatic bacterium that colonizes plastic [73]. PET plastics are one of the most common and widely used materials. In its macro or microform, PET degradation or hydrolysis is prompted by one of the most efficient enzymes, named IsPETase**,** isolated from *Ideonella sakaiensis*. In recent years, much research has been aimed at improving the stability and efficacy of IsPETase. Numerous recent reports have detailed point mutations that have been systematically engineered to make IsPETase a better fit for industrial use for the degradation of microplastics [74]. Another organism, *Pseudomonas aestusnigri*, with its enzyme PE-H at 30°C was found to break down amorphous PET. A Y250S variant was created using structural modeling and mutagenesis due to the rearrangement of the active site conformation. This variant showed improved PET hydrolytic activity and novel structural qualities required for efficient polyester degradation [6,75].

An enzyme or a couple of enzymes with the capability of degradation are not enough for the enormous amount of microplastic that must be washed off from the biosystem. To at least achieve the primary goal of degrading the microplastics, the combination of different enzymes from a particular type of organism is highly preferred, i.e., a bacterial, fungal, etc. This application could eliminate toxicity or toxic metabolites formed during degradation [77]. In general, the composition of the microbial community and essential microbial respiratory processes of the bacteria are influenced by the redox environment. As a result, microbes can interact actively with microplastics, coupling accessible redox mediators to polymer breakdown [73]. As always said, no matter the numerous mechanisms and biodegradation processes, curbing the actual problem is to lessening the use of any type of plastic or at least decrease the habit of inconsiderable disposal of plastic waste [71,72]. Recent studies indicate that fish, crabs, and other aquatic creatures readily consume microplastics. This, in turn, leads to bio amplification if plastics enter the food chain [70]. Another critical research to improve sustainability in food and agriculture is innovation in the performance and economics of bioderived and biodegradable plastics that avoid microplastic accumulation. It is strongly recommended that the food and agriculture sectors invest heavily in biodegradation technology to reduce microplastics in food and agricultural goods [74].

4. Metagenomic analysis

Various microbial communities can be drawn out, which, possibly, with the help of the enzymes they manufacture, contribute to the breakdown of microplastics. Not all enzymes produced by the microbial population are efficient enough to participate in the degradation process. To understand the nature of the microbial community and anticipate its ability to participate in in-situ biodegradation, a metagenomic study of the microbial population participating in plastic biodegradation is recommended as a solution to this problem [78]. Detailed metagenomic analysis of microbiomes and mining of associated genes and enzymes involved in biodegradation is now possible because of advances in bioinformatics and sequencing methods. Therefore, metagenomics could be a valuable method to discover effective plastic-degrading genes and enzymes in uncultivable microbial populations [[104], [112]]. The metagenomic analysis evaluated the genomic capabilities of aquatic plastic biofilms, as well as the levels of protein expression [79]. As the previous topics suggest, biofilms are one of the peculiar properties encountered in the process of degradation of microplastics. The composition or characterization of these biofilms depends on the strata or atmospheric level at which they are formed. This can be proved by shotgun metagenomic studies. At the sediment-water interface of a coastal lagoon, biofilms that break down plastic and microcosms made of bioplastic were shotgun metagenomic sequenced. According to a study conducted by Pinnell and Turner in 2019, plastic biofilms showed the same community composition as the ceramic biofilm control. This finding suggests that plastic-degrading microorganisms can be investigated through metagenetic studies. By examining the microbial community within the “plastisphere” and identifying novel genes or enzymes involved in the degradation of various polymers, we can uncover a vast and unexplored microbial gene pool. This approach holds great potential for biotechnological applications and further advancement in the field of valorization, as highlighted by Kirstein et al. [84].

According to environmental microbiologists, only 2% of entire microbiomes can be grown in the research lab, leaving a large fraction of uncultured fungus, bacteria, and other microorganisms undiscovered [80].

New developments in computational tools and next-generation sequencing techniques have allowed the parallel investigation of many biological samples by processing millions of DNA/RNA fragments [81]. The metagenomic analysis of any microbial biosystem can be broadly divided into the following ways, irrespective of the state., (a) structural metagenomic approach, (b) functional metagenomic approach, and comparative metagenomic approach [82].

4.1. Structural metagenomic approach

The primary goal of a structural metagenomic approach is to reveal the microbial community structure of any specific ecosystem by sequencing environmental samples. This will primarily provide the taxonomic identity of the microbial community in a culture-independent manner. However, it may also be used to investigate other aspects, such as identifying novel genes, predicting gene functions, and involving genes in various metabolic processes. Additionally, it will help establish connections between community members' preferences for the environment. Assigning minor or significant geo-ecological functions to microbiomes in the evolution of the community structure also provides information about the microbial population dynamics of a particular ecosystem at various spatial and temporal scales [78].

4.2. Functional metagenomic approach

Functional metagenomics helps determine the expression of a gene based on its sequencing or information about the structure. Beginning with the extraction of DNA from ambient sources, it predicts the likely required genes from a metagenome library and then moves on to heterologous expression for activity-based screening and functional validation. As a result, functional metagenomics is utilized in conjunction with sequence-based structural metagenomics to aid gene identification from the massive metagenomic database [78,83].

4.3. Comparative metagenomic approach

Additionally, a comparative metagenomic analysis of the various “plastispheres” of broad ecosystems could help identify the core microbial community, or the microorganisms that consistently persist over time to carry out a significant portion of plastic degradation and appear to be common in “plastispheres” across various geographical locations. Methods of adaptability, viability, and survival in their varied biological contexts (from marine to terrestrial) with the ability to degrade plastic could also be studied. Therefore, it is feasible to accelerate the degradation process by altering the microbial community and its metabolic processes in the plastisphere [78,84].

4.4. Analysis of microbial community structures through metagenomics

Using the three techniques above, the community structure of a microbiome can be deciphered. Community structure, physiochemical structure, and habitats, among others, are known to vary among microbial community belonging to similar ecological communities. The microbial population associated with plastics has a different makeup and evolves as the plastic deteriorates. According to reports, the varied species in the “specific” assemblage are congruent with types of plastic and can be recognized from other communities [78]. There are mainly two types of colonizers attributed to biofilm formation, i.e. primary colonizers and secondary colonizers. After 24–36 h, depending on the type of substrate and habitats, the buildup of primary colonizers modifies the subtratum, trying to make it favorable for further colonization by various secondary colonizers. Microorganisms arrive later in the biofilm formation process and may have unique features, indicating they are secondary colonizers. The structure of the microbial community evolves with time, and the relative proportions of secondary colonizers increase. The evolution of biofilm formation is represented by this progressive transition in community structure from primary to secondary colonizers over the duration [85].

Due to this variation in plastisphere characterization, metagenomic studies are limited to the structural analysis of the microbiome [84]. Although it helps the discovery of new microbial species, quantification of their abundance in the local microbial niche, and quantification of their rarity, the classification of these species into “core” to “specific” and “rare” species depends on their richness and specificity. Their functional involvement in the breakdown of polymers is still unknown. Purohit et al. [78] illustrated that some enzymes that can be used for the degradation of microplastics on the laboratory scale are not always suitable for performing the exact mechanism in a natural environment. For example, PETase hydrolysis is one of the most frequently used on disposed PET plastics in marine environments. A different form of the same enzyme can be obtained from *Ideonella sakaiensis* in iPETase. This enzyme is not suitable for the degradation of plastics in an aquatic environment. Researchers are now using a functional metagenomic method to address this problem by harvesting PET hydrolase homologs from various microbial sources. PET hydrolases are expected to be widely distributed in marine and terrestrial metagenomes based on conserved amino acids and can be exploited using various genetic engineering techniques for suitable modifications to the desired organism [78,83].

4.5. Deciphering a possible explication from metagenomic studies

The key benefit of metagenomic analysis is its rapid and effective means of highlighting the structural and functional importance of the relevant microbial niche [82]. A viable solution is developed based on all the data offered by metagenomics to meet the requirements of the microplastic breakdown process (Fig. 5). This answer can be divided into two categories, namely (a) modification of the external environment-microbial community and (b) modification of the internal cell primordia – genetic manipulation.

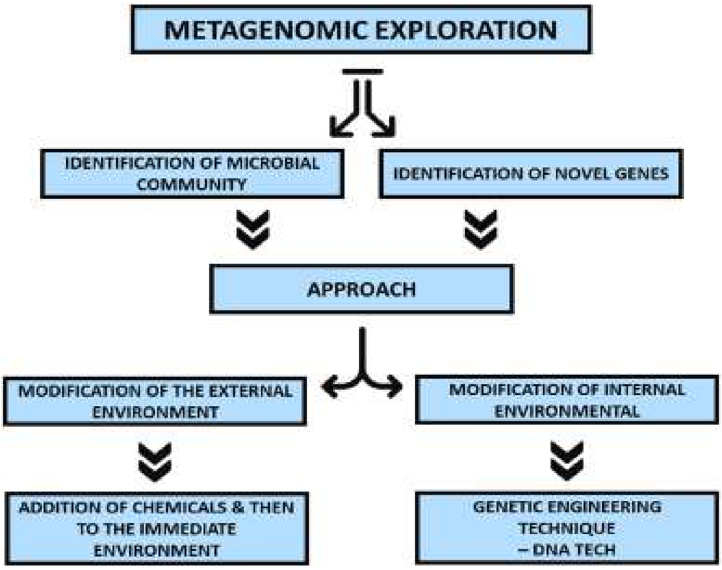


Fig. 5. Deciphering a possible explication of metagenomic study's.

The first category describes the modification of the environment in which the microbial bio community is present. These modifications can be applied using various chemicals or molecular methods or by introducing different sources of nutrition to the microorganisms in the community. This modification will eventually enhance the structure of the microbial component, resulting in better degradation of plastics.

The second describes the modification of genes or enzymes using microorganisms that are tailored to fit the need. In this way, the functional characterization of a particular microbial community can be altered by delivering the genes of interest into the organism's genome [78]. As a result, we can conclude that the development of metagenomic methods aids in the fabrication of proteins with enhanced characteristics, as well as the discovery of novel genes and the functional investigation of those genes through heterologous expression. To provide specialized solutions to problems, the biotechnological potential of metagenomics is emphasized, making it possible to obtain increasingly important information about the microbial world in order to address a range of societal and environmental problems.

4.6. Metagenomic analysis of plastic degrading enzymes in landfills

Around 21–42% of the plastic generated worldwide is reportedly disposed of in landfills [86]. Gaytán et al. [106], in their study on the polyurethane and xenobiotic biodegradation procedure and the evaluation of the product, revealed that the BP8 community breaks down various groups and bonds, including ester bonds, C-C bonds, aromatic recalcitrant urethanes, and ether groups. This was accomplished using oxidation and hydrolysis processes in all types of copolymer segments. The five genomes reconstructed using metagenomic analysis based on proximity ligation contained three genomes from the novel species. The identification of genes associated with different enzymes, such as putative enzymes and metabolic processes responsible for the biodegradative function of the BP8 population for additives and copolymers, was found in the metagenome. This work is the first to identify possible genes for microbial populations collected from landfills and water polyurethane dispersions systems that perform biodegradative processes. They also present viable solutions for the contaminations caused by xenobiotics and PU. Phylogenetic analysis identified well-supported clades for Paracoccus, Chryseobacterium, Parapedobacter, and Ochrobactrum intermedium, all of which are members of the Microbacteriaceae family.

Similarly, Kumar et al. [5,6] conducted a metagenomic analysis of the solid waste disposal site in Gujarat, India. Their study predicted thirty phyla, fifty-eight classes, 125 orders, 278 families, and 2468 distinct species. The most prevalent species in the soil and compost samples were Proteobacteria, Bacteroidetes, Firmicutes, and Actinobacteria. However, the leachate samples exhibited a predominance of phyla Firmicutes (54.24%), Actinobacteria (43.67%), and Proteobacteria (1.02%). The study also identified probable genes related to the decomposition of other plastics, such as PE, PS, and PET. Their research found a link between numerous gene sources actively participating in plastic waste biodegradation at landfill sites and the structured microbial community. Through the analysis of the Kyoto Encyclopedia of Genes and Genomes (KEGG), they found a total of 11 significant metabolic pathways, out of which the top five metabolic pathways were carbohydrate metabolism (21.92%), lipid metabolism (6.95%), energy metabolism (14.53%), amino acid metabolism (18.12%), and metabolism of cofactors and vitamins (10.34%). According to the KEGG annotations, in parallel to the above, only about 10.82% of the metabolic pathways predicted the general function, while 9.62% predicted amino acid transport and metabolism, 8.45% predicted ribosomal translation structure, and 7.67% indicated energy generation and conversion.

Sonnendecker et al. [91] studied PET plastic recycling by polyester hydrolase enzyme using metagenomic analysis at compost sites in Leipzig, Germany. Their study found that amorphous PET films are entirely hydrolyzed by polyester hydrolase PHL7, which was isolated from a compost metagenome. This enzyme releases 91 mg of terephthalic acid every hour. The PET film deterioration rates, measured by vertical scanning interferometry, were $6.8\,\mu m\,h^{-1}$. According to structural studies, leucine at position 210 is crucial for PHL7's robust PET-hydrolyzing activity in any energy-intensive pre-treatments; $0.6\ mg_{enzyme}\ gPET^{-1}$ destroys the post-consumer thermo-form PET packaging completely in 24 h at 70 °C in an aqueous buffer. Polyester hydrolases can function as catalysts in environmentally friendly, sustainable PET recycling processes by recovering terephthalic acid from the enzymatic hydrolysate and using it to create virgin PET. In a study conducted by Zrimec et al. [115], the microbial potential of plastic degradation concerning the trends in plastic pollution, they developed a list of approximately thirty thousand non-redundant homologs enzymes that could break down ten distinct kinds of plastic. They also discovered that the quantity of enzymes in the ocean rises with distance downwards. After collecting further pollution measurements, they also discovered that the abundance of enzymes in soil and ocean ecosystems was strongly correlated with changes in marine and nation-specific plastic pollution. Thakur et al. [87] conducted a metagenomic study to search for novel enzymes in Delhi, India, solid waste landfills. They found that, based on operational taxonomic unit (OTUs), Proteobacteria were the most prevalent species in all samples, followed by Actinobacteria, Firmicutes, Bacteriodetes, and Chlorofexi. Verrucomicrobia and Acidobacteria were among the other relatively dominating species that were highly prevalent in other samples, while the Parcubacteria and Tenericutes species were enriched in other samples. It was discovered that the average percentage of the phylum proteobacteria in all samples was 40.54%, followed by Actinobacteria, the second dominating phylum, and firmicutes, the third most prevalent. They speculated that members of the phylum Firmicutes play a significant role in the breakdown of cellulose in landfills and are one of the most critical bio-degraders of biomass there. Other phyla included Chlorofexi and Bacteroidetes. Iodidimonas, a rare genus, was detected only in sample V. In contrast, Flavifexus was present only in sample T. A different uncommon species from the phylum Bacteroidetes, Patricia, was discovered in samples V and T.

4.7. Metagenomic analysis of plastic degrading enzymes in marine

Anthropogenic activities and other causes have strained coastal and marine ecosystems for many years. The environment is being physically destroyed and polluted. Due to unsustainable development and building operations, one of the severe risks humans have posed to marine and coastal systems is the build-up of debris or litter. As a result of poor garbage disposal, the ocean's surface is covered with five trillion bits of floating plastic waste [88].

Pinnell et al. [53] conducted a study on the Benthic microbial community in the marine environment in Texas, USA, and found that Proteobacteria Operational taxonomic units of Proteobacteria (OTU) were the most prevalent across the four types of communities at the phylum level of all operational taxonomic units in saltwater, pottery, PET, and PHA samples, respectively. Cyanobacteria were the next most prevalent phylum in the saltwater community (25%). The PHA biofilm communities were the only ones where Chloroflexi (4%), Spirochaetes (4%), and Firmicutes (2%) were present among the most numerous phyla. Synechococcus and Prochlorococcus, the two genera of Cyanobacteria, made up almost 20% of all operational taxonomic units in the seawater community but only accounted for 1% of the three biofilm communities. In the PET and ceramic biofilm communities, members of the uncultured genera Desulfobacteraceae, Rhodobacteraceae, and Flammeovirgaceae were among the five most prevalent genera, accounting for about 20% of all OTUs. 25% of all OTUs in the PHA biofilm were represented by three genera of Desulfobacteraceae and one genera of Desulfobulbaceae that were not cultivated, highlighting the dominance of SRM in that community. Six high-quality metagenome-assembled genomes were recovered from the co-assembled PHA biofilm metagenomes. The first genomes assembled with identified metagenomes were Desulfovibrio, the Desulfobacteraceae family, the Desulfobulbaceae family, the Spirochaetaceae family, and the Gammaproteobacteria order.

Bryant et al. [89] conducted a study on microbial diversity and activity in the North Pacific Subtropical Gyre. To ascertain the metabolic activities of the microplastic, the authors employed the Chlorophyll analysis approach in conjunction with a few additional methods and discovered that heterotrophic and photosynthetic microorganisms were attracted to plastic garbage. Additionally, they discovered that multispecies microbial biofilms, including pennate diatoms and coccus, rod and spiral-shaped cells, were connected to the frontal membranes of bryozoans. On bryozoan surfaces, bacteria with long filaments and prostheses were also observed. Similar cell morphologies could be visible on plastic particle surfaces, with some cells nesting inside the pores of the material. The Rhodobacteraceae and Cyanobacteria subsection III family I group, which includes Phormidium and Leptolyngbya, were the most common microbial families in both tests, according to their research. Additionally, Hyphomonadaceae, Flavobacteraceae, Saprospiraceae, and Flammeovirgaceae regularly contributed to microbial plastic communities. Vibrionaceae, on the other hand, was rare in the samples from their analysis but quite frequent in one sample from the Atlantic.

Similarly, Meyer-Cifuentes et al. [90] researched the biodegradation of plastic by marine microbial populations. They conducted three separate experiments: detection of CO_2 synthesis and breakdown products, meta-omic analysis of various microorganisms, and identification of potential genes and proteins. A varied community was discovered by assembling and profiling metagenome, mainly made up of Alphaproteobacteria, Gammaproteobacteria, Flavobacteria, and Actinobacteria, albeit in smaller quantities. Throughout the duration of the time series experiment, the abundance profiles remained constant. In this experiment, the six most prevalent bins were three from the Rhodobacteraceae family, including two Pseudooceanicola spp., one unidentified Rhodobacteraceae bacteria, and one each from Marinobacter, Aequorivita, and Micavibrionaceae. Six orthologues of the three PETases were discovered, sakaiensis PETase (A0A0K8P6T7, GAP38373) (IsPETase), leaf compost cutinase (AEV21261.1) and Thermobifida fusca cutinase (ADV92528.1). Furthermore, four possible enzymes resemble MHETases and can break down polymers and waste products left behind by those breakdowns. Our findings demonstrate that only a few genes and organisms are active during biodegradation, although many can carry out each stage of degradation (Table 2)

Table 2. Studies done in metagenomic analysis of plastic-degrading microbes and their enzymes.

Aim of the study	**Type of plastic**	**Ecosystem**	**Phylum/Family**	**Discovery**	**Location of sampling**	**Reference**
Degradation of Recalcitrant Polyurethane and Xenobiotic.	PU, PE-PU-A, N-methyl pyrrolidone, isopropanol and glycol ethers	Landfills	Microbacteriaceae, Paracoccus, Chryseobacterium, Parapedobacter, and Ochrobactrum intermedium.	BP8 community functions & three novel species metagenome.	Nezahualcóyotl Estado de México, México.	Gaytán et al. [106]
Metagenomic analysis of the solid waste disposal site.	Soil waste compost	Landfills	Proteobacteria, Bacteroidetes, Firmicutes, and Actinobacteria. Firmicutes, Actinobacteria, and Proteobacteria.	2468 distinct species & eleven significant metabolic pathways.	Gujarat, India.	Kumar et al. [5,6])
Use of metagenomic polyester	PET	Landfills	-	PHL7's role in plastic degradation.	Leipzig, Germany.	Sonnendecker et al. [91]

Aim of the study	Type of plastic	Ecosystem	Phylum/Family	Discovery	Location of sampling	Reference
hydrolase to recycle plastic.						
Relation between global plastic degrading microbial populations and trends in pollution.	Plastic (10) PVA, PLA, PU, PHB, PBS, PET, PBAT, PE, PEG, PHO Additive (4) Phthalate PA, DBP, TP,	Landfills and marine	Acidobacteriota, Actinobacteriota, Alphaproteobacteria, Bacteroidota, Bdellovibrionota, Chloroflexota, Desulfobacterota, Gammaproteobacteria, Gemmatimonadota, Latescibacterota, Marinisomatota, Myxococcota, Planctomycetota, Poribacteria, Spirochaetota, Thermoplasmatota, and Verrucomicrobiota.	30,000 non-redundant enzyme homologs.	169 samples from 38 countries.	Zrimec et al. [115]
Using metagenomics for finding new microbial enzymes in the solid-waste dump.	compost	Landfills	Proteobacteria, Actinobacteria, Firmicutes, Bacteriodetes, and Chlorofexi. Verrucomicrobia and Acidobacteri. Parcubacteria and Tenericutes.	Novel enzymes, and bacterial Communities.	Delhi, India.	Thakur et al. [87]
Shotgun metagenomic analysis of microbes acting on Coastal plastic and bioplastic.	biofilms of plastic and bioplastic	Marine	Proteobacteria, cyanobacteria, Chloroflexi, Spirochaetes, and Firmicutes.	novel species of Desulfovibrio, Desulfobacteraceae, and Desulfobulbaceae	Texas, USA.	Pinnell et al [53]
Study the diversity of the microbial population and their activities	Microplastic	Marine	Rhodobacteraceae, Cyanobacteria, Phormidium, and Leptolyngbya. Hyphomonadaceae, Flavobacteraceae,	che genes, secretion system genes, and nifH genes.	North Atlantic Subtropical Gyre.	Bryant et al. [89]

Aim of the study	Type of plastic	Ecosystem	Phylum/Family	Discovery	Location of sampling	Reference
in North Pacific Gyre.			Saprospiraceae, Flammeovirgaceae, and Vibrionaceae.			
Microbial symbiotic biodegradation of aromatic copolyester.	aromatic-aliphatic copolyester	Marine	Alphaproteobacteria, Gammaproteobacteria, Flavobacteria, and Actinobacteria. Rhodobacteraceae, Pseudooceanicola spp., Marinobacter, Aequorivita, and Micavibrionaceae.	6 PETase-like enzymes and 4 MHETase-like enzymes.	Helgoland, Germany. Athens, Greece. Elba, Italy	Meyer-Cifuentes et al. [90]

5. Case studies

In a study carried out to establish and validate a suitable technique to extract and quantify microplastics of varying sizes and forms from sewage sludge samples, it was found that over 190 days, soils containing sludge with the highest microplastic concentration produced the least biomass and no mature fruits were borne. Several factors, such as soil humidity and temperature, precipitation, and air temperature, influence biomass production, the availability of soil nutrients being the most critical among them. Both surplus and deficit nutrients adversely affect biomass and tomato production [92,93]. Overall, alterations in the soil's C: N ratio, which changed the availability of nutrients, significantly influenced the growth rate [94].

Microplastic contamination occurs not only in the soil but also in water bodies and in more significant proportions. Microplastics were found in every sample of water tested, including drinking water, according to research to determine the number of microplastic particles in freshwater and drinking water. Microplastics of 10 μm size were the most prevalent in both treated and untreated water. Even particles down to the size of 1 μm were also identified as polyethylene. PET, PP and PE formed the majority of 12 other microplastic materials that were obtained. However, raw water was shown to have a more significant proportion of microplastics than treated water [95]. The quantification of microplastics was also carried out for 16 months near the Ofanto River in the Apulia region of southeast Italy. Black flakes and transparent fragments of microplastics were found at various concentrations. Their origin was mostly found to be land-based [96]. The effects of microplastics and other pollutants of various types in the aquatic ecosystem caused more significant damage to zebrafish than the contaminants were present alone, according to an investigation in which environmental circumstances were recreated in the laboratory. This combination resulted in adverse failure of the fish's internal organs [42,43]. In another similar study, the impacts of microplastics were studied at actual ambient levels where the microplastics were detected in the gills, intestines, and life of Oryzias melastigma, also called the marine medaka. These microplastics caused structural damage and increased oxidative stress in the tissues that made up the vital organs. The fecundity of the fish was also markedly reduced [9,10]. Similar toxicity effects were also observed in other aquatic beings, such as amphipods, crustaceans, and aquatic gastropods. Fish and other underwater organisms in areas that support mangrove growth serve as a food source for a large population. Recently, further research has been conducted to detect microplastic traces in these organisms. Among the other polymers, polycarbonates, and polystyrenes were detected in the highest concentrations [97]. The mudskipper fish from India's Ulhas River estuary provided another set of findings. These fish are selective feeders, so micro-sized plastic particles were easily ingested. In contrast, the larger ones were inhibited, leading to a more significant accumulation of these microplastics in the gills. Microplastics were also found to accumulate in other fishes, such as long-tailed tuna (*Thunnus tonnggol*) and Sawtooth barracuda (*Sphyraena putnamiae*) [97].

Microplastics were also accumulated in several regions of the aquatic plant *Utricularia Vulgaris,* such as the leaves, shoots, and bladders of the plant. This accumulation elevates the antioxidative enzyme activity of the plant, thus increasing oxidative stress that leads to damage to plant parts [98]. Microplastics were detected in the roots of *Vicia faba* using laser confocal scanning electron microscopy, and a comparable impact of microplastics was also identified there [99]. A study conducted in the 11 most secluded and protected regions of the United States reported the accumulation of primary and secondary microplastics in dry and wet atmospheric depositions. A total of 339 samples (wet - 263, dry −103) were taken and most of these particles were synthetic microfibers of size 20 to approximately 3 mm and other particles of size 4–188 mm [100]. Microplastics have also been found in air debris collected from many places [101,102]. The build-up of minute plastic particles in arable soils, which might have unanticipated effects on soil quality and output, is now causing significant concern. Four agricultural areas and a buffer zone of the riparian forest at Dian Lake in southern China were investigated for the prevalence and distribution of plastic particles in mixed soil fractions. In 50 soil samples, plastic particles were discovered in sizes ranging from 0.05 to 1 mm. Compared to buffer soil, the concentration of microplastics in vegetable soil was greater, indicating the use of soil additives [103]. Microplastics have also been found consistently in several of China's inland water systems. It was discovered that most of these had secondary origins[114]. A significant accumulation of microplastics was also detected in one of the most critical drinking water sources of China's Nanning city, both in the surface waters and in the sediments. Polypropylene and polyethylene were detected at the highest concentrations [71,72].

6. Conclusions

Microplastic pollution continues to pose a significant challenge in the fields of environmental engineering, ecology, and materials science. Exploring the biodegradation of microplastics through research can enhance our understanding of how to mitigate their presence in the environment and develop innovative technologies to combat pollution. The efficient degradation of microplastics by microbes using various enzymes highlights the importance of studying enzyme activities, particularly in the context of micropollutants, which have emerged as a major environmental concern. Applying such knowledge on a broader scale could lead to the development of more effective degradation mechanisms for heavily polluted areas facing multiple pollution problems. In-depth comparative studies focusing on identifying the most suitable enzymes for microplastic degradation are crucial, particularly when dealing with high volumes of micropollutants. While traditional methods are valuable for unlocking the potential of different microorganisms, interdisciplinary approaches like structural or functional metagenomics hold significant importance, especially in the face of escalating environmental pollution. By incorporating these approaches into projects, concrete conclusions can be drawn within a short timeframe. In the future, it is essential to extend these techniques to encompass the larger ecosystems that serve as primary carriers of microplastics.

Thoroughly investigating microplastics, including their distribution, associated risks, spatial dispersion, temporal trends, and the interplay of external factors with microbe behavior using chemical and visual cues, is crucial. Understanding the health risks posed by microplastics and other chemical pollutants in the environment is also of paramount importance. Furthermore, the development of beneficial microbial agents is necessary to effectively reduce microplastic pollution. This comprehensive review provides valuable insights into the metagenomics of microplastic-degrading organisms, shedding light on their environmental roles. However, further investigations are still needed to explore the use of metagenomic approaches for identifying and characterizing microplastic-degrading organisms, as well as understanding the environmental factors influencing their growth and activity. Continued research in this area will yield useful insights and aid in the development of effective strategies to combat plastic pollution.

Authors contributions

All authors had full access to all the contents of the review paper and take responsibility for the integrity and accuracy of the text and analysis. Study concept and design: CNR. Acquisition of data: KVSSNM, AM, JCJR and ACVS. Analysis and interpretation of data: KVSSNM, AM, JCJR, ACVS,VP and CNR. Drafting of the manuscript: KVSSNM, AM, JCJR, ACVS, BM, YR, SKM, PK,VP,MH and CNR. Overall supervision: CNR, FB,MH.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Recommended articles

Data availability

Data will be made available on request.

References

[1] T. Tsering, M. Sillanpää, M. Sillanpää, M. Viitala, S.P. Reinikainen
Microplastics pollution in the brahmaputra river and the indus river of the Indian himalaya
Sci. Total Environ., 789 (2021), Article 147968, 10.1016/j.scitotenv.2021.147968 ↗
View PDF View article View in Scopus ↗ Google Scholar ↗

[2] H.A. Leslie, M.J. Van Velzen, S.H. Brandsma, D. Vethaak, J.J. Garcia-Vallejo, M.H. Lamoree
Discovery and Quantification of Plastic Particle Pollution in Human Blood
Environment International (2022), Article 107199, 10.1016/j.envint.2022.107199 ↗
View PDF View article View in Scopus ↗ Google Scholar ↗

[3] P.K. Rai, J. Lee, R.J.C. Brown, K.-H. Kim

Environmental fate, ecotoxicity biomarkers, and potential health effects of micro- and nano-scale plastic contamination
J. Hazard Mater., 403 (123910) (2021), Article 123910, 10.1016/j.jhazmat.2020.123910 ↗
View PDF View article View in Scopus ↗ Google Scholar ↗

[4] S.L. Wright, F.J. Kelly
Plastic and human health: a micro issue
Environ. Sci. Technol., 51 (12) (2017), pp. 6634-6647, 10.1021/acs.est.7b00423 ↗
View in Scopus ↗ Google Scholar ↗

[5] R. Kumar, P. Pandit, D. Kumar, Z. Patel, L. Pandya, M. Kumar, C. Joshi, M. Joshi
Landfill microbiome harbour plastic degrading genes: a metagenomic study of solid waste dumping site of Gujarat, India
Sci. Total Environ., 779 (146184) (2021), Article 146184, 10.1016/j.scitotenv.2021.146184 ↗
View PDF View article View in Scopus ↗ Google Scholar ↗

[6] R. Kumar, P. Pandit, D. Kumar, Z. Patel, L. Pandya, M. Kumar, ..., M. Joshi
Landfill microbiome harbour plastic degrading genes: a metagenomic study of solid waste dumping site of Gujarat, India
Sci. Total Environ., 779 (2021), Article 146184, 10.1016/j.scitotenv.2021.146184 ↗
View PDF View article View in Scopus ↗ Google Scholar ↗

[7] J.R. Jambeck, R. Geyer, C. Wilcox, T.R. Siegler, M. Perryman, A. Andrady, ..., K.L. Law
Plastic waste inputs from land into the ocean
Science, 347 (6223) (2015), pp. 768-771, 10.1126/science.1260352 ↗
Google Scholar ↗

[8] L.J. Meijer, T. van Emmerik, R. van der Ent, C. Schmidt, L. Lebreton
More than 1000 rivers account for 80% of global riverine plastic emissions into the ocean
Sci. Adv., 7 (18) (2021), 10.1126/sciadv.aaz5803 ↗
eaaz5803
Google Scholar ↗

[9] J. Wang, Y. Li, L. Lu, M. Zheng, X. Zhang, H. Tian, ..., S. Ru
Polystyrene microplastics cause tissue damages, sex-specific reproductive disruption and transgenerational effects in marine medaka (Oryzias melastigma)
Environ. Pollut., 254 (2019), Article 113024, 10.1016/j.envpol.2019.113024 ↗
View PDF View article View in Scopus ↗ Google Scholar ↗

[10] T. Wang, X. Zou, B. Li, Y. Yao, Z. Zang, Y. Li, ..., W. Wang
Preliminary study of the source apportionment and diversity of microplastics: taking floating microplastics in the South China Sea as an example
Environ. Pollut., 245 (2019), pp. 965-974, 10.1016/j.envpol.2018.10.110 ↗
View PDF View article View in Scopus ↗ Google Scholar ↗

[11] S.M. Al-Salem, P. Lettieri, J. Baeyens

The valorization of plastic solid waste (PSW) by primary to quaternary routes: from re-use to energy and chemicals

Prog. Energy Combust. Sci., 36 (1) (2010), pp. 103-129, 10.1016/j.pecs.2009.09.001 ↗

View PDF View article View in Scopus ↗ Google Scholar ↗

[12] K.K. Leonas

The use of recycled fibers in fashion and home products

Textiles and clothing sustainability (2017), pp. 55-77, 10.1007/978-981-10-2146-6_2 ↗

Google Scholar ↗

[13] M. Faber, M. Marinković, E. de Valk, S.L. Waaijers-van der Loop

Paints and Microplastics. Exploring the Possibilities to Reduce the Use and Release of Microplastics from Paints. Feedback from the Paint Sector

(2021), 10.21945/RIVM-2021-0060 ↗

Google Scholar ↗

[14] E.E. Burns, A.B. Boxall

Microplastics in the aquatic environment: evidence for or against adverse impacts and major knowledge gaps

Environ. Toxicol. Chem., 37 (11) (2018), pp. 2776-2796, 10.1002/etc.4268 ↗

View in Scopus ↗ Google Scholar ↗

[15] A. Patchaiyappan, K. Dowarah, S.Z. Ahmed, M. Prabakaran, S. Jayakumar, C. Thirunavukkarasu, S.P. Devipriya

Prevalence and characteristics of microplastics present in the street dust collected from Chennai metropolitan city, India

Chemosphere, 269 (2021), Article 128757, 10.1016/j.chemosphere.2020.128757 ↗

View PDF View article View in Scopus ↗ Google Scholar ↗

[16] E. Watt, M. Picard, B. Maldonado, M.A. Abdelwahab, D.F. Mielewski, L.T. Drzal, ..., A.K. Mohanty

Ocean plastics: environmental implications and potential routes for mitigation–a perspective

RSC Adv., 11 (35) (2021), pp. 21447-21462, 10.1039/D1RA00353D ↗

View in Scopus ↗ Google Scholar ↗

[17] J. Zalasiewicz, C.N. Waters, J.A.I. Do Sul, P.L. Corcoran, A.D. Barnosky, A. Cearreta, ..., Y. Yonan

The geological cycle of plastics and their use as a stratigraphic indicator of the Anthropocene

Anthropocene, 13 (2016), pp. 4-17, 10.1016/j.ancene.2016.01.002 ↗

View PDF View article View in Scopus ↗ Google Scholar ↗

[18] J. Boucher, D. Friot

Primary Microplastics in the Oceans: a Global Evaluation of Sources, 43, Iucn, EN (2017), 10.2305/IUCN.CH.2017.01 ↗

Google Scholar ↗

[19] C.J. Rhodes

Solving the plastic problem: from cradle to grave, to reincarnation

Sci. Prog., 102 (3) (2019), pp. 218-248, 10.1177/0036850419867204 ↗

View in Scopus ↗ Google Scholar ↗

[20] H.S. Auta, C.U. Emenike, S.H. Fauziah
Distribution and importance of microplastics in the marine environment: a review of the sources, fate, effects, and potential solutions
Environ. Int., 102 (2017), pp. 165-176, 10.1016/j.envint.2017.02.013 ↗
View PDF View article View in Scopus ↗ Google Scholar ↗

[21] R.K. Mishra, N. Mohammad, N. Roychoudhury
Soil pollution: causes, effects and control
Sang, 3 (1) (2016), pp. 1-14, 10.1088/1755-1315/790/1/012009 ↗
Google Scholar ↗

[22] T.D. Nielsen, J. Hasselbalch, K. Holmberg, J. Stripple
Politics and the plastic crisis: a review throughout the plastic life cycle
Wiley Interdisciplinary Reviews: Energy Environ., 9 (1) (2020), Article e360, 10.1002/wene.360 ↗
View in Scopus ↗ Google Scholar ↗

[23] L.W. Chin, T.H. Fung
R.E. Hester, R.M. Harrison (Eds.), Plastic in Marine Litter, Plastics and the Environment (2018), pp. 21-59, 10.1039/9781788013314-00021 ↗
Google Scholar ↗

[24] M.L. Pedrotti, S. Petit, A. Elineau, S. Bruzaud, J.C. Crebassa, B. Dumontet, ..., A. Cózar
Changes in the floating plastic pollution of the Mediterranean Sea in relation to the distance to land
PLoS One, 11 (8) (2016), Article e0161581, 10.1371/journal.pone.0161581 ↗
Google Scholar ↗

[25] M. Cole, P. Lindeque, C. Halsband, T.S. Galloway
Microplastics as contaminants in the marine environment: a review
Mar. Pollut. Bull., 62 (12) (2011), pp. 2588-2597, 10.1016/j.marpolbul.2011.09.025 ↗
View PDF View article View in Scopus ↗ Google Scholar ↗

[26] N.L. Hartline, N.J. Bruce, S.N. Karba, E.O. Ruff, S.U. Sonar, P.A. Holden
Microfiber masses recovered from conventional machine washing of new or aged garments
Environ. Sci. Technol., 50 (21) (2016), pp. 11532-11538, 10.1021/acs.est.6b03045 ↗
View in Scopus ↗ Google Scholar ↗

[27] C.W. Gattringer
The economics of marine plastic pollution
Oxford Research Encyclopedia of Environmental Science (2021), 10.1016/0025-326X(95)00246-J ↗
Google Scholar ↗

[28] S. Ju, G. Shin, M. Lee, J.M. Koo, H. Jeon, Y.S. Ok, ..., J. Park
Biodegradable chito-beads replacing non-biodegradable microplastics for cosmetics
Green Chem., 23 (18) (2021), pp. 6953-6965, 10.1016/j.jcin.2021.06.013 ↗

View in Scopus ↗ Google Scholar ↗

[29] N. Gao, X. Kong, H. Lv, Z. Sun, Y. Liu
An effective fluorescent probe method applied in the analysis of microplastics
J. Coast Res., 111 (SI) (2020), pp. 70-77, 10.2112/JCR-SI111-012.1 ↗
View in Scopus ↗ Google Scholar ↗

[30] A. Iannuzzi
Greener Products: the Making and Marketing of Sustainable Brands
CRC Press (2017)
Google Scholar ↗

[31] M.A. Browne, P. Crump, S.J. Niven, E. Teuten, A. Tonkin, T. Galloway, R. Thompson
Accumulation of microplastic on shorelines woldwide: sources and sinks
Environ. Sci. Technol., 45 (21) (2011), pp. 9175-9179, 10.1021/es201811s ↗
View in Scopus ↗ Google Scholar ↗

[32] A.K. Forrest, M. Hindell
Ingestion of plastic by fish destined for human consumption in remote South Pacific Islands
Australian Journal of Maritime & Ocean Affairs, 10 (2) (2018), pp. 81-97, 10.1080/18366503.2018.1460945 ↗
View in Scopus ↗ Google Scholar ↗

[33] J. Hammer, M.H. Kraak, J.R. Parsons
Plastics in the marine environment: the dark side of a modern gift
Rev. Environ. Contam. Toxicol. (2012), pp. 1-44, 10.1007/978-1-4614-3414-6_1 ↗
View in Scopus ↗ Google Scholar ↗

[34] A. Ahamad, P. Singh, D. Tiwary (Eds.), Plastic and Microplastic in the Environment: Management and Health Risks, John Wiley & Sons (2022)
Google Scholar ↗

[35] A.H. Said, M.S. Kyewalyanga, F.E. Msuya, A.J. Mmochi, E.W. Mwihia, E. Skjerve, ..., J.L. Lyche
Health Problems Related to Algal Bloom Among Seaweed Farmers in Coastal Areas of Tanzania
(2018)
http://hdl.handle.net/20.500.11810/5570 ↗
Google Scholar ↗

[36] C. Moore
Plastic Ocean: How a Sea Captain's Chance Discovery Launched a Determined Quest to Save the Oceans
Penguin (2011)
Google Scholar ↗

[37] C. Thaysen, K. Stevack, R. Ruffolo, D. Poirier, H. De Frond, J. DeVera, ..., C.M. Rochman
Leachate from expanded polystyrene cups is toxic to aquatic invertebrates (Ceriodaphnia dubia)

Front. Mar. Sci., 5 (2018), p. 71, 10.3389/fmars.2018.00071 ↗

View in Scopus ↗ Google Scholar ↗

[38] C. Trestrail, M. Walpitagama, C. Hedges, A. Truskewycz, A. Miranda, D. Wlodkowic, ..., D. Nugegoda
Foaming at the mouth: ingestion of floral foam microplastics by aquatic animals
Sci. Total Environ., 705 (2020), Article 135826, 10.1016/j.scitotenv.2019.135826 ↗

View PDF View article View in Scopus ↗ Google Scholar ↗

[39] Z. Safee, D. Ishamuddin
Study on concrete with partial replacement of sand by floral foam
Politeknik & Kolej Komuniti Journal of Engineering and Technology, 5 (1) (2020), pp. 19-33

Google Scholar ↗

[40] M. Arias-Andres, K. Rojas-Jimenez
Ecological and public health effects of microplastics pollution
Microplastic Pollution, Springer, Cham (2022), pp. 429-444, 10.1007/978-3-030-89220-3_19 ↗

Google Scholar ↗

[41] H. Du, Y. Xie, J. Wang
Environmental impacts of microplastics on fishery products: an overview
Gondwana Res. (2021), 10.1016/j.gr.2021.08.013 ↗

Google Scholar ↗

[42] H. Cheng, Y. Feng, Z. Duan, X. Duan, S. Zhao, Y. Wang, ..., L. Wang
Toxicities of microplastic fibers and granules on the development of zebrafish embryos and their combined effects with cadmium
Chemosphere, 269 (2021), Article 128677, 10.1016/j.chemosphere.2020.128677 ↗

View PDF View article View in Scopus ↗ Google Scholar ↗

[43] S. Rainieri, N. Conlledo, B.K. Larsen, K. Granby, A. Barranco
Combined effects of microplastics and chemical contaminants on the organ toxicity of zebrafish (Danio rerio)
Environ. Res., 162 (2018), pp. 135-143, 10.1016/j.envres.2017.12.019 ↗

View PDF View article View in Scopus ↗ Google Scholar ↗

[44] S. Abbasi, A. Turner
Human exposure to microplastics: a study in Iran
J. Hazard Mater., 403 (2021), Article 123799, 10.1016/j.jhazmat.2020.123799 ↗

View PDF View article View in Scopus ↗ Google Scholar ↗

[45] G. Jaikumar, N.R. Brun, M.G. Vijver, T. Bosker
Reproductive toxicity of primary and secondary microplastics to three cladocerans during chronic exposure
Environ. Pollut., 249 (2019), pp. 638-646, 10.1016/j.envpol.2019.03.085 ↗

View PDF View article View in Scopus ↗ Google Scholar ↗

[46] J. Hwang, D. Choi, S. Han, J. Choi, J. Hong
An assessment of the toxicity of polypropylene microplastics in human derived cells

Sci. Total Environ., 684 (2019), pp. 657-669, 10.1016/j.scitotenv.2019.05.071 ↗

View PDF View article View in Scopus ↗ Google Scholar ↗

[47] W. Huang, B. Song, J. Liang, Q. Niu, G. Zeng, M. Shen, ..., Y. Zhang
Microplastics and associated contaminants in the aquatic environment: a review on their ecotoxicological effects, trophic transfer, and potential impacts to human health
J. Hazard Mater., 405 (2021), Article 124187, 10.1016/j.jhazmat.2020.124187 ↗

View PDF View article View in Scopus ↗ Google Scholar ↗

[48] P.Y. Katare, M.S. Sankhla, M. Singhal, B. Ekta, K.P. Jadhav, T.N. Bhagyashri, L. Bhardwaj
Microplastics in aquatic environments: sources, ecotoxicity, detection & remediation
Biointerface Res. Appl. Chem, 12 (2021), pp. 3407-3428, 10.33263/BRIAC123.34073428 ↗

Google Scholar ↗

[49] J.N. Hahladakis, C.A. Velis, R. Weber, E. Iacovidou, P. Purnell
An overview of chemical additives present in plastics: migration, release, fate and environmental impact during their use, disposal and recycling
J. Hazard Mater., 344 (2018), pp. 179-199, 10.1016/j.jhazmat.2017.10.014 ↗

View PDF View article View in Scopus ↗ Google Scholar ↗

[50] M. Niaounakis
Management of Marine Plastic Debris
William Andrew (2017)

Google Scholar ↗

[51] J.M. Fang, P.A. Fowler, C. Escrig, R. Gonzalez, J.A. Costa, L. Chamudis
Development of biodegradable laminate films derived from naturally occurring carbohydrate polymers
Carbohydr. Polym., 60 (1) (2005), pp. 39-42, 10.1016/j.carbpol.2004.11.018 ↗

View PDF View article View in Scopus ↗ Google Scholar ↗

[52] X.F. Wei, F. Nilsson, H. Yin, M.S. Hedenqvist
Microplastics originating from polymer blends: an emerging threat?
Environ. Sci. Technol., 55 (8) (2021), pp. 4190-4193, 10.1021/acs.est.1c00588 ↗

View in Scopus ↗ Google Scholar ↗

[53] L.J. Pinnell
Characterizing the Microbial Response to Plastic and Bioplastic Debris in the Marine Environment
Doctoral dissertation, Texas A&M University-Corpus Christi) (2019)
https://hdl.handle.net/1969.6/87857 ↗

Google Scholar ↗

[54] A. Amobonye, P. Bhagwat, S. Singh, S. Pillai
Plastic biodegradation: frontline microbes and their enzymes
Sci. Total Environ., 759 (2021), Article 143536, 10.1016/j.scitotenv.2020.143536 ↗

View PDF View article View in Scopus ↗ Google Scholar ↗

[55] F. Xie, T. Zhang, P. Bryant, V. Kurusingal, J.M. Colwell, B. Laycock
Degradation and stabilization of polyurethane elastomers
Prog. Polym. Sci., 90 (2019), pp. 211-268, 10.1016/j.progpolymsci.2018.12.003 ↗
View PDF View article View in Scopus ↗ Google Scholar ↗

[56] L.D. Ellis, N.A. Rorrer, K.P. Sullivan, M. Otto, J.E. McGeehan, Y. Román-Leshkov, ..., G.T. Beckham
Chemical and biological catalysis for plastics recycling and upcycling
Nat. Catal., 4 (7) (2021), pp. 539-556, 10.1038/s41929-021-00648-4 ↗
View in Scopus ↗ Google Scholar ↗

[57] A.A. Shah, F. Hasan, A. Hameed, S. Ahmed
Biological degradation of plastics: a comprehensive review
Biotechnol. Adv., 26 (3) (2008), pp. 246-265, 10.1016/j.biotechadv.2007.12.005 ↗
View PDF View article View in Scopus ↗ Google Scholar ↗

[58] A. Gricajeva, A.K. Nadda, R. Gudiukaite
Insights into polyester plastic biodegradation by carboxyl ester hydrolases
J. Chem. Technol. Biotechnol., 97 (2) (2022), pp. 359-380, 10.1002/jctb.6745 ↗
View in Scopus ↗ Google Scholar ↗

[59] S. Miri, R. Saini, S.M. Davoodi, R. Pulicharla, S.K. Brar, S. Magdouli
Biodegradation of microplastics: better late than never
Chemosphere, 286 (2022), Article 131670, 10.1016/j.chemosphere.2021.131670 ↗
View PDF View article View in Scopus ↗ Google Scholar ↗

[60] J. Ru, Y. Huo, Y. Yang
Microbial degradation and valorization of plastic wastes
Front. Microbiol., 11 (2020), p. 442, 10.3389/fmicb.2020.00442 ↗
View in Scopus ↗ Google Scholar ↗

[61] Q. Hu, V.M. Jayasinghe-Arachchige, R. Prabhakar
Degradation of a main plastic pollutant polyethylene terephthalate by two distinct proteases (neprilysin and cutinase-like enzyme)
J. Chem. Inf. Model., 61 (2) (2021), pp. 764-776, 10.1021/acs.jcim.0c00797 ↗
View in Scopus ↗ Google Scholar ↗

[62] W. Maity, S. Maity, S. Bera, A. Roy
Emerging roles of PETase and MHETase in the biodegradation of plastic wastes
Appl. Biochem. Biotechnol., 193 (8) (2021), pp. 2699-2716, 10.1007/s12010-021-03562-4 ↗
View in Scopus ↗ Google Scholar ↗

[63] F. Kawai, T. Kawase, T. Shiono, H. Urakawa, S. Sukigara, C. Tu, M. Yamamoto
Enzymatic hydrophilization of polyester fabrics using a recombinant cutinase Cut 190 and their surface characterization
Journal of Fiber Science and Technology, 73 (1) (2017), pp. 8-18, 10.2115/fiberst.fiberst.2017-0002 ↗
Google Scholar ↗

[64] S.K. Kale, A.G. Deshmukh, M.S. Dudhare, V.B. Patil
Microbial degradation of plastic: a review
J. Biochem. Technol., 6 (2) (2015), pp. 952-961, 10.17140/phoj-4-136 ↗
Google Scholar ↗

[65] K. Kathiresan
Polythene and Plastics-degrading microbes from the mangrove soil
Rev. Biol. Trop., 51 (3–4) (2003), pp. 629-633
Retrieved
Accessed 29th May 2022
View in Scopus ↗ Google Scholar ↗

[66] R. Vignesh, R.C. Deepika, P. Manigandan, R. Janani
Screening of plastic degrading microbes from various dumped soil samples
Int Res J Eng Tech, 3 (4) (2016), pp. 2493-2498
Google Scholar ↗

[67] S. Yoshida, K. Hiraga, I. Taniguchi, K. Oda
Ideonella sakaiensis, PETase, and MHETase: from identification of microbial PET degradation to enzyme characterization
Methods in Enzymology, 648, Academic Press (2021), pp. 187-205, 10.1016/bs.mie.2020.12.007 ↗
View PDF View article View in Scopus ↗ Google Scholar ↗

[68] G.J. Palm, L. Reisky, D. Böttcher, H. Müller, E.A. Michels, M.C. Walczak, ..., G. Weber
Structure of the plastic-degrading Ideonella sakaiensis MHETase bound to a substrate
Nat. Commun., 10 (1) (2019), pp. 1-10, 10.1038/s41467-019-09326-3 ↗
Google Scholar ↗

[69] R.A. Wilkes, L. Aristilde
Degradation and metabolism of synthetic plastics and associated products by Pseudomonas sp.: capabilities and challenges
J. Appl. Microbiol., 123 (3) (2017), pp. 582-593, 10.1111/jam.13472 ↗
View in Scopus ↗ Google Scholar ↗

[70] Y. Yang, W. Liu, Z. Zhang, H.P. Grossart, G.M. Gadd
Microplastics provide new microbial niches in aquatic environments
Appl. Microbiol. Biotechnol., 104 (15) (2020), pp. 6501-6511, 10.1007/s00253-020-10704-x ↗
View in Scopus ↗ Google Scholar ↗

[71] B. Zhang, X. Yang, L. Chen, J. Chao, J. Teng, Q. Wang
Microplastics in soils: a review of possible sources, analytical methods and ecological impacts
J. Chem. Technol. Biotechnol., 95 (8) (2020), pp. 2052-2068, 10.1002/jctb.6334 ↗
View in Scopus ↗ Google Scholar ↗

[72] X. Zhang, Y. Leng, X. Liu, K. Huang, J. Wang

Microplastics' pollution and risk assessment in an urban river: a case study in the Yongjiang River, Nanning City, South China

Exposure and Health, 12 (2) (2020), pp. 141-151, 10.1007/s12403-018-00296-3 ↗

Google Scholar ↗

[73] K.L. Rogers, J.A. Carreres-Calabuig, E. Gorokhova, N.R. Posth

Micro-by-micro interactions: how microorganisms influence the fate of marine microplastics

Limnology and Oceanography Letters, 5 (1) (2020), pp. 18-36, 10.1002/lol2.10136 ↗

View in Scopus ↗ Google Scholar ↗

[74] H.S. Zurier, J.M. Goddard

Biodegradation of microplastics in food and agriculture

Curr. Opin. Food Sci., 37 (2021), pp. 37-44, 10.1016/j.cofs.2020.09.001 ↗

View PDF View article View in Scopus ↗ Google Scholar ↗

[75] R. Wei, N. Wierckx

Editorial: microbial degradation of plastics

Front. Microbiol., 12 (2021), Article 635621, 10.3389/fmicb.2021.635621 ↗

View in Scopus ↗ Google Scholar ↗

[76] R. Wei, N. Wierckx

Microbial degradation of plastics

Front. Microbiol., 12 (2021), 10.3389/fmicb.2021.635621 ↗

Google Scholar ↗

[77] J. Yuan, J. Ma, Y. Sun, T. Zhou, Y. Zhao, F. Yu

Microbial degradation and other environmental aspects of microplastics/plastics

Sci. Total Environ., 715 (2020), Article 136968, 10.1016/j.scitotenv.2020.136968 ↗

View PDF View article View in Scopus ↗ Google Scholar ↗

[78] J. Purohit, A. Chattopadhyay, B. Teli

Metagenomic exploration of plastic degrading microbes for biotechnological application

Curr. Genom., 21 (4) (2020), pp. 253-270, 10.2174/1389202921999200525155711 ↗

View in Scopus ↗ Google Scholar ↗

[79] S. Oberbeckmann, D. Bartosik, S. Huang, J. Werner, C. Hirschfeld, D. Wibberg, ..., S. Markert

Genomic and proteomic profiles of biofilms on microplastics are decoupled from artificial surface properties

Environ. Microbiol., 23 (6) (2021), pp. 3099-3115, 10.1111/1462-2920.15531 ↗

View in Scopus ↗ Google Scholar ↗

[80] S. Yoshida, K. Hiraga, T. Takehana, I. Taniguchi, H. Yamaji, Y. Maeda, ..., K. Oda

A bacterium that degrades and assimilates poly (ethylene terephthalate)

Science, 351 (6278) (2016), pp. 1196-1199, 10.1126/science.aad6359 ↗

View in Scopus ↗ Google Scholar ↗

[81] D. Danso, J. Chow, W.R. Streit

Plastics: environmental and biotechnological perspectives on microbial degradation
Appl. Environ. Microbiol., 85 (19) (2019), Article e01095-19, 10.1128/AEM.01095-19 ↗
View in Scopus ↗ Google Scholar ↗

[82] L.D.F. Alves, C.A. Westmann, G.L. Lovate, G.M.V. de Siqueira, T.C. Borelli, M.E. Guazzaroni
Metagenomic approaches for understanding new concepts in microbial science
International Journal of Genomics, 2018 (2018), 10.1155/2018/2312987 ↗
Google Scholar ↗

[83] K.N. Lam, J. Cheng, K. Engel, J.D. Neufeld, T.C. Charles
Current and future resources for functional metagenomics
Front. Microbiol., 6 (2015), p. 1196, 10.3389/fmicb.2015.01196 ↗
Google Scholar ↗

[84] I.V. Kirstein, A. Wichels, E. Gullans, G. Krohne, G. Gerdts
The plastisphere–uncovering tightly attached plastic “specific” microorganisms
PLoS One, 14 (4) (2019), Article e0215859, 10.1371/journal.pone.0215859 ↗
View in Scopus ↗ Google Scholar ↗

[85] C. De Tender, L.I. Devriese, A. Haegeman, S. Maes, J. Vangeyte, A. Cattrijsse, ..., T. Ruttink
Temporal dynamics of bacterial and fungal colonization on plastic debris in the North Sea
Environ. Sci. Technol., 51 (13) (2017), pp. 7350-7360, 10.1021/acs.est.7b00697 ↗
View in Scopus ↗ Google Scholar ↗

[86] P. He, L. Chen, L. Shao, H. Zhang, F. Lü
Municipal solid waste (MSW) landfill: a source of microplastics? -Evidence of microplastics in landfill leachate
Water Res., 159 (2019), pp. 38-45, 10.1016/j.watres.2019.04.060 ↗
View PDF View article View in Scopus ↗ Google Scholar ↗

[87] K. Thakur, M. Chownk, V. Kumar, A. Purohit, A. Vashisht, V. Kumar, S.K. Yadav
Bioprospecting potential of microbial communities in solid waste landfills for novel enzymes through metagenomic approach
World J. Microbiol. Biotechnol., 36 (3) (2020), p. 34, 10.1007/s11274-020-02812-7 ↗
View in Scopus ↗ Google Scholar ↗

[88] G.G.N. Thushari, J.D.M. Senevirathna
Plastic pollution in the marine environment
Heliyon, 6 (8) (2020), Article e04709, 10.1016/j.heliyon.2020.e04709 ↗
View PDF View article View in Scopus ↗ Google Scholar ↗

[89] J.A. Bryant, T.M. Clemente, D.A. Viviani, A.A. Fong, K.A. Thomas, P. Kemp, D.M. Karl, A.E. White, E.F. DeLong
Diversity and activity of communities inhabiting plastic debris in the North Pacific gyre
mSystems, 1 (3) (2016), 10.1128/mSystems.00024-16 ↗
Google Scholar ↗

[90] I.E. Meyer-Cifuentes, J. Werner, N. Jehmlich, S.E. Will, M. Neumann-Schaal, B. Öztürk

Synergistic biodegradation of aromatic-aliphatic copolyester plastic by a marine microbial consortium
Nat. Commun., 11 (1) (2020), p. 5790, 10.1038/s41467-020-19583-2 ↗

View in Scopus ↗ Google Scholar ↗

[91] C. Sonnendecker, J. Oeser, P.K. Richter, P. Hille, Z. Zhao, C. Fischer, H. Lippold, P. Blázquez-Sánchez, F. Engelberger, C.A. Ramírez-Sarmiento, T. Oeser, Y. Lihanova, R. Frank, H.-G. Jahnke, S. Billig, B. Abel, N. Sträter, J. Matysik, W. Zimmermann
Low carbon footprint recycling of post-consumer PET plastic with a metagenomic polyester hydrolase
ChemSusChem, 15 (9) (2022), Article e202101062, 10.1002/cssc.202101062 ↗

View in Scopus ↗ Google Scholar ↗

[92] M.R. Karim, Y.Q. Zhang, D. Tian, F.J. Chen, F.S. Zhang, C.Q. Zou
Genotypic differences in zinc efficiency of Chinese maize evaluated in a pot experiment
J. Sci. Food Agric., 92 (12) (2012), pp. 2552-2559

CrossRef ↗ View in Scopus ↗ Google Scholar ↗

[93] N. Msilini, H. Attia, N. Bouraoui, S. M'rah, R. Ksouri, M. Lachaâl, Z. Ouerghi
Responses of Arabidopsis thaliana to bicarbonate-induced iron deficiency
Acta Physiol. Plant., 31 (4) (2009), pp. 849-853, 10.1007/s11738-009-0318-z ↗

View in Scopus ↗ Google Scholar ↗

[94] R. Hernández-Arenas, A. Beltrán-Sanahuja, P. Navarro-Quirant, C. Sanz-Lazaro
The effect of sewage sludge containing microplastics on growth and fruit development of tomato plants
Environ. Pollut., 268 (2021), Article 115779, 10.1016/j.envpol.2020.115779 ↗

View PDF View article View in Scopus ↗ Google Scholar ↗

[95] M. Pivokonsky, L. Cermakova, K. Novotna, P. Peer, T. Cajthaml, V. Janda
Occurrence of microplastics in raw and treated drinking water
Sci. Total Environ., 643 (2018), pp. 1644-1651, 10.1016/j.scitotenv.2018.08.102 ↗

View PDF View article View in Scopus ↗ Google Scholar ↗

[96] C. Campanale, F. Stock, C. Massarelli, C. Kochleus, G. Bagnuolo, G. Reifferscheid, V.F. Uricchio
Microplastics and their possible sources: the example of Ofanto river in southeast Italy
Environ. Pollut., 258 (2020), Article 113284, 10.1016/j.envpol.2019.113284 ↗

View PDF View article View in Scopus ↗ Google Scholar ↗

[97] J. John, A.R. Nandhini, P. Velayudhaperumal Chellam, M. Sillanpää
Microplastics in mangroves and coral reef ecosystems: a review
Environ. Chem. Lett. (2021), pp. 1-20, 10.1007/s10311-021-01326-4 ↗

Google Scholar ↗

[98] H. Yu, X. Zhang, J. Hu, J. Peng, J. Qu
Ecotoxicity of polystyrene microplastics to submerged carnivorous Utricularia vulgaris plants in freshwater ecosystems
Environ. Pollut., 265 (2020), Article 114830, 10.1016/j.envpol.2020.114830 ↗

View PDF View article View in Scopus ↗ Google Scholar ↗

[99] X. Jiang, H. Chen, Y. Liao, Z. Ye, M. Li, G. Klobučar
Ecotoxicity and genotoxicity of polystyrene microplastics on higher plant Vicia faba
Environ. Pollut., 250 (2019), pp. 831-838, 10.1016/j.envpol.2019.04.055 ↗
View PDF View article View in Scopus ↗ Google Scholar ↗

[100] J. Brahney, M. Hallerud, E. Heim, M. Hahnenberger, S. Sukumaran
Plastic rain in protected areas of the United States
Science, 368 (6496) (2020), pp. 1257-1260, 10.1126/science.aaz5819 ↗
View in Scopus ↗ Google Scholar ↗

[101] G. Chen, Q. Feng, J. Wang
Mini-review of microplastics in the atmosphere and their risks to humans
Sci. Total Environ., 703 (2020), Article 135504, 10.1016/j.scitotenv.2019.135504 ↗
View PDF View article View in Scopus ↗ Google Scholar ↗

[102] C.E. Enyoh, A.W. Verla, E.N. Verla, F.C. Ibe, C.E. Amaobi
Airborne microplastics: a review study on method for analysis, occurrence, movement and risks
Environ. Monit. Assess., 191 (11) (2019), pp. 1-17, 10.1007/s10661-019-7842-0 ↗
Google Scholar ↗

[103] K. Zhang, H. Shi, J. Peng, Y. Wang, X. Xiong, C. Wu, P.K. Lam
Microplastic pollution in China's inland water systems: a review of findings, methods, characteristics, effects, and management
Sci. Total Environ., 630 (2018), pp. 1641-1653, 10.1016/j.scitotenv.2018.02.300 ↗
View PDF View article View in Scopus ↗ Google Scholar ↗

[104] N. Basak, S.S. Meena
Exploring the plastic degrading ability of microbial communities through metagenomic approach
Mater. Today: Proc. (2022), 10.1016/j.matpr.2022.02.308 ↗
Google Scholar ↗

[105] A. Bollinger, S. Thies, E. Knieps-Grünhagen, C. Gertzen, S. Kobus, A. Höppner, ..., K.E. Jaeger
A novel polyester hydrolase from the marine bacterium Pseudomonas aestusnigri–structural and functional insights
Front. Microbiol., 11 (2020), p. 114, 10.3389/fmicb.2020.00114 ↗
View in Scopus ↗ Google Scholar ↗

[106] I. Gaytán, A. Sánchez-Reyes, M. Burelo, M. Vargas-Suárez, I. Liachko, M. Press, S. Sullivan, M.J. Cruz-Gómez, H. Loza-Tavera
Degradation of recalcitrant polyurethane and xenobiotic additives by a selected landfill microbial community and its biodegradative potential revealed by proximity ligation-based metagenomic analysis
Front. Microbiol., 10 (2019), p. 2986, 10.3389/fmicb.2019.02986 ↗
Google Scholar ↗

[107] C.N. Reddy, J.A. Modestra, A.N. Kumar, S.V. Mohan
Waste Remediation Integrating with Value Addition: Biorefinery Approach Towards Sustainable Bio-based Technologies
V. Kalia (Ed.), Microbial Factories, Springer, New Delhi (2015)
https://doi.org/10.1007/978-81-322-2598-0_14 ↗
Google Scholar ↗

[108] J. Karger-Kocsis, L. Mészáros, T. Bárány
Ground tyre rubber (GTR) in thermoplastics, thermosets, and rubbers
J. Mater. Sci., 48 (1) (2013), pp. 1-38, 10.1007/s10853-012-6564-2 ↗
View in Scopus ↗ Google Scholar ↗

[109] X. Peng, M. Chen, S. Chen, S. Dasgupta, H. Xu, K. Ta, ..., S. Bai
Microplastics contaminate the deepest part of the world's ocean
Geochem. Perspect. Lett, 9 (2018), pp. 1-5, 10.7185/geochemlet.1829 ↗
View in Scopus ↗ Google Scholar ↗

[110] L.J. Pinnell, J.W. Turner
Shotgun metagenomics reveals the benthic microbial community response to plastic and bioplastic in a coastal marine environment
Front. Microbiol., 1252 (2019), 10.3389/fmicb.2019.01252 ↗
Google Scholar ↗

[111] S. Venkata Mohan, G.N. Nikhil, P. Chiranjeevi, C. Nagendranatha Reddy, M.V. Rohit, A.N. Kumar, O. Sarkar
Waste biorefinery models towards sustainable circular bioeconomy: Critical review and future perspectives
Bioresour Technol., 215 (2016 Sep), pp. 2-12, 10.1016/j.biortech.2016.03.130 ↗
Epub 2016 Mar 29. PMID: 27068056
View PDF View article View in Scopus ↗ Google Scholar ↗

[112] L. Ufarté, É. Laville, S. Duquesne, G. Potocki-Veronese
Metagenomics for the discovery of pollutant degrading enzymes
Biotechnol. Adv., 33 (8) (2015), pp. 1845-1854, 10.1016/j.biotechadv.2015.10.009 ↗
View PDF View article View in Scopus ↗ Google Scholar ↗

[113] X.F. Wei, M.S. Hedenqvist, L. Zhao, A. Barth, H. Yin
Risk for the release of an enormous amount of nanoplastics and microplastics from partially biodegradable polymer blends
Green Chem., 24 (22) (2022), pp. 8742-8750
View article CrossRef ↗ View in Scopus ↗ Google Scholar ↗

[114] G.S. Zhang, Y.F. Liu
The distribution of microplastics in soil aggregate fractions in southwestern China
Sci. Total Environ., 642 (2018), pp. 12-20, 10.1016/j.scitotenv.2018.06.004 ↗
View PDF View article View in Scopus ↗ Google Scholar ↗

[115] J. Zrimec, M. Kokina, S. Jonasson, F. Zorrilla, A. Zelezniak, Plastic-degrading potential across the global microbiome correlates with recent pollution trends, mBio. 2021 Oct 26;12(5):e0215521, doi:10.1128/mBio.02155-21. Epub 2021 Oct 26. PMID: 34700384; PMCID: PMC8546865.

Google Scholar ↗

[116] P.W.S. Joyce, L.J. Falkenberg, Microplastics, both non-biodegradable and biodegradable, do not affect the whole organism functioning of a marine mussel, Sci. Total Environ. 2022 Sep 15;839:156204. doi:10.1016/j.scitotenv.2022.156204. Epub 2022 May 24. PMID: 35623533.

Google Scholar ↗

Cited by (2)

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Review

Valorization of agro-industrial biowaste to biomaterials: An innovative circular bioeconomy approach

Bishwambhar Mishra [a] [1], Yugal Kishore Mohanta [b] [1], C. Nagendranatha Reddy [a], S. Deepak Mohan Reddy [a], Sanjeeb Kumar Mandal [a], Rajasri Yadavalli [a], Hemen Sarma [c]

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Abstract

Population growth and increased food demand have increased global waste. Converting biowaste into biomaterials has been the subject of extensive research, and various strategies have been investigated. Microorganisms can ferment a large amount of useable carbon in biowaste from the food and agricultural industries to produce valuable goods. Those who advocate for a "circular bioeconomy" aim to establish a system that eliminates waste by recycling and reusing its components. Various novel biomaterials, such as collagen, chitosan, pullulan, hydroxyapatite, cellulose, gelatin, and carbon-based nanocomposites, can be derived from biowaste through bioprocessing. This paper demonstrates to what extent we have succeeded in transforming biowaste into biomaterials with commercial value. Furthermore, this article discusses the most recent developments in waste valorization and circular economy concepts and the promising future of transforming agro-industrial wastes into functional biomaterials and their applications.

Previous Next

Keywords

Biomaterials; Volarization; Biowaste; Bioeconomy; Sustainability

1. Introduction

Waste management is a major concern in today's society. Population growth, industrial expansion, and widespread economic prosperity are just a few of the factors that have contributed to the accumulation of waste. The World Bank estimates annual waste output at 2.01 billion metric tons, with a potential increase to 3.40 billion metric tons by 2050 (Kaza et al., 2018). Most trash is burned, chemically treated, dumped into waterways, or buried in landfills. Forty percent of garbage is simply dumped with no further processing. Poor waste disposal is hazardous to people's health and the environment because it pollutes the air, water, and soil and facilitates disease transmission (Tyagi & Kumar, 2021). People are now considering how productive various waste materials can be due to new technologies and standards focusing on making energy from waste. However, there are a few drawbacks that reduce environmental sustainability and waste management efficiency. Agro-industrial waste, produced when agricultural items are processed industrially, accounts for a significant portion of global garbage. Liquid and solid waste streams from processing, such as peels, seeds, pomace, and byproduct streams, are high in biomass and contain a wide range of essential nutrients. These wastes could be used as low-cost and efficient raw materials to create value-added products, such as pigments, bioactive compounds, enzymes, and biofuels (Mishra et al., 2018, 2019).

Industrial biotechnology has enabled the development of new methods of reusing waste that are more cost-effective and long-lasting than older methods. Submerged and solid-state fermentation are biotransformation processes that convert agro-industrial byproducts into marketable goods. In addition to using waste and addressing environmental issues, wholesale production of augmented goods provides a strategy for boosting the green economy in pursuit of goals for long-term sustainability. Given the Earth's severe difficulties in resource use and waste generation, circular economies (CEs) have been proposed as a solution to shift away from linear systems and toward more cyclical ones. Despite their obvious advantages, fully circular systems are not always self-sustaining (Barros et al., 2021). The circular bioeconomy (CBE) concept was developed on the premise that shifting to a renewable-resource-based economy could reduce adverse environmental effects (Mishra et al., 2023).

Bioeconomy (BE) is driven by the manufacturing and transforming sustainable natural resources into high-value bio-based products, such as food, feed, medicines, biochemicals, and electricity (European Commission, 2018). The boldness of organic matter plays a vital role in generating food, fodder, and biofuels for transportation (de Souza & Pacca, 2021) and power, thermal energy, and the construction of structures (Barros et al., 2021). However, all businesses, including those in the BE sector, have had a difficult time in recent years due to the effects of the COVID-19 pandemic on the three pillars of sustainability (Ranjbari et al., 2021). Santagata et al. (2021) discovered a circular bioeconomy strategy for food waste and comprehensively examined the processes involved in recovery and recycling. The primary objectives that have been reported, include improved resource management, prevention of economic losses, the creation of employment opportunities, and the ability to influence stakeholder behavior.

This critical review investigates the current trends and feasibility of integrating biowaste into the circular bioeconomy, while highlighting the potential of bioconversion of agro-industry biowaste into biomaterials *via* microbial factories as a promising domain of the circular economy (Seng et al., 2021; Sze et al., 2020). Therefore, a CE theory is proposed to use renewable resources, emphasizing the importance of inherent wastefulness for environmentally responsible crop management. To better use the waste produced, the agricultural industry has adopted a circular economy to reduce waste production and increase waste value through economically viable methods. Furthermore, several valuable metabolites, energy, and materials may be created by processing agricultural waste, which might be commercialized to enhance bioproduct technologies. With an eye toward a secure future, this research details agricultural biomass production and bioeconomic perspectives.

This paper describes the progress in converting biowaste into biomaterials with marketable properties. The current study summarizes the current state of the art and the promising future of converting agro-industrial wastes into valuable biomaterials and their applications, focusing on waste valorization and the circular bioeconomy.

2. Most commonly available agro-industrial biowaste

Biomass is the main component of biowaste, and it decomposes in aerobic and anaerobic environments (Romero-Güiza et al., 2016). Good biowaste management is essential in protecting the environment and improving living conditions. Furthermore, when combined with value-addition, it has the potential to solve energy and waste management issues while also making money. Table 1 summarizes the benefits and drawbacks of using various biowastes for biomaterials, and the potential challenges.

Table 1. Opportunities and environmental problems of biowaste and its valorization to biomaterials.

Biowaste types	**Opportunity to create value-added products**	**Major environmental concerns**	**Reference**
Paper industry waste	• High organic content • Easily separable, homogeneous, and processed with minimal effort.	• Depending on the pulping method, several waste products may be created. • Open disposal can result in odors and contamination. • High sulfides, bases, and acids disrupt fermentation and necessitate specialized pretreatments.	Kamali & Khodaparast, 2015; Rahman et al., 2014
Food industry waste	• Easy to collect • It can assist in eradicating stench concerns and many health and environment issues. • Food waste like oils can be converted directly into biodiesel using	• Require pretreatment to convert complex polymeric material into free sugars. • Oil characteristics are impacted by increased operational temperatures and produce free fatty acids that affect biodiesel profitability. • Possibly excessive in salts, which would interfere with fermentation using microbes	Bernstad Saraiva Schott et al., 2016; Mishra et al., 2019, 2022; Ravindran & Jaiswal, 2016
Animal foods processing	• With its abundant organic material and microbial flora, bio waste can be utilized	• Anaerobic digestion requires a large tank and processing	Nagai et al., 2001; Nouri et al., 2016;

Biowaste types	Opportunity to create value-added products	Major environmental concerns	Reference
waste	directly for anaerobic digestion to generate biogas. By trans esterifying cattle oils and fats with alcohol, biofuel can be made immediately	vessel, from which Fumes could result. • Recovering fats and oil from leftover meat necessitates pre-processing steps.	Santagata et al., 2021
Municipal solid waste	• It can be directly used in anaerobic digestion processes. Greywater has an abundant supply of organic and nutrient -rich matter for algae development, which enhances waste management and quality of life.	• There is much odor, so it needs to be done in a special, sealed-off area.	Ebrahimian et al., 2020a; Lee et al., 2020; Stąsiek & Szkodo, 2020

2.1. Paper industry wastes

Pulp and paper are the third-biggest pollutants (Rahman et al., 2014). Pulping destroys the wood bonds. The paper industry employs chemical and mechanical methods to convert wood into pulp. The pulping process influences pulp quality and yield. The pulp for newspaper and tissue paper is produced mechanically. Sulfite pulping is used to produce specialty rayon, paper, and photographic film. Containerboard pulp is produced chemo-mechanically (Kamali & Khodaparast, 2015; Rahman et al., 2014). Pulping processes generate diterpenes, chlorinated resin acids, juvabione, and unsaturated fatty acids (Kamali & Khodaparast, 2015). Pulping, deinking, and wastewater treatment yield solid waste. For example, 1 ton of paper yields 40–50 kg of sludge (Kamali & Khodaparast, 2015). These organic-rich industrial wastes could harm marine and terrestrial ecosystems if dumped in the open environment. These wastes can be used immediately in anaerobic digestion and other waste-to-energy technologies (Rahman et al., 2014).

2.2. Food industry waste

Food processing units, restaurants, and grocery stores have proliferated to match population expansion. Progress in waste management has led to food waste accumulation (Ravindran & Jaiswal, 2016). Breweries, meat processing plants, candy factories, and vegetable oil plants all produce large amounts of waste (Ravindran & Jaiswal, 2016). Non-standard fruits, fruit peels, pulp, and filter sludge are examples of solid wastes. Starch, sugar, and solid organic matter are the liquid wastes from washing fruits, vegetables, and meat. After a few uses, cooking oils are discarded. By 2020, the annual production of used cooking oil is expected to reach 18 million tons (da Silva César et al., 2017). Since it does not dissolve in water, it is dumped directly into the environment, which is extremely harmful to the environment. Biorefineries convert food waste into biofuels, enzymes, and nutraceuticals.

2.3. Animal food processing wastes

Dairy and poultry farms in third-world countries generate a lot of animal waste in the form of manure or meat processing byproducts. The animal wastes from meat treatment facilities consist of flesh, fur, tallow, debris, meat, skeletons, and plumes (Bernstad Saraiva Schott et al., 2016). These include things with a lot of organic matter, which can make things smell and, if not treated, can lead to the growth of harmful microorganisms. This natural decomposition mechanism produces methane, a more harmful gas than CO_2. In addition, animal waste tank runoff can contaminate groundwater. As a result, animal waste conversion to biomaterials has gained momentum in the past few years (Santagata et al., 2021).

2.4. Municipal solid wastes

Population growth, urbanization, and economic development increase municipal solid waste (MSW). A resident of a developing or emerging nation produces 100–400 kg of MSW annually. Every ten years, MSW production doubles, reaching 2.2 billion tons by 2025 and 4.2 billion tons by 2050. Mistreatment of MSWs has been documented in Thailand, Bangladesh, India, and China (Ferronato & Torretta, 2019). Governments and waste management bodies in developing and growing countries are facing challenges. MSW is managed through landfills, recycling, and thermal and biological treatments. Waste-to-energy involves merging landfill and waste combustion technologies for energy recovery (Cheng & Hu, 2010; Lee et al., 2020).

3. Biowaste treatment valorization technologies

Because of the state of the economy and the environment, we must all do our part to recycle and reduce waste. Numerous conventional and innovative approaches, along with technologies, are persistently emerging and improving to enable the conversion of waste into valuable resources, such as fuels, biological chemicals, and materials. As a result, a wide range of approaches to modifying and transforming substances can be used, most of which can be classified under the headings of biology and chemistry (Lee et al., 2019).

3.1. Biological conversion technologies

Waste that has undergone a managed transformation by living organisms is said to have undergone a biological treatment process. These also include biochemical conversion processes (Lohri et al., 2017). In contrast to thermochemical transformations, biochemical reactions require far less energy input but move much slower. Traditional biological and chemical processes, such as anaerobic digestion, alcohol fermentation, and photobiological methods, can produce biofuels (Lee et al., 2019; Lohri et al., 2017).

3.1.1. Composting

Composting, or the controlled aerobic breakdown of organic materials, is centuries-old. Compost can be made from various organic solid wastes, including green waste (grass, branches, woodchips, and leaves), agricultural waste, food waste, manure, and even human feces (Lohri et al., 2017). Microbes come in various forms, and they all work together to decompose organic compounds into water, heat, and carbon dioxide. Therefore, it is vital to adjust organic material content, grain size, ventilation, warmth, hydration, and ionic strength to hasten decomposition and generate high-quality compost (Dedinec et al., 2015). In addition, given that this method depends on dynamic microbial activity, it is necessary to monitor the moisture levels of the feedstock and supplement them with water throughout the process (Taiwo et al., 2016). When done correctly, it goes through three stages: (1) the mesophilic phase, (2) the thermophilic phase, and (3) the cooling and maturation phase (Lohri et al., 2017).

3.1.2. Anaerobic digestion

Biomethanation or biomethanization is a robust method for decomposing liquid and solid organic matter by interfering with bacterial activity in an anoxic environment (Vögeli et al., 2014). Anaerobic digestion has expanded beyond its original context in wastewater treatment to include the organic fractionation of agricultural and municipal solid wastes (Jimenez et al., 2015). Industrial food waste (including slaughterhouse waste), sewage sludge, energy crops, and algal biomass are all materials that can be used as anaerobic digestion feedstocks (Romero-Güiza et al., 2016). Fermentation (acidogenesis and acetogenesis), hydrolysis, and methanogenesis are the steps involved in the anaerobic biodegradation of organic materials into CH_4, CO_2, and trace amounts of H_2S. Fermentation employs the simple biomolecules produced during hydrolysis to produce ethanol, acetic acid, volatile fatty acids, and H_2 and CO_2 gas mixtures. Biogas is generated when methanogens metabolize a gas mixture into mainly CH_4 (60%–70%) and carbon dioxide (CO_2) (30%–40%). Methanogenesis is stimulated by several factors, including the primary biomass nutrients (C, N, and P) and the trace elements (iron, zinc, and cobalt) (Lee et al., 2019). Lipid-based biomass hydrolyzes more slowly than carbohydrate- and protein-based biomass but produces more methane overall due to its higher lipid content. Many factors influence biogas yield and energy content, including the nutrient profile of the biomass, temperature, pH, and the rate at which the biomass is loaded. Methanogenesis depends on an ideal operating pH for the formation of CH_4 in biogas. The energy content of biogas increases as its pH increases (due to a gradual increase in NH_3 concentration), as CO_2 is dissolved in the fermentation broth, and as CH_4 concentration increases. An acidic environment and a high working temperature stimulate microbial activity and CH_4 generation (Günerken et al., 2015).

3.1.3. Alcoholic fermentation

Yeast or bacteria are used in the alcoholic fermentation of biomass containing fermentable sugars transformed from the cellulose and hemicellulose of biomass into bioethanol. Microalgae like *Scenedesmus*, *Chlorella*, *Spirulina*, and *Dunaliella* has been discovered to store substantial quantities of glycogen, cellulose, and starch (Lee et al., 2019). These complex polysaccharides can be used as feedstock for bioethanol synthesis. As bacteria have trouble metabolizing polysaccharides, hydrolysis is done before feeding to convert polysaccharides into monosaccharides. Sugars can be hydrolyzed with acids, bases, or enzymes, with the former being the most prevalent. Although sugars can be quickly and easily converted in acidic environments, the benefits of these quick and inexpensive therapies are not without drawbacks. Enzymatic processes are efficient and waste-free, but they are costly and complex (Lee et al., 2019). Hydrolysis efficacy and time can be increased by performing primary cell disruption operations (Günerken et al., 2015). For the raw alcohol (10%–15% ethanol) produced, ethanol concentration *via* distillation is required (Bibi et al., 2017). Thermochemical processes (liquefaction, gasification, or pyrolysis) convert the residual solid waste into valuable byproducts. Scientists are currently investigating the prospect of modifying the DNA of specific microalgal strains to increase their production of lucrative byproducts. One such initiative is based on using photosynthesis to convert CO_2 directly into biofuels via genetic modifications. Along this pathway, no additional energy is needed to synthesize or break down the proteins necessary for storing energy and cellular structure. Plants use the Calvin cycle to generate glucose and other metabolites, in which ribulose-1, 5-bisphosphate, combines with carbon dioxide to form two 3-phosphoglycerates (John et al., 2011). Instead, researchers have been working on implanting genes necessary for ethanol production into cells that produce 3-phosphoglycerate, rerouting the molecule to construct ethanol.

3.1.4. Photobiological hydrogen production

Microalgae have the intrinsic ability to generate hydrogen gas when exposed to light. An enzyme called hydrogenase lowers H^+ to H_2 without oxygen during photosynthesis. As a result, the process emits O_2 gas, which inhibits the hydrogenase enzyme and prevents H_2 gas formation. Consequently, microalgae grown for H_2 generation require anaerobic conditions (Lee et al., 2019). The photosynthetic H_2 of microalgae can be harvested in two ways. First, when light is present, we can take advantage of the simultaneous production of

O_2 and H_2 gas, and the two gases can react. Second, hydrogenase enzymes utilize the electrons released during the oxidation of water molecules to generate hydrogen gas. The second strategy employs a two-stage method: the first cultivates the microalgae under standard conditions, and the second promotes continuous H_2 production in anaerobic and low-sulfur settings. Theoretically, technique one produces more hydrogen gas than technique two, but O_2 quickly stifles H_2 production (Lee etal., 2019). By temporarily activating the PSII system without an aerobic environment, H_2 generation in low-sulfur cultures is perpetuated for extended durations. With a periodic injection of sulfur, cell reconstitution and a threefold increase in total H_2 yield were achieved compared to control cultures with no added sulfur (Kim etal., 2010).

3.1.5. Transesterification (acid/base and enzyme catalysis)

Biodiesel production via transesterification employs three catalysts: acids, bases, and enzymes. In contrast to acid-catalyzed transesterification, base-catalyzed transesterification can produce substantial yields of fatty acid methyl ester quickly and with highly mild reaction conditions, making it a standard industrial process. While enzymatic catalysts are environmentally friendly and produce high-quality results, they still require refinement before being employed in commercial settings. To make biodiesel, a two-step esterification and transesterification method is usually employed. The granular lipid content can be converted into biodiesel utilized in conventional internal combustion engines by *trans*-esterifying triacylglycerols to generate fatty acid alkyl esters (catalyst being acid, base, or lipase). Due to the high energy consumption, significant water and salt demands, and demands on conventional transesterification processes, the development of enzymatic esterification reactions mediated by intra- or extracellular lipases was pursued (El Muller etal., 2014). However, because of their sensitivity to alcohol and heat, enzymes as catalysts often produce lower biodiesel yields than other options. Protein engineering, immobilized enzymes, and whole-cell catalysts are only a few approaches for increasing the efficiency of enzyme catalysis. Nano-MgO, nano-SiO_2, and nano-ZnO (heterogenous catalysts) converted *Mangifera indica* oil into biodiesel. Nano-SiO_2 significantly affected catalytic reactivity and drove reactions to obtain maximal yields because of its highly acidic characteristics (Jadhav & Tandale, 2018). This demonstrates that heterogeneous catalysts are effective in converting feedstocks into biodiesel, which has the added benefit of being recyclable (Sharma etal., 2018). The traditional two-step esterification procedure for making biodiesel from *Pongamia pinnata* crude oil is unnecessary. The same results can be obtained with a one-step direct transesterification process using sequential acid-base catalysis. This procedure was replicated using transesterification-transesterification techniques (Yunus Khan etal., 2018). The 1.5-fold reduction in production time required for biodiesel products is one of the most encouraging aspects of direct transesterification technology.

3.2. Thermochemical conversion of biowaste

At very high temperatures, organic compounds are broken down and reformed into biochar (a solid), syngas (a gas), and oxygen-enriched bio-oil (a liquid) (Lee etal., 2019). Thermochemical conversion typically involves one of three methods: gasification, pyrolysis, or liquefaction. The decision-making process is influenced by biomass feedstock type and quantity, energy output, and environmental considerations (Chen etal., 2015). However, many studies have shown that thermal conversion technology is the best choice for the industry. It employs cutting-edge thermochemical conversion technology, works faster, uses less water, and can convert waste plastics into energy (Uzoejinwa etal., 2018). It has been recognized as a simple and efficient method of producing value-added biofuels.

3.2.1. Torrefaction

Torrefaction is a mild thermochemical process typically occurring between 200°C and 300°C in an airless environment (Shankar Tumuluru et al., 2011). The degradation reactions weaken the fibrous nature of the biomass and increase its carbon content while maintaining a high solid yield (Sarker et al., 2021). Water vapor, smoke, oxygen, and hydrogen are reduced during combustion. When the oxygen-hydrogen ratio decreases, the carbon-hydrogen ratio rises, and thus the calorific value of biomass rises (Patra et al., 2022). The product's high hydrophobicity increases friability (Robbins et al., 2012). Biochar does not decompose or attract microorganisms; hence, it can be stored indefinitely without risk of spoilage. The resulting biomass is sold on the open market as a smokeless, solid fuel and is also utilized in power plants as a co-combustion agent alongside coal (Kundu et al., 2018).

3.2.2. Pyrolysis

The pyrolysis process involves the thermal decomposition of organic waste in anoxic conditions at temperatures ranging from 350°C to 550°C and can even exceed 700°C. Pyrolysis oil (py-oil) or bio-oil, a liquefied fuel produced during the pyrolysis process, can replace fuel oil for heating applications or electricity generation. Producing bio-oil from pyrolysis has the advantage of being a liquid, making it more convenient for storage and transport than the fuel gases created by the gasification process (Dhyani & Bhaskar, 2018). Slow, rapid, and flash pyrolysis are the three main categories of pyrolysis processes, distinguished by their respective temperatures and pressures. Slow pyrolysis at low temperatures, higher heating rates, and a long vapor residence time contribute to biochar production. Contrarily, fast pyrolysis, in which temperatures are kept at or below 500°C and residence periods are kept to a minimum, mainly yields bio-oil.

Flash pyrolysis, in contrast, has a much shorter reaction time and heating rate than rapid pyrolysis. Flash pyrolysis is being thoroughly investigated to create liquid fuel because of the substantial py-oil yields of over 75 wt% and the advantages of minimally charged, energy-efficient, and environmentally benign technology (Lee et al., 2019). Further, work is being done to enhance py-oil quality as a drop-in replacement for regular oil. The physical upgrading of bio-oil by hot vapor filtration reduces its primary particle size, which delays the breaking down of oil over time (Rahman et al., 2018).

3.2.3. Gasification

Biomass gasification, or syngas synthesis, is an oxidation process at high temperatures (Reddy et al., 2016). The byproduct gas is a mixture of several components, including but not limited to CH_4, CO, H_2, and CO_2. Like other thermochemical conversion processes, gasification generates biochar, bio-oil, and combustible syngas. Like other thermochemical conversion processes, gasification generates biochar, bio-oil, and combustible syngas. Syngas can be converted into hydrogen gas, biofuel, biomethane, heat, electricity, and chemicals, among other forms of energy and fuel. Compared to pyrolysis and torrefaction, gasification can be performed in the air at temperatures between 800°C and 1200°C. Gasification is one of the most effective methods for extracting hydrogen gas from biomass (Ahmad et al., 2016). The efficient utilization of biomass feedstocks for heat and electricity generation means that biomass gasification can recover more energy than combustion or pyrolysis. As a result, biowaste gasification is widely regarded as the most effective method of recycling a wide variety of biomass feedstocks, including those from the food and beverage industries and household and industrial waste streams. Gasifying agents like oxygen and steam are used in the gasification process, and several variables influence the outcome of the process. These variables include gasifier type, gasifying agent, catalyst, particle size, equivalency ratio, temperature, catalyst, feedstock, and reactor type (Robbins et al., 2012). In retrospect, the gasification process generates massive amounts of CO_2 and CO from source materials rich in carbon and oxygen, such as municipal and agricultural waste (Watson et al., 2018).

Furthermore, releasing sulfur as H_2S complicates gas separation and treatment, necessitating gas treatment techniques for feedstock with high sulfur content. According to a study by Salimi et al. (2018) on energy production from lignocellulosic waste, hydrothermal gasification techniques utilize new alloyed precursors built on activated graphene and carbon nanosheets. Metal-based catalysts accelerating the reforming reaction can increase hydrogen and methane generation (Salimi et al., 2018). By heating and maintaining high temperatures with external energy, plasma gasification can convert potentially dangerous organic matter, primarily into syngas and ash. Bandages, biological waste (cytotoxic medicines, antibiotics), and laboratory trash containing biomolecules or organisms are all medically related products that can be treated by the plasma gasification method (Messerle et al., 2018).

3.2.4. Liquefaction

Liquefaction processes generate bio-oils at low temperatures and high pressures, with or without catalysts and hydrogen. Hydrothermal liquefaction (HTL) is a proven method for converting biomass into bio-oil by employing subcritical water at temperatures between 250°C and 374°C and pressures between 40 and 220 bars. Chemicals dissolved in water, solid sediments, and gases and the decomposition and repolymerization reactions involved in bio-oil conversion are all components of HTL processes (Dimitriadis & Bezergianni, 2017). High-moisture-content biomass is commonly used in the HTL process because it reduces the need for a drying or dewatering step, resulting in cost savings. As a result, biomass feedstocks with appropriate moisture content, such as algae and woody biomass, are ideal for bio-oil synthesis. Due to its composition, which consists primarily of hemicellulose (15%–35%), lignin (20%–35%), and cellulose (30%–50%), woody biomass is an appropriate feedstock for HTL. Both the presence of a catalyst and the solvent used affect the amount of bio-oil extracted from woody biomass. Since deep eutectic solvents are advantageous in many ways, including being simple to produce, non-toxic, and stable at low temperatures, Alhassan employed them as a stimulant in the hydrothermal transformation (HTL) of deoiled Jatropha cake. Approximately 41%–54% of the high-energy bio-crude was reportedly recovered in the study (Alhassan et al., 2016). Another study led by Costanzo et al. investigated the extraction of bio-crude oil from algae. They employed a two-step HTL process, first employing a low-temperature HTL and then a high-temperature HTL in conjunction with hydrodenitrogenation and hydrodeoxygenation catalysts. The resulting crude was comparable to conventional gasoline (Costanzo et al., 2016).

3.3. Advanced and hybrid conversion technologies

3.3.1. Advanced HiTAG/HiTSG technology for efficient conversion of biomass and municipal waste

An innovative new method called high-temperature airflow and air/steam (HiTAG/HiTSG) thermochemical transformation of solid waste from municipalities into biofuels, such as hydrogen, syngas, and electricity, has the potential to have significant environmental advantages (Stsiek et al., 2020). Many scientific institutions have active research and development programs to maximize the use of various types of biomass and municipal waste (Oumer et al., 2018). High-temperature conversion technologies can achieve more than 90% conversion efficiencies and manage a wide range of biomass and waste streams. Drying, pyrolysis, gasification, and combustion are the main physicochemical processes used in heat conversion (Fasolini et al., 2019). Gasification is a more effective and cleaner alternative to direct incineration for converting biomass and MSW to fuel. In contrast, if cutting-edge, low-cost ideas like HiTAG were developed, they could aid in mitigating environmental damage. This processing facility includes a ceramic regenerator to heat the feed gas to the proper temperature, a steam generator, an H_2 separation ceramic membrane, and a gas cleaning machine, among other components. A small preheater provides a high-temperature (up to 1600°C) air or air-steam mixture to aid the transformation. Almost any dry organic matter can be gasified to produce a clean-burning fuel at high temperatures and pressures (HiTAG/HiTSG) (Li et al., 2019). This cutting-edge method could replace fossil fuels in most applications and reduce greenhouse gas emissions (Stsiek et al., 2020). It aims to achieve high-level thermal conversion of biomass and waste to fuel gas under various situations.

3.3.2. Hybrid thermo-biochemical process for adept lignocellulosic biomass conversion

Traditionally, lignocellulosic biomass was processed either biochemically, by converting biomass into reduced sugars through pre-treatment and microbial fermentation to yield fuel products, or thermochemically, by pyrolysis or gasification to yield intermediate products such as syngas or bio-oil for use in the production of fuels and chemicals (subjective to upgradation). Another option is hybrid treatments, such as a sequential thermochemical–biochemical approach (Shen et al., 2015). Depending on the thermochemical process mode chosen, the blended thermochemical–biochemical process may begin with accelerated biomass pyrolysis to pyrolytic substrates or with microbial fermentation of feedstock to syngas. Hybrid methods pave the way to advanced biofuels that perform similarly to petroleum-based transportation blends. Hybrid methods combine the best features of traditional thermochemical and biochemical approaches while minimizing their drawbacks. Since thermochemical methods can overcome biomass resistance, there is no need for time-consuming and costly pre-treatment procedures or enzyme combinations. It can convert any biomass into fermentable intermediates, independent of its composition (Daniell et al., 2012). In addition, microbial fermentation can be easily scaled up since it can be done effectively in ambient conditions. Fast pyrolysis is a phase in the pyrolysis-fermentation process that yields primitive bio-oil and can be done close to the biomass production facility. Furthermore, unwanted oxygenates, such as polysaccharides and organic acids, can be subjected to microbial fermentation to generate fuels and chemicals, and undefined biofuels can be transformed into drop-in hydrocarbon fuels (Bridgwater, 2012).

3.3.3. Integrative treatment process for solid organic waste

MSW, which includes food scraps, yard trimmings, and sewage sludge, is produced in massive quantities by large urban areas worldwide. Rising energy demand and a lack of landfill space are major global challenges (Bernstad Saraiva Schott et al., 2016). Incineration can lessen MSW output but also generate much ash that must be managed. Anaerobic digestion, a low-cost method for treating organic waste and recovering bioenergy, can also be used under anoxic conditions to convert organic matter into biogas (20%–40% CO_2 and 50%–70% CH_4) (Garfí et al., 2016). However, anaerobic digestion (AD) can only treat organic waste broken down by microorganisms, like food scraps, animal manure, and sewage sludge.

Furthermore, natural breakdown by AD is not economically practical because refractory materials like wood contain high levels of lignin, cellulose, and hemicellulose that must be removed through costly pre-treatments (Romero-Güiza et al., 2016). For the most part, carbonaceous solid wastes can be treated, and thermal energy can be generated through thermal processes, such as gasification. In contrast to incineration, which only recovers thermal energy, gasification can convert all types of carbon-containing solid waste into marketable gases (CO, CO_2, H_2, and CH_4) and other significant commodities (Watson et al., 2018). Therefore, the development of a hybrid system is required to process various MSW types and efficiently recover energy. Fig. 1 outlines the various sources of biowaste and their valorization techniques across biowaste and technology boundaries.

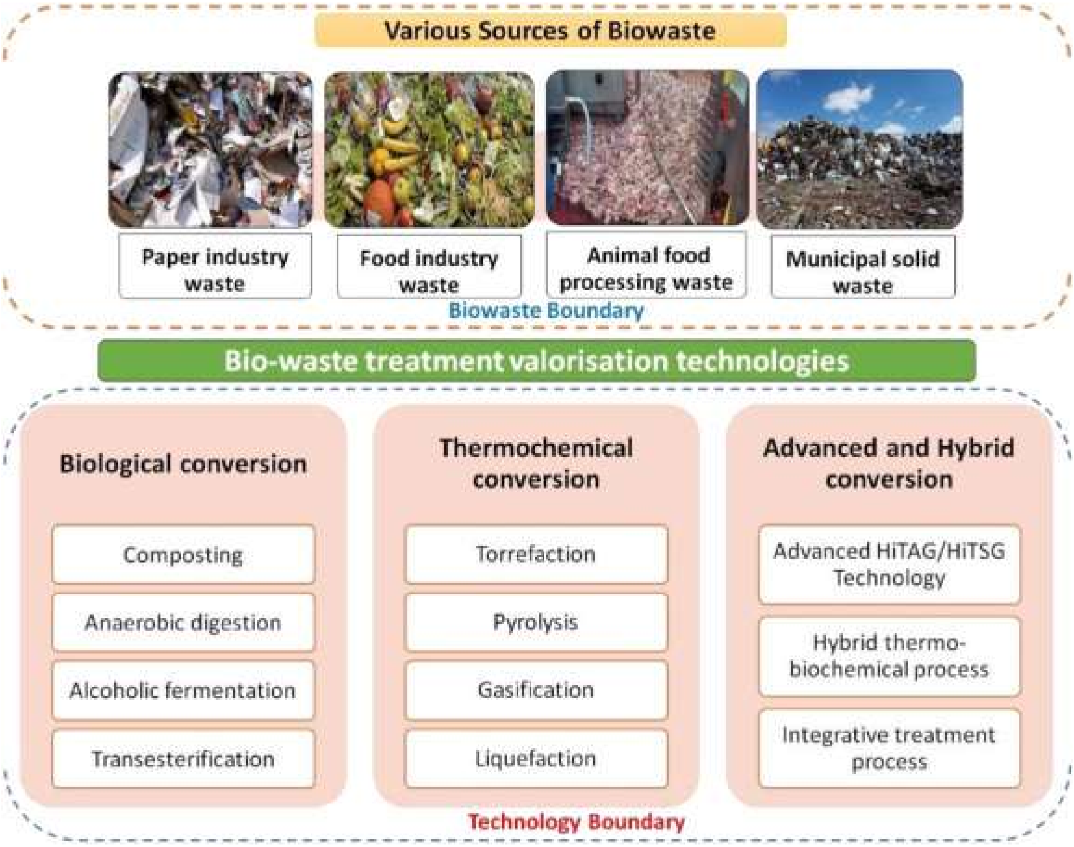

Fig. 1. Outline of potential origins of biowastes and available methods of valorization to obtain value-added products.

AD and gasification make it easier to convert trash into energy using a distributed energy system. A decentralized waste-to-energy system can manage multiple types of solid wastes that are energy-efficient and inexpensive to transport. Waste treatment solutions such as dispersed anoxic gasification/digestion stations and monolithic incineration plants present a promising and appealing approach to better waste management (Zhang et al., 2018). Researchers developed a system that converts waste into biological and thermal energy using a gasifier and a distributed AD reactor. The decentralization potential and size of waste facilities in a hybrid conversion system vary depending on resource availability, spatial constraints, and urban planning. A pilot study used a 1000L AD reactor to convert biodegradable food waste into biogas. A 10kW gasifier was used to process the dry solid waste, and producer gas was obtained from wood chips. Biogas was mixed with product gas and used in other applications that required more heat. During gasification, the waste heat was used to warm the mesophilic AD, creating an internal heat recovery mechanism that made biodegradation possible (Zhang et al., 2018). However, unified waste-to-energy schemes have yet to be studied to determine how underlying heat recovery systems affect energy usage efficiency.

4. Biowaste to biomaterials

Biomaterials are developed to fabricate biomedical devices that perform the same or similar functions as the human body. For direct contact with living organisms, biomaterials must meet stringent requirements. These include functionalization, therapeutic acceptability (nontoxicity, non-allergenicity, non-hypersensitivity), tensile stability, optimum volume and compactness, and cost-effectiveness. The generation of such chemicals, whether from organic materials or recyclable scraps, is a significant problem under investigation in various ways. This section describes the production of various biowaste-based products. Fig.2 illustrates the conversion of different groups of biowastes into specific functional biomaterials.

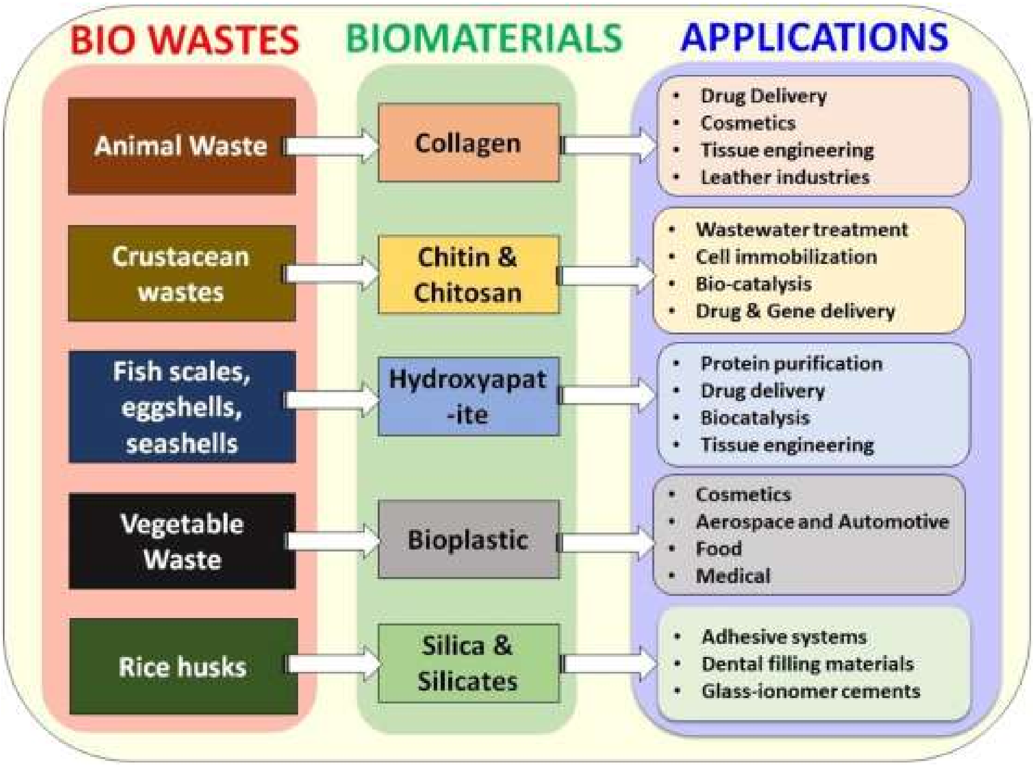

Fig.2. Systematic look at how biowaste is turned into biomaterials and what it can be used for.

4.1. Collagen and collagen-based biopolymers

Collagen can be recovered from a variety of meat processing wastes, most notably pig flesh (46%), bovine hides (29%), and swine and cattle bones (23%), which account for 30% of mammal protein content. Collagen contains glycine at a 33% concentration and a high proportion of proline and hydroxyproline residues (23% of the total amino acid composition). Making gelatin involves heating collagen until it becomes gelatinous. It is inexpensive and widely available. Casting, extrusion, and electrospinning are just some of the methods developed to use this material's biodegradability, pliability, and moisture/oxygen barrier qualities, all of which make it ideal for use in food and medical applications (Gómez-Guillén etal., 2011).

Collagen types I, II, and IV have been successfully isolated from animal skin, bone, scale, and cartilage using an environmentally friendly method that also adheres to the European Union's zero-waste goal. Combining mechanical processes, including pH modification, homogenization, and sonication, with acids, saline, and enzymatic processes, allows collagen to be successfully recovered and processed from fish, echinoderms, and jellyfish waste. Many marine animals, particularly dinoflagellates, cephalopods, starfish, jellyfish, and various fish, have had collagen type I isolated from their tissues. The qualities of marine collagen include excellent film-forming ability, cytocompatibility, minimal allergenicity, significant environmental friendliness, and cell growth potential. These qualities are useful in nutraceuticals, cosmetics, and biomedicine as drug delivery vehicles or wound dressings. Collagen is desirable for texturizing, coarsening, and gel production due to its high-water absorption capacity (Gómez-Guillén etal., 2011).

Keratin, collagen, elastin, and fibrin are all fibrillar proteins found in living creatures. For example, fibrinogen (fibrin precursor protein)-rich blood can account for 4%–7.5% of an animal's total weight. In comparison, the protein content of blood varies by species but rarely exceeds 30% (Kerton et al., 2013). Collagen is the most abundant protein in mammals, accounting for more than 30% of total protein content.

Collagens utilized in the commercial sector are extracted using enzymes from animal muscle tissue, which employs acid, essential, or balanced solubilization techniques. However, these procedures are costly because of the low to medium extraction yields and the collagen degradation during the process. For instance, enzymes may split the cross-linked terminal region of collagen, producing feeble mimics of healthy cells. As a result, biowastes, specifically the organic portion of fish waste have been investigated as a cheap and environmentally friendly source of collagen in the search for ways to increase outputs and formulations (Gómez-Guillén et al., 2011; Katarzyna et al., 2020; Shenoy et al., 2022).

4.2. Chitin and chitosan-derived biomaterials

The aquaculture industry generates much biowaste, which might be used as a source of raw materials to make things like chitin and chitosan, which have commercial uses. Multiple studies have demonstrated the efficacy of bacterial proteases in deproteinization—enzymatic deproteinization of mineralized shrimp waste results in chitin and a protein hydrolysate rich in nutrients. Chitosan is theoretically created annually, mainly from leftover shrimp, fish scales, and crab shells. With rising fisheries, aquaculture, and seafood consumption comes a corresponding rise in biowaste that can be recovered economically as competent polymers (Oliveira Cavalheiro et al., 2007). A crustacean shell comprises about 20% calcium and magnesium carbonate, 20% protein, and 15% chitin (Kerton et al., 2013). Chitin and its primary metabolite, chitosan, are examples of natural amino polysaccharide polymers with biomaterial potential. Chitin from crustacean debris contains N_2, contrary to many other biomass types, and is frequently used in the pharmaceutical, CO_2 capture, or fabric industries to emulsify food ingredients. It is advertised as a supplement that reduces inflammation, promotes weight loss, lowers cholesterol, and balances blood pressure. Biodegradable polymers can be produced from chitosan. Chitin is found in 13.5%–43.8% of shrimp shell waste (Karnaouri et al., 2019) and 4%–37% of squid shell waste. It is estimated that between 16% and 20% of chitin from crabs and lobsters can be saved (Gogoi & Hazarika, 2017).

Commercial chitin is derived from crustacean byproducts of the fishing industry. The most frequent contributors are krill, lobster, prawns, crabs, and shrimp carapaces. Chitin makes up 20%–30% of the bulk of these biomass residues, protein 30%–40%, mineral salts, particularly calcium carbonate and phosphate, 30%–50%, and lipids 0%–12%. Since chitin is frequently found in crab shells, it must be isolated by removing protein, inorganic components, and coloring agents (canthaxanthin, astatine, astaxanthin, lutein, and b-carotene). At the same time, deproteinization (the removal of proteins) is carried out at room temperature through the solvent extraction process. Crystalline chitin stands out from other biomaterials due to its numerous advantageous properties, including biocompatibility, biodegradability, antimicrobial activities, antigenicity, and eco-safety. As a result, many chitin equivalents have been synthesized, including N- and O-sulfonated chitin (useful because of its resemblance to the blood anticoagulant heparin) and dibutyryl- and carboxymethyl-chitin (with biological uses in the delivery of drugs) (Peniche et al., 2008).

A different, similarly effective method of producing chitosan from shrimp shells involved the conventional processes of deproteinization and demineralization, accompanied by delignification (discoloration) using ethanol. After that, a NaOH (12.5 M) aqueous solution was added to the chitin, and the mixture was cooled and frozen for 24 h. The produced chitosan exhibited satisfactory physicochemical properties, including low ash content (0.063%), good solubility in acetic acid (1%), and a crystallinity index of around 40% (de Queiroz Antonino et al., 2017).

4.3. Hydroxyapatite

Hydroxyapatite ($Ca_{10}(PO_4)_6(OH)_2$) is one of many essential materials used as skeletal reinforcement materials and scaffoldings for implantable devices due to its bioactive components, bioactivity, and non-inflammatory nature. Natural wastes, like animal carcasses, eggshells, seashells, fish scales, and algae, have been suggested as potential starting points for hydroxyapatite extraction (Khoo et al., 2015). Bones from bovine, swine or fish species are often treated by washing them in an alkaline solution and then calcining them at temperatures between 600 °C and 1400 °C to remove any remaining proteins. Natural hydroxyapatite was isolated from bovine bones using three protocols: thermal breakdown, subcritical water, and alkaline hydrothermal processes (Khoo et al., 2015).

Polluting landfills with discarded eggshells is a common occurrence. Eggshell disposal costs approximately $100,000 annually in US egg processing facilities (Laca et al., 2017). Recycling this trash has both financial and environmental benefits. However, more research is needed to investigate recycling eggshells' commercialization and industrial upscaling potential. Depending on the heat used, trash can replace limestone ($CaCO_3$) or lime (CaO). The average price per ton for commercially ground limestone or lime is around $100. In addition, the intensity of the heat treatment results in differently colored material, which can affect the use of the scrap (Zahouily et al., 2005). Previous research has demonstrated the benefits of using eggshell ash instead of lime for treating soil (TAHIR et al., 2006). According to a life cycle assessment, the calcination process, which entails warming the mussel shells to 800 °C, has high energy expenditure. The conventional processing and production method for lime from limestone includes a heat treatment with the corresponding energy expenses. The $CaCO_3$ in eggshells has been used as a neutralizing agent in laboratory-scale demonstrations of eggshell waste valorization to synthesize fumaric acid (Adams et al., 2022). Eggshell waste has also been repurposed in the lab as an adsorbent for cleaning wastewater and drinking water. Recycling eggshells into high-value goods like hydroxyapatite can have a significant financial impact in addition to having a positive environmental impact. The cosmetics industry and a sizable industrial co-composting market have described small-scale pilot applications of eggshell waste commoditization. Since the organic substance on eggshells decomposes quickly, the optimal locations for eggshell retrieval are similar to those of processors.

The eggshell membranes and $CaCO_3$ shell are recycled, and eggshell waste is handled and processed by an egg processing company in the UK. The savings cover the cost of processing by avoiding landfill disposal. The business offers inexpensive $CaCO_3$ powder from eggshells as plastic fillers. While the polymer costs over $2000 per ton, conventional limestone $CaCO_3$ powder costs only around $2000 per ton. Therefore, for eggshell $CaCO_3$ filler to have a more significant market role, its price must meet this requirement.

Another advantage of shelled $CaCO_3$ dust is its smaller particle size compared to ordinary limestone powder. Fine-tuning procedures like thermal processing, chemical modification, and physical treatment help lower processing costs. Price, availability, supply continuity, performance, and the need for conventional alternatives influence the industry's decision to use eggshell $CaCO_3$ powder.

4.4. Bioplastics

Bioplastics are organic polymers derived from feedstock and naturally degradable plastics that break down into organic compounds and hydrocarbons, primarily carbon dioxide when exposed to naturally occurring microbes such as fungi, bacteria, and algae. However, not all organic polymers are compostable because, unlike cellulose, cellulose acetate does not degrade in the ecosystem. Despite containing about 30% renewable carbon, bio-PET (polyethylene terephthalate) is not a biodegradable polymer like bio-based ethylene glycol. According to European Bioplastics, the primary forces driving this growth are fully bio-based and biodegradable biopolymers such as PHAs (polyhydroxyalkanoates) and PLA (polylactic acid), which are increasing global capacity for bioplastics production from roughly 2.05 million tons in 2017 to nearly 2.44 million tons in 2022 (Xu et al., 2019). Bio-PE (polyethylene) and bio-PET (polyethylene terephthalate), two nonbiodegradable polymers derived from biomass, account for more than 56% (1.2 million tons) of global bioplastics productivity. Bio-PE production is expected to increase due to the emergence of innovative complete bio-stationed alternatives such as bio-PEF (polyethylene furanoate), which has improved barrier and rheological properties for packaging beverages, fodder, and other products.

Bio-established PET production, in contrast, is expected to remain flat in the coming years. A new study has proposed using myofibrillar proteins derived from extracting the waste of gilded catfish (*Brachyplatystoma rousseauxii*) to create novel plastic materials. Following extraction, the proteins were mixed with aqueous glycerol (a plasticizer) and cast onto silicone supports, where they dried to form biofilms. The process design was optimized using response surface methodology to yield a bioplastic with 40% plasticizer (m/m) and 0.79% protein (m/v). The material is flexible, resistant, low in solubility, and permeable to water vapor due to its protein composition, making it ideal for food packaging.

Robust biofilms, with tensile strengths of 4.91 MPa, have been linked to sulfhydryl groups on the surface of myofibrillar proteins. Covalent S–S bonds could be made with these compounds. However, because fish muscle proteins are hydrophilic, the bioplastic was ineffective at keeping moisture out (water vapor permeability, WVP, was between 6 and 14 $gm^{-1}s^{-1}Pa^{-1}$). After all, they have polar amino acids and hydroxyl (OH) groups (Perotto et al., 2018). The mechanical properties of biofilms depended greatly on the type of biowaste from which they were made. For example, the residual silica in rice hulls stiffened the material, while the high concentration of triglycerides in cocoa pod husks caused the film to break under high stress and strain. These interactions, as well as the comparison of other characteristics (elastic modulus and how it interacts with water) with those of prevalent polymeric materials (polypropylene, polyethylene, and polyester) and kitchen waste, suggest that specific applications of biodegradable plastics in encasing and biomedical applications may be possible (Batista et al., 2019).

Another area of investigation in this research is the creation of recyclable plasticizers from organic wastes that can decrease the fragility, crystalline nature, melting point, and thermal properties of bioplastics while increasing their flexibility and toughness (Batista et al., 2019).

Plasticizers like poly(3-hydroxybutyric acid) and poly(lactic acid) are two examples of totally renewable materials (PHBs). Tannic acid (1,2,3,4,6-penta-O-{3,4-dihydroxy-5-[(3,4,5-trihydroxybenzoyl)oxy]benzoyl}-D-glucopyranose) is obtained from leftover lignocellulosic biomass. Citric acid, ethyl citrate (1,2,3-propanetricarboxylic acid, 2-hydroxy-, 2-ethyl ester), and bioethanol recovered from orange waste. It is also worth noting that synthetic plastics use more bio-plasticizers to replace conventional ones. Recently, it has been proposed that PVC, one of the most valuable polymeric materials, can be efficiently plasticized using highly divided polycaprolactone produced by solvent-free co-polymerization of e-caprolactone and glycidol (a glycerol derivative), to name a few examples. Proponents claim that using these bio-based plasticizers instead of traditional petro-based chemicals like phthalate esters increases PVC's thermal stability and stretchability by a factor of 20 (Perotto et al., 2018; Xu et al., 2019).

4.5. Silica and silicates

Preparing silica and silicate salts from biowaste is becoming more popular. Plants initiate the dynamical circuit of silicon in the chemosphere by absorbing silicic acid (H_4SiO_4) from soil moisture. The hydrated amorphous silica then forms and accumulates in phytoliths, which gives plants their rigidity when the silicic acid polymerizes. Many aquatic and terrestrial plants have hydrated amorphous silica in their roots, trunks, foliage, husks, blades, and cores. Regarding biowaste, rice husks (RHs) represent one of the most silica-rich sources (20–22 wt% of rice grains). The applicability of bio-silica and its byproducts is becoming more appealing due to the silica concentration of calcium carbonate. Typical methods for extracting biogenic silica from RHs include acidic pre-treatments to remove trace amounts of metals, followed by pyrolytic operations at temperatures and times ranging from 500 to 700 °C and 8–24 h, respectively (Adam et al., 2012; Xu et al., 2019). Another study suggested using rice husk, sugarcane bagasse, and bamboo culm—all renewable but inexpensive agricultural byproducts to remove SiO_2 *via* microwave-assisted solid-state ashing. The same study used MW-mediated magnesiothermic reduction to turn biogenic amorphous silica into pure crystalline Si. Unlike commercial Si nanopowders, the product had an easy-to-understand 3D porous structure. The pores were 50–80 nm in diameter, with walls 23 nm thick. Biowaste can be used to produce biogenic silicates by chemically extracting Ca from RHs or by using inorganic biowastes, such as egg or oyster shells, as a source of Ca to produce the necessary silicate salts (Shen, 2017; Shukla et al., 2022; Xu et al., 2019). A summary of reported biomaterials synthesized from various biowastes and critical findings have been enlisted in Table 2.

Table 2. Comprehensive summary of reported biomaterials synthesized from various biowaste.

S.L No	Name of biowaste	Prepared biomaterials	Key findings	Reference
1	The skin of marine puffer fish	Collagens	• Acid-soluble collagen (ASC) 43.1% and Pepsin-soluble collagen (PSC) 56.6% were made. • NIH_3T_3 cell lines showed that both types of collagen were 100% biocompatible.	Iswariya et al. (2018)
2	The outer skin of cuttlefish (*Sepia lycidas*)	Collagens	• A solubilized collagen (PSC) was made with 10% pepsin (w/v) and a 35% yield (dry weight basis)	Nagai et al. (2001)
3	Fish bones	Hydroxyapatite powder	• The powder's particles ranged from 0.657 to 19.81 m, with a mean size of 3.259 m.	Abdulkadhim and Abdulameer (2021)
4	Skin of brown-backed toadfish (*Lagocephalus loveri*), processing wastes	Collagen	• Compared to other vertebrates, the total amount of collagen that could be extracted was 54.3% based on lyophilized dry weight.	Senaratne et al. (2006)
5	The skin of *Brama australis*, the fish from the warm-water sea	Collagen	• The skin of *B. australis* produced about 1.5% collagen based on the wet weight of the raw material.	Sionkowska et al. (2015)

S.L No	**Name of biowaste**	**Prepared biomaterials**	**Key findings**	**Reference**
6	Egg shell	Flower-like Hydroxyapatite nanostructure	• The Hydroxyapatite nanostructure was a good substance with biocompatibility, drug adsorption/desorption behavior, antibacterial activity, and photoluminescence property.	Kumar and Girija (2013)
7	Sole fish skin	Collagen	• The best conditions yielded a maximum collagen yield of 19.27 0.05 mg/g of fish skin. • SDS-PAGE was used to determine that the extracted collagen was the type I collagen.	Arumugam et al. (2018)
8	Marine shell waste	Hydroxyapatite microspheres	• Prepared Hydroxyapatite microspheres have a high specific surface area and an opposing surface potential. • Hydroxyapatite microspheres were used to adsorb Congo red (CR) in solution.	Wang et al. (2021)
9	Outer skin waste of *Loligo uyii*	Type V like collagens	• The estimated net yield of acid-soluble collagen from *L. uyii* is 10.54% • When pepsin was used to break down the leftover material, 31.16% soluble collagen was found.	
10	Scales of Tilapia fish (*Oreochromis mossambicus*)	Hydroxyapatite and chitosan composite scaffold	• Scaffolds made of a mix of hydroxyapatite and chitosan were very good at taking heavy metal ions out of waste water.	Liaw et al. (2020)
11	Shrimp shell waste	Wheat gluten based-bioplastics	• Compared to a wheat gluten-based bioplastic without shrimp shell loading, the structural rigidity of the wheat gluten composite with 2.5 wt percent of shrimp shell powder was twice as high.	Veeruraj et al. (2012)
12	Shells of the marine crab (*Portunus sanguinolentus*)	Chitosan	• The extracted chitosan was shown to be anti-virulent and antibiofilm.	Rubini et al. (2018)

S.L No	Name of biowaste	Prepared biomaterials	Key findings	Reference
13	Carapace (exoskeleton)	Chitosan	• An orthorhombic structure with 30% crystallinity, like shrimp chitosan, was found	Águila-Almanza et al. (2021)
14	Shrimp waste (*Penaeus merguiensis*)	Chitin & chitosan	• Chitin was turned into chitosan using the microwave, an autoclave, and old-fashioned methods • The autoclave method gave the highest yield (87%) of the three	Sedaghat et al. (2017)
15	Cuttlefish-bone biowaste	Mayenite-embedded Ag_2CO_3 nanocomposite	• AgC@m-M is a strong photocatalyst and a good agent for recovering waste oil.	Darwish et al. (2021)
16	Shrimp waste	Chitin & chitosan	• Chitosan was good at fighting free radicals	Sedaghat et al. (2016)
17	Wastes of Persian Gulf shrimp	Chitosan	• It was found that 19.47% of the chitosan preparation had the highest degree of deacetylation (89.34%) and the highest molecular weight (806,931 Da).	Nouri et al. (2016)
18	Larvae of blowfly (*Chrysomya megacephala*)	Chitosan	• Chitosan was an excellent antioxidant, with an IC50 value of 1.2 mg/ml.	Song et al. (2013)
19	Eggshell biowaste	Hydroxyapatite	• The parameters for making nanohydroxyapatite from eggshell biowaste were shown using a microwave method on a lab scale and a pilot-scale microwave reactor.	Muthu et al. (2020)
20	*Cirrhinus mrigala* fish scale wastes	Nanostructured hydroxyapatite crystalline powders	• Nanostructured hydroxyapatite crystalline powders made from waste fish scales from *Cirrhinus mrigala* showed good biocompatibility. • It is a possible alternative biomaterial for many medical uses.	Sathiskumar et al. (2019)
21	Eggshells	Hydroxyapatite	• Hydroxyapatite was able to kill bacteria and stop biofilms from forming.	Umesh et al. (2021)

S.L No	Name of biowaste	Prepared biomaterials	Key findings	Reference
22	Eggshell	Hydroxyapatite	• The study showed that using used eggshells as a source of calcium along with microwave irradiation was an excellent way to make nano-hydroxyapatite particles.	Goh etal. (2021)
23	Municipal food waste	Bioplastic polyhydroxyalkanoates (PHA)	• PHA can work better than polyurethane made from fossil fuels • PHA made from first-generation biomass (such as sugarcane and maize) is better for the environment and costs society (four times lower impacts and eight times lower costs than polyurethane).	Andreasi Bassi etal. (2021)
24	The organic fraction of municipal solid waste	Polyhydroxyalkanoates (PHAs),	• The amount of biodegradable PHAs found in the organic part of municipal solid waste was 40 g/kg.	Ebrahimian etal. (2020b)
25	Rice husk waste	Pure silica	• The mean quality of extracts of silica obtained in various techniques varied from 84.81 to 99.66 wt percent. • When the greener method was used to make silica, it was very pure, with a surface area of up to 625 m^2/g.	Azat etal. (2019)
26	Rice husk, bamboo leaves, sugarcane bagasse, and groundnut shell	Silica nanoparticles	• The amount of silica found in different places ranged from 52% to 78%.	Vaibhav etal. (2015)

4.6. C-based and hybrid C-based nanomaterials

4.6.1. Carbon dots

Carbon dots are typically made using top-down approaches like laser ablation, arc discharge, and electrochemical reactions. However, bottom-up approaches, including hydrothermal, thermal, and microwave-aided processes, enable the construction of carbon dots from molecular predecessors. Carbon dots' carbonization, size, and shape can be tailored to a specific application due to their synthesizability; however, challenges in reproducibility between batches, surface property control, purification, and characterization may limit their practical use. The application of organic ingredients, notably biomass residues, has been investigated as preliminary substituents for manufacturing carbon dots, which can be made from various materials. Much new ground is ahead, and some new ideas are beginning to emerge.

Some biowastes, such as fruit waste, fish bones, and RHs, react well to hydrothermally aided processing. According to a study, heating aqueous dispersions of citrus maxima peel for 3h at 200°C results in a stable carbon dot dispersion between 2 and 4nm, an excitation peak at 365nm, an emission peak at 444nm, and a bright blue coloration under UV light (6.9% quantum yield).

Even without any label, these carbon dots worked well as sensitive tags, recognizing mercuric ions in the aqueous phase with a concentration range of 0.23nm (Ashokkumar et al., 2012). A similar technique, starting with orange seed coat debris, produced carbon dots with an average particle diameter of 2.9nm and a PL quantum efficiency of 2.88%. Potential uses in nanobiotechnology were posited due to the restricted size distribution. A microwave-assisted hydrothermal approach has also been used to produce carbon dots from biowaste, focusing on processing an aqueous environment of geese plumage, a significant poultry industry waste, at 180°C in a microwave autoclave (2kW). A solution containing carbon dots (Mw=3500) was dialyzed against Milli-Q water to produce a homogeneous dispersion of them (Ashokkumar et al., 2016).

4.6.2. Nano-carbons and nanocomposites

As useable synthetic pathways beginning with biowastes have been implemented, there has been a recent uptick in interest in nano-carbon collagen, primarily made from leather waste, which shows promise as a potential source. In one of the early waste-to-wealth techniques, collagen was recovered from goat flesh cutting. The recovered collagen was treated by ignition at temperatures ranging from 500°C to 1000°C in an argon flow (Ashokkumar et al., 2016; Lakshmi et al., 2018). Onion-shaped C-based nanostructures up to 20nm were created; each was composed of some imperfectly spherical shells of black carbon layers separated by roughly 3.36(Å). XPS and elemental studies revealed that the graphitic layers were doped with O- (6%–15%) and N-atoms (3%–15%), resulting in C═O and -O–C(O)O- groups and N-bearing aromatic rings, respectively. The electrical conductivity of these materials was $4.61 \times 10^{-1}\,\mathrm{S\,m^{-1}}$ which is on par with that of pure graphene powder and is especially noticeable at 1000°C. As a second illustration, aqueous AcOH and superparamagnetic iron oxide nanoparticles (SPIONs) were mixed with collagen isolated from raw cowhide trimming waste. Following moderate ignition (401°C, 12h) before freeze-drying, the collagen fibrils rearranged with the nanocrystals to produce a sponge-like, extremely porous interconnecting substance (41°C, 18h) (Ashokkumar et al., 2016).

Since the inclusion of SPIONs into the matrix material did not affect the collagen threefold helix conformation, the distinctly different 3D morphology of the composite compared to a natural collagen sponge can be attributed to the potent interactions of the two components. The increased proliferation of model cells (293T) demonstrated that adding SPIONs to the collagen sponge increased its dimensional integrity and made it biocompatible. Furthermore, adding SPIONs significantly improved collagen's macromolecular structure and cell viability (Xu et al., 2019).

5. Economic, environmental, and health effects of biowaste valorization

5.1. Economic impacts

Reduced capital costs are an essential aspect of successful economic and business models. These can be achieved in two ways: (a) by manufacturing high-value goods from zero-cost materials; or (b) by employing zero-waste production techniques, eliminating the need for costly waste disposal. Since biowastes can be valorized, they can be used as inputs in other industries, fostering a mutually beneficial relationship (Baldassarre et al., 2019). As a result, businesses can improve their image among consumers and investors while also reducing biowaste production (Barros et al., 2021). Closing material and energy consumption cycles during product design improves the supply chain, logistics, and manufacturing operations. When resources and goods enter a circular system, better, more cost-effective strategic planning is possible. Using environmentally friendly solutions and sustainable energy and transitioning from a linear to a CE model can help industries improve their competitiveness, revenues, job creation, and creativity. Several industrial aspects must be considered when idealizing agro-industrial recyclable waste. These include increasing the technical proficiency of interested parties through (i) the classification and proper repository design of biomass resources for processing plants, (ii) the assessment of extraction efficiency relying on the organic composition of feedstocks, and (iii) the assessment of the retrieval procedures to obtain ample supply while preventing potentially harmful environmental pathways. Companies that embrace more circular methods save money in the short and long term. These savings include reduced costs for raw materials, waste disposal, and resource recovery projects.

5.2. Environmental and health impacts

Adopting circular economy-based approaches to commodifying biowaste to manufacture biomaterials could contribute to various objectives, including minimization of biohazardous material, upcycling into high-value goods, and environmental protection (Omran et al., 2018). This switch is essential to reduce greenhouse gas emissions from treating such biowastes using conventional methods and safeguarding the environment from the harmful chemicals and gases produced in landfilling or incineration processes. Every stage of a product's life cycle, including manufacturing, consumer use, and final disposal, has unique environmental effects. Smart manufacturing and digital transformation facilitate environmental performance (Olah et al., 2020). Despite the previously mentioned positive environmental effects of converting agro-industrial biowastes into biomaterials, it is critical to study, measure, and comprehend the risk to public health associated with using of such nanomaterials. Nanotoxicology is important for analyzing bio-nano interactions (Tarrahi et al., 2021). Nanotoxicological investigations can tell us if and to what extent green nanomaterials (NMs) threaten the environment and living things, even though their properties are similar to those of chemically and physically manufactured NMs (Hu et al., 2016). The “reduction, refinement, and replacement (3Rs)” philosophy is currently used as an alternative to *in vivo* animal experimentation. This philosophy is implemented to avoid unethical practices and overcome the limitations of animal testing (Huang et al., 2021).

6. Discussion

We all know that converting biowaste into value-added products has always been difficult. Waste availability, purity, and composition have long been contested in commercial or large-scale production. Biowaste is a significant source of environmental contamination and a massive repository of valuable resources due to the high amount of organic and biodegradable components it contains that may be repurposed. The conversion of biowaste into resources *via* biorefinery is an unavoidable development that could help reduce carbon emissions and the rising environmental problems associated with solid waste. This paper investigates the current achievements and potential trends in the use of commonly available biowaste to produce essential biomaterials (such as collagens, hydroxyapatite, bioplastics, chitosan, chitin, polyhydroxyalkanoates, pure silica, *etc.*). To achieve the goal of a circular bioeconomy, various techniques for converting biowaste into high-value resources are required. Furthermore, the use of recycling technologies and incorporating bioconversion to improve process performance are critically examined. Because data on biowaste generation from public research is currently insufficient, it is necessary to identify, quantify, and investigate the periodicity of these residues to determine which are the major products for their treatment toward value-added products (Kee et al., 2021; Srivastava et al., 2023).

The fundamental understanding of mechanisms is critical and necessary to ease the transition of biowaste valorization technology from lab-scale to pilot-industrial scale. However, due to the complexities of biowaste feedstock, determining the paths and processes of the above-mentioned technologies for conversion remains a challenge. Furthermore, many technical limitations in conversion procedures prevent large-scale biowaste valorization. For example, the pyrolysis process requires a long heating time, yet uneven heating may affect biochar quality. Biowaste for pyrolysis should have dry, unmixed, and uniform physical and chemical qualities. In reality, most biowaste is a mix of wet domestic and commercial wastes.

Furthermore, the thermochemical conversion process generates tar, which reduces the system's overall efficiency. In addition, thermochemical conversion processes such as pyrolysis emit gaseous byproducts that harm the environment. More work needs to be done in the biochemical approach to improve the performance of enzyme activity and feedstock properties. Because of the heterogeneous character of municipal organic solid waste, its larger particle size and refractory woody components are very difficult to valoriz (Cheng etal., 2020; Kee etal., 2021; Srivastava etal., 2023).

7. Conclusions and future direction

This article thoroughly explains the underlying implications of biowaste's potential as a resource in a circular economy system. Additionally, we have demonstrated that the circular economy has full potential regarding sustainability, environmental, and social development. We assessed the biowaste used as a resource feature and employed several treatment methods worldwide to develop various biomaterials. A systematic approach to improving biowaste circularity that benefits society has also been presented. The economic and environmental effects of converting biowaste into valuable biomaterials are analyzed. Handling biowastes is a complex process that requires the cooperation of governments, rules, regulations, stakeholders, corporations, products, consumers, and public opinion. A multidisciplinary approach can make these processes sustainable, leading to a zero-waste economy and a more environmentally friendly bio-based society. Achieving this objective necessitates cross-industry and public–private collaboration to devise a plan with significant economic, social, and environmental benefits. In the future, the primary goals must be to raise public awareness that the rising global population and quality of life contribute to an increase in waste production, as well as to demonstrate how advanced biowaste valorization can be used as an input into other processes to recover and reuse specific biomaterials. Life cycle assessment (LCA)-based approaches must additionally be advanced to improve the sustainability of biowaste management systems. Furthermore, there are several significant obstacles related to LCA system boundaries that continue to present challenges for biowaste management. In that situation, LCA researchers were asked to tackle significant issues, such as the environmental impact assessment of the unorganized waste industry or the informal biowaste sector. The waste-to-wealth concept seeks to create a future sustainable lifestyle in which waste is valued for its environmental benefits and the development of new technologies, livelihoods, and jobs. Physical, chemical, or biological processes allow biowastes to undergo drastic changes that result in various valuable products and materials. In light of this potential, several positive aspects of the transition to a circular economy should be evaluated, including developing novel products, analyzing alternative company and market structures, and encouraging consumers to change their habits and routines toward waste management. However, because of the highly heterogeneous nature of biomass waste, it is difficult to imagine the type of final or categories of end-products and specify their properties, making developing valorization strategies challenging. Many of these studies, though, are still in their early stages and must surpass the discovery of a new method or technique to include an in-depth evaluation of both technological and socio-ecological constraints, such as the simplification of detoxification guidelines, harvesting yields, upscaling concerns, caloric expenditure and expense, pollutant impacts, and the general acceptance and acceptance of new technology development. The proper valorization and utilization of biowastes generated from diverse sources safeguard the environment and contribute to creating a more sustainable society.

Author contributions

Conceptualization, B.M., and Y.K.M; Data curation: H.S, B.M., C.N.R, R.Y., S.K.M., and S.D.M.R; Writing—original draft preparation, B.M., Y.K.M., C.N.R, S.D.M.R; Writing—review and editing, H.S., C.N.R., R.Y., and S.K.M.; Visualization, H.S, Y.K.M., and C.N.R. All authors have read and agreed to the published version of the manuscript.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Recommended articles

References

Abdulkadhim and Abdulameer, 2021 A. Abdulkadhim, N. Abdulameer
Experimental and numerical study to prepare hydroxyapatite powder from fish bones
Transactions on Electrical and Electronic Materials, 22 (2021), pp. 481-488
Google Scholar ↗

Adam et al., 2012 F. Adam, J.N. Appaturi, A. Iqbal
The utilization of rice husk silica as a catalyst: Review and recent progress
Catalysis Today, 190 (2012), pp. 2-14
Google Scholar ↗

Adams et al., 2022 S.M. Adams, E. Atikpo, V.S. Aigbodion, R. Njoku, L.I. Odo
$CaCO_3$ derived from eggshell waste for improving the hardness values and wear behavior of composite coating on mild steel via co-deposition
The International Journal of Advanced Manufacturing Technology, 119 (2022), pp. 5483-5496
Google Scholar ↗

Águila-Almanza et al., 2021 E. Águila-Almanza, S.S. Low, H. Hernández-Cocoletzi, A. Atonal-Sandoval, E. Rubio-Rosas, J. Violante-González, P.L. Show
Facile and green approach in managing sand crab carapace biowaste for obtention of high deacetylation percentage chitosan
Journal of Environmental Chemical Engineering, 9 (2021), p. 105229
Google Scholar ↗

Ahmad et al., 2016 A.A. Ahmad, N.A. Zawawi, F.H. Kasim, A. Inayat, A. Khasri

Assessing the gasification performance of biomass: A review on biomass gasification process conditions, optimization and economic evaluation
Renewable and Sustainable Energy Reviews, 53 (2016), pp. 1333-1347
Google Scholar ↗

Alhassan et al., 2016 Y. Alhassan, N. Kumar, I.M. Bugaje
Hydrothermal liquefaction of de-oiled *Jatropha curcas* cake using deep eutectic solvents (DESs) as catalysts and co-solvents
Bioresource Technology, 199 (2016), pp. 375-381
Google Scholar ↗

Andreasi Bassi et al., 2021 S. Andreasi Bassi, A. Boldrin, G. Frenna, T.F. Astrup
An environmental and economic assessment of bioplastic from urban biowaste. The example of polyhydroxyalkanoate
Bioresource Technology, 327 (2021), p. 124813
Google Scholar ↗

Arumugam et al., 2018 G.K.S. Arumugam, D. Sharma, R.M. Balakrishnan, J.B.P. Ettiyappan
Extraction, optimization and characterization of collagen from sole fish skin
Sustainable Chemistry and Pharmacy, 9 (2018), pp. 19-26
Google Scholar ↗

Ashokkumar et al., 2016 M. Ashokkumar, A. Cristian Chipara, N. Tharangattu Narayanan, A. Anumary, R. Sruthi, P. Thanikaivelan, R. Vajtai, S.A. Mani, P.M. Ajayan
Three-dimensional porous sponges from collagen biowastes
ACS Applied Materials & Interfaces, 8 (2016), pp. 14836-14844
Google Scholar ↗

Ashokkumar et al., 2012 M. Ashokkumar, N.T. Narayanan, A.L.M. Reddy, B.K. Gupta, B. Chandrasekaran, S. Talapatra, P.M. Ajayan, P. Thanikaivelan
Transforming collagen wastes into doped nanocarbons for sustainable energy applications
Green Chemistry, 14 (2012), pp. 1689-1695
Google Scholar ↗

Azat et al., 2019 S. Azat, A.V. Korobeinyk, K. Moustakas, V.J. Inglezakis
Sustainable production of pure silica from rice husk waste in Kazakhstan
Journal of Cleaner Production, 217 (2019), pp. 352-359
Google Scholar ↗

Barros et al., 2021 M.V. Barros, R. Salvador, G.F. do Prado, A.C. de Francisco, C.M. Piekarski
Circular economy as a driver to sustainable businesses
Cleaner Environmental Systems, 2 (2021), p. 100006
Google Scholar ↗

Batista et al., 2019 J.T.S. Batista, C.S. Araújo, M.R.S. Peixoto Joele, J.O.C. Silva, L.F.H. Lourenço
Study of the effect of the chitosan use on the properties of biodegradable films of myofibrillar proteins of fish residues using response surface methodology
Food Packaging and Shelf Life, 20 (2019), p. 100306

Google Scholar ↗

Bernstad Saraiva Schott et al., 2016 A. Bernstad Saraiva Schott, H. Wenzel, J. la Cour Jansen
Identification of decisive factors for greenhouse gas emissions in comparative life cycle assessments of food waste management - an analytical review
Journal of Cleaner Production, 119 (2016), pp. 13-24

Google Scholar ↗

Bibi et al., 2017 R. Bibi, Z. Ahmad, M. Imran, S. Hussain, A. Ditta, S. Mahmood, A. Khalid
Algal bioethanol production technology: A trend towards sustainable development
Renewable and Sustainable Energy Reviews, 71 (2017), pp. 976-985

Google Scholar ↗

Bridgwater, 2012 A.V. Bridgwater
Review of fast pyrolysis of biomass and product upgrading
Biomass and Bioenergy, 38 (2012), pp. 68-94

Google Scholar ↗

Cheng and Hu, 2010 H. Cheng, Y. Hu
Municipal solid waste (MSW) as a renewable source of energy: Current and future practices in China
Bioresource Technology, 101 (2010), pp. 3816-3824

Google Scholar ↗

Cheng et al., 2020 S.Y. Cheng, X. Tan, P.L. Show, K. Rambabu, F. Banat, A. Veeramuthu, B.F. Lau, E.P. Ng, T.C. Ling
Incorporating biowaste into circular bioeconomy: A critical review of current trend and scaling up feasibility
Environmental Technology & Innovation, 19 (2020), p. 101034

Google Scholar ↗

Chen et al., 2015 W.H. Chen, B.J. Lin, M.Y. Huang, J.S. Chang
Thermochemical conversion of microalgal biomass into biofuels: A review
Bioresource Technology, 184 (2015), pp. 314-327

Google Scholar ↗

Costanzo et al., 2016 W. Costanzo, R. Hilten, U. Jena, K.C. Das, J.R. Kastner
Effect of low temperature hydrothermal liquefaction on catalytic hydrodenitrogenation of algae biocrude and model macromolecules
Algal Research, 13 (2016), pp. 53-68

Google Scholar ↗

Daniell et al., 2012 J. Daniell, M. Köpke, S. Simpson
Commercial biomass syngas fermentation
Energies, 5 (2012), pp. 5372-5417

Google Scholar ↗

Darwish et al., 2021 A.S. Darwish, D.I. Osman, H.A. Mohammed, S.K. Attia

Cuttlefish bone biowaste for production of holey aragonitic sheets and mesoporous mayenite-embedded Ag_2CO_3 nanocomposite: Towards design high-performance adsorbents and visible-light photocatalyst for detoxification of dyes wastewater and waste oil recovery
Journal of Photochemistry and Photobiology A: Chemistry, 421 (2021), p. 113523
Google Scholar ↗

Dedinec et al., 2015 A. Dedinec, N. Markovska, I. Ristovski, G. Velevski, V.T. Gjorgjievska, T.O. Grncarovska, P. Zdraveva
Economic and environmental evaluation of climate change mitigation measures in the waste sector of developing countries
Journal of Cleaner Production, 88 (2015), pp. 234-241
Google Scholar ↗

Dhyani and Bhaskar, 2018 V. Dhyani, T. Bhaskar
Acomprehensive review on the pyrolysis of lignocellulosic biomass
Renewable Energy, 129 (2018), pp. 695-716
Google Scholar ↗

Dimitriadis and Bezergianni, 2017 A. Dimitriadis, S. Bezergianni
Hydrothermal liquefaction of various biomass and waste feedstocks for biocrude production: A state of the art review
Renewable and Sustainable Energy Reviews, 68 (2017), pp. 113-125
Google Scholar ↗

da Silva César et al., 2017 A. da Silva César, D.E. Werderits, G.L. de Oliveira Saraiva, R.C. da Silva Guabiroba
The potential of waste cooking oil as supply for the Brazilian biodiesel chain
Renewable and Sustainable Energy Reviews, 72 (2017), pp. 246-253
Google Scholar ↗

de Queiroz Antonino et al., 2017 R.S.C.M. de Queiroz Antonino, B.R.P. Lia Fook, V.A. de Oliveira Lima, R.Í. de Farias Rached, E.P.N. Lima, R.J. da Silva Lima, C.A. Peniche Covas, M.V. Lia Fook
Preparation and characterization of chitosan obtained from shells of shrimp (litopenaeus vannamei Boone)
Marine Drugs, 15 (2017), p. 141
Google Scholar ↗

de Souza and Pacca, 2021 J.F.T. de Souza, S.A. Pacca
Carbon reduction potential and costs through circular bioeconomy in the Brazilian steel industry
Resources, Conservation and Recycling, 169 (2021), p. 105517
Google Scholar ↗

Ebrahimian et al., 2020a F. Ebrahimian, K. Karimi, R. Kumar
Sustainable biofuels and bioplastic production from the organic fraction of municipal solid waste
Waste Management, 116 (2020), pp. 40-48
Google Scholar ↗

Ebrahimian et al., 2020b F. Ebrahimian, K. Karimi, R. Kumar

Sustainable biofuels and bioplastic production from the organic fraction of municipal solid waste

Waste Management, 116 (2020), pp. 40-48

Google Scholar ↗

EL Muller et al., 2014 E. EL Muller, A.R. Sheik, P. Wilmes

Lipid-based biofuel production from wastewater

Current Opinion in Biotechnology, 30 (2014), pp. 9-16

Google Scholar ↗

Fasolini et al., 2019 A. Fasolini, R. Cucciniello, E. Paone, F. Mauriello, T. Tabanelli

Ashort overview on the hydrogen production via aqueous phase reforming (APR) of cellulose, C6-C5 sugars and polyols

Catalysts, 9 (2019), p. 917

Google Scholar ↗

Ferronato and Torretta, 2019 N. Ferronato, V. Torretta

Waste mismanagement in developing countries: A review of global issues

International Journal of Environmental Research and Public Health, 16 (2019), p. 1060

Google Scholar ↗

Garfí et al., 2016 M. Garfí, J. Martí-Herrero, A. Garwood, I. Ferrer

Household anaerobic digesters for biogas production in Latin America: A review

Renewable and Sustainable Energy Reviews, 60 (2016), pp. 599-614

Google Scholar ↗

Gogoi and Hazarika, 2017 G. Gogoi, S. Hazarika

Coupling of ionic liquid treatment and membrane filtration for recovery of lignin from lignocellulosic biomass

Separation and Purification Technology, 173 (2017), pp. 113-120

Google Scholar ↗

Goh et al., 2021 K.W. Goh, Y.H. Wong, S. Ramesh, H. Chandran, S. Krishnasamy, S. Ramesh, A. Sidhu, W.D. Teng

Effect of pH on the properties of eggshell-derived hydroxyapatite bioceramic synthesized by wet chemical method assisted by microwave irradiation

Ceramics International, 47 (2021), pp. 8879-8887

Google Scholar ↗

Gómez-Guillén et al., 2011 M.C. Gómez-Guillén, B. Giménez, M.E. López-Caballero, M.P. Montero

Functional and bioactive properties of collagen and gelatin from alternative sources: A review

Food Hydrocolloids, 25 (2011), pp. 1813-1827

Google Scholar ↗

Günerken et al., 2015 E. Günerken, E. D'Hondt, M.H.M. Eppink, L. Garcia-Gonzalez, K. Elst, R.H. Wijffels

Cell disruption for microalgae biorefineries

Biotechnology Advances, 33 (2015), pp. 243-260

Google Scholar ↗

Iswariya et al., 2018 S. Iswariya, P. Velswamy, T.S. Uma
Isolation and characterization of biocompatible collagen from the skin of puffer fish (lagocephalus inermis)
Journal of Polymers and the Environment, 26 (2018), pp. 2086-2095

Google Scholar ↗

Jadhav and Tandale, 2018 S.D. Jadhav, M.S. Tandale
Optimization of transesterification process using homogeneous and nano-heterogeneous catalysts for biodiesel production from Mangifera indica oil
Environmental Progress & Sustainable Energy, 37 (2018), pp. 533-545

Google Scholar ↗

Jimenez et al., 2015 J. Jimenez, E. Latrille, J. Harmand, A. Robles, J. Ferrer, D. Gaida, C. Wolf, F. Mairet, O. Bernard, V. Alcaraz-Gonzalez, H. Mendez-Acosta, D. Zitomer, D. Totzke, H. Spanjers, F. Jacobi, A. Guwy, R. Dinsdale, G. Premier, S. Mazhegrane, *et al.*
Instrumentation and control of anaerobic digestion processes: A review and some research challenges
Reviews in Environmental Science and Biotechnology, 14 (2015), pp. 615-648

Google Scholar ↗

John et al., 2011 R.P. John, G.S. Anisha, K.M. Nampoothiri, A. Pandey
Micro and macroalgal biomass: A renewable source for bioethanol
Bioresource Technology, 102 (2011), pp. 186-193

Google Scholar ↗

Kamali and Khodaparast, 2015 M. Kamali, Z. Khodaparast
Review on recent developments on pulp and paper mill wastewater treatment
Ecotoxicology and Environmental Safety, 114 (2015), pp. 326-342

Google Scholar ↗

Karnaouri et al., 2019 A. Karnaouri, I. Antonopoulou, A. Zerva, M. Dimarogona, E. Topakas, U. Rova, P. Christakopoulos
Thermophilic enzyme systems for efficient conversion of lignocellulose to valuable products: Structural insights and future perspectives for esterases and oxidative catalysts
Bioresource Technology, 279 (2019), pp. 362-372

Google Scholar ↗

Katarzyna and Alina, 2020 A. Katarzyna, S. Alina
Current methods of collagen cross-linking: Review
International Journal of Biological Macromolecules, 151 (2020), pp. 550-560

Google Scholar ↗

Kaza et al., 2018 S. Kaza, L.C. Yao, P. Bhada-Tata, F. Van Woerden
What a waste 2.0: A global snapshot of solid waste management to 2050
World Bank, Washington, DC (2018)

Google Scholar ↗

Kee et al., 2021 S.H. Kee, J.B.V. Chiongson, J.P. Saludes, S. Vigneswari, S. Ramakrishna, K. Bhubalan
Bioconversion of agro-industry sourced biowaste into biomaterials via microbial factories–A viable domain of circular economy
Environmental Pollution, 271 (2021), p. 116311
Google Scholar ↗

Kerton et al., 2013 F.M. Kerton, Y. Liu, K.W. Omari, K. Hawboldt
Green chemistry and the ocean-based biorefinery
Green Chemistry, 15 (2013), pp. 860-871
Google Scholar ↗

Khoo et al., 2015 W. Khoo, F.M. Nor, H. Ardhyananta, D. Kurniawan
Preparation of natural hydroxyapatite from bovine femur bones using calcination at various temperatures
Procedia Manufacturing, 2 (2015), pp. 196-201
Google Scholar ↗

Kim et al., 2010 J.P. Kim, K.R. Kim, S.P. Choi, S.J. Han, M.S. Kim, S.J. Sim
Repeated production of hydrogen by sulfate re-addition in sulfur deprived culture of *Chlamydomonas reinhardtii*
International Journal of Hydrogen Energy, 35 (2010), pp. 13387-13391
Google Scholar ↗

Kumar and Girija, 2013 G.S. Kumar, E.K. Girija
Flower-like hydroxyapatite nanostructure obtained from eggshell: A candidate for biomedical applications
Ceramics International, 39 (2013), pp. 8293-8299
Google Scholar ↗

Kundu et al., 2018 K. Kundu, A. Chatterjee, T. Bhattacharyya, M. Roy, A. Kaur
Thermochemical conversion of biomass to bioenergy: A review
A. Singh, R. Agarwal, A. Agarwal, A. Dhar, M. Shukla (Eds.), Prospects of alternative transportation fuels, Springer, Singapore (2018)
Google Scholar ↗

Laca et al., 2017 A. Laca, A. Laca, M. Díaz
Eggshell waste as catalyst: A review
Journal of Environmental Management, 197 (2017), pp. 351-359
Google Scholar ↗

Lakshmi et al., 2018 S.D. Lakshmi, P.K. Avti, G. Hegde
Activated carbon nanoparticles from biowaste as new generation antimicrobial agents: A review
Nano-Structures & Nano-Objects, 16 (2018), pp. 306-321
Google Scholar ↗

Lee et al., 2020 D.J. Lee, J.S. Lu, J.S. Chang
Pyrolysis synergy of municipal solid waste (MSW): A review
Bioresource Technology, 318 (2020), p. 123912
Google Scholar ↗

Lee et al., 2019 S.Y. Lee, R. Sankaran, K.W. Chew, C.H. Tan, R. Krishnamoorthy, D.T. Chu, P.L. Show
Waste to bioenergy: A review on the recent conversion technologies
BMC Energy, 1 (2019), p. 4
Google Scholar ↗

Liaw et al., 2020 B.S. Liaw, T.T. Chang, H.K. Chang, W.K. Liu, P.Y. Chen
Fish scale-extracted hydroxyapatite/chitosan composite scaffolds fabricated by freeze casting—an innovative strategy for water treatment
Journal of Hazardous Materials, 382 (2020), p. 121082
Google Scholar ↗

Li et al., 2019 S. Li, H. Zheng, Y. Zheng, J. Tian, T. Jing, J.S. Chang, S.H. Ho
Recent advances in hydrogen production by thermo-catalytic conversion of biomass
International Journal of Hydrogen Energy, 44 (2019), pp. 14266-14278
Google Scholar ↗

Lohri et al., 2017 C.R. Lohri, S. Diener, I. Zabaleta, A. Mertenat, C. Zurbrügg
Treatment technologies for urban solid biowaste to create value products: A review with focus on low- and middle-income settings
Reviews in Environmental Science and Biotechnology, 16 (2017), pp. 81-130
Google Scholar ↗

Messerle et al., 2018 V.E. Messerle, A.L. Mosse, A.B. Ustimenko
Processing of biomedical waste in plasma gasifier
Waste Management, 79 (2018), pp. 791-799
Google Scholar ↗

Mishra et al., 2023 B. Mishra, Y.K. Mohanta, S. Varjani, S.K. Mandal, N.S.V. Lakshmayya, P. Chaturvedi, M.K. Awasthi, Z. Zhang, R. Sindhu, P. Binod, R.R. Singhania, V. Kumar
Acritical review on valorization of food processing wastes and by-products for pullulan production
Journal of Food Science and Technology, 60 (2023), pp. 2121-2131
Google Scholar ↗

Mishra et al., 2019 B. Mishra, S. Varjani, G. Karthikeya Srinivasa Varma
Agro-industrial by-products in the synthesis of food grade microbial pigments: An eco-friendly alternative
B. Parameswaran, S. Varjani, S. Raveendran (Eds.), Green bio-processes, Springer, Singapore (2019)
Google Scholar ↗

Mishra et al., 2018 B. Mishra, D. Zamare, A. Manikanta

Selection and utilization of agro-industrial waste for biosynthesis and hyper-production of pullulan: A review
S. Varjani, B. Parameswaran, S. Kumar, S. Khare (Eds.), Biosynthetic technology and environmental challenges, Springer, Singapore (2018)
Google Scholar ↗

Muthu et al., 2020 D. Muthu, G.S. Kumar, V.S. Kattimani, V. Viswabaskaran, E.K. Girija
Optimization of a lab scale and pilot scale conversion of eggshell biowaste into hydroxyapatite using microwave reactor
Ceramics International, 46 (2020), pp. 25024-25034
Google Scholar ↗

Nagai et al., 2001 T. Nagai, E. Yamashita, K. Taniguchi, N. Kanamori, N. Suzuki
Isolation and characterisation of collagen from the outer skin waste material of cuttlefish (*Sepia lycidas*)
Food Chemistry, 72 (2001), pp. 425-429
Google Scholar ↗

Nouri et al., 2016 M. Nouri, F. Khodaiyan, S.H. Razavi, M. Mousavi
Improvement of chitosan production from Persian Gulf shrimp waste by response surface methodology
Food Hydrocolloids, 59 (2016), pp. 50-58
Google Scholar ↗

Oliveira Cavalheiro et al., 2007 J.M. Oliveira Cavalheiro, E. Oliveira de Souza, P.S. Bora
Utilization of shrimp industry waste in the formulation of tilapia (*Oreochromis niloticus* Linnaeus) feed
Bioresource Technology, 98 (2007), pp. 602-606
Google Scholar ↗

Oumer et al., 2018 A.N. Oumer, M.M. Hasan, A.T. Baheta, R. Mamat, A.A. Abdullah
Bio-based liquid fuels as a source of renewable energy: A review
Renewable and Sustainable Energy Reviews, 88 (2018), pp. 82-98
Google Scholar ↗

Patra et al., 2022 B.R. Patra, R.N. Mohapatro, S. Routray, R. Swain, S. Nanda, A.K. Dalai
Thermochemical conversion of organic waste: New horizons for production of green energy
S. Nanda, D.V. Vo (Eds.), Innovations in thermochemical technologies for biofuel processing, Elsevier, Amsterdam (2022)
Google Scholar ↗

Peniche et al., 2008 C. Peniche, W. Argüelles-Monal, F.M. Goycoolea
Chitin and chitosan: Major sources, properties and applications
M.N. Belgacem, A. Gandini (Eds.), Monomers, polymers and composites from renewable resources, Elsevier, Amsterdam (2008)
Google Scholar ↗

Perotto et al., 2018 G. Perotto, L. Ceseracciu, R. Simonutti, U.C. Paul, S. Guzman-Puyol, T.N. Tran, I.S. Bayer, A. Athanassiou
Bioplastics from vegetable waste *via* an eco-friendly water-based process
Green Chemistry, 20 (2018), pp. 894-902
Google Scholar ↗

Rahman et al., 2014 M.O. Rahman, A. Hussain, H. Basri
Acritical review on waste paper sorting techniques
International journal of Environmental Science and Technology, 11 (2014), pp. 551-564
Google Scholar ↗

Rahman et al., 2018 M.M. Rahman, R. Liu, J. Cai
Catalytic fast pyrolysis of biomass over zeolites for high quality bio-oil - a review
Fuel Processing Technology, 180 (2018), pp. 32-46
Google Scholar ↗

Ranjbari et al., 2021 M. Ranjbari, Z. Shams Esfandabadi, M.C. Zanetti, S.D. Scagnelli, P.O. Siebers, M. Aghbashlo, W. Peng, F. Quatraro, M. Tabatabaei
Three pillars of sustainability in the wake of COVID-19: A systematic review and future research agenda for sustainable development
Journal of Cleaner Production, 297 (2021), p. 126660
Google Scholar ↗

Ravindran and Jaiswal, 2016 R. Ravindran, A.K. Jaiswal
Exploitation of food industry waste for high-value products
Trends in Biotechnology, 34 (2016), pp. 58-69
Google Scholar ↗

Reddy et al., 2016 S.N. Reddy, S. Nanda, J.A. Kozinski
Supercritical water gasification of glycerol and methanol mixtures as model waste residues from biodiesel refinery
Chemical Engineering Research and Design, 113 (2016), pp. 17-27
Google Scholar ↗

Robbins et al., 2012 M.P. Robbins, G. Evans, J. Valentine, I.S. Donnison, G.G. Allison
New opportunities for the exploitation of energy crops by thermochemical conversion in Northern Europe and the UK
Progress in Energy and Combustion Science, 38 (2012), pp. 138-155
Google Scholar ↗

Romero-Güiza et al., 2016 M.S. Romero-Güiza, J. Vila, J. Mata-Alvarez, J.M. Chimenos, S. Astals
The role of additives on anaerobic digestion: A review
Renewable and Sustainable Energy Reviews, 58 (2016), pp. 1486-1499
Google Scholar ↗

Rubini et al., 2018 D. Rubini, S. Farisa Banu, B.N. Veda Hari, D. Ramya Devi, S. Gowrishankar, S. Karutha Pandian, P. Nithyanand

Chitosan extracted from marine biowaste mitigates staphyloxanthin production and biofilms of Methicillin- resistant *Staphylococcus aureus*
Food and Chemical Toxicology, 118 (2018), pp. 733-744
Google Scholar ↗

Salimi et al., 2018 M. Salimi, A. Tavasoli, S. Balou, H. Hashemi, K. Kohansal
Influence of promoted bimetallic Ni-based catalysts and Micro/Mesopores carbonaceous supports for biomass hydrothermal conversion to H_2-rich gas
Applied Catalysis B: Environmental, 239 (2018), pp. 383-397
Google Scholar ↗

Santagata et al., 2021 R. Santagata, M. Ripa, A. Genovese, S. Ulgiati
Food waste recovery pathways: Challenges and opportunities for an emerging bio-based circular economy. A systematic review and an assessment
Journal of Cleaner Production, 286 (2021), p. 125490
Google Scholar ↗

Sarker et al., 2021 T.R. Sarker, S. Nanda, A.K. Dalai, V. Meda
Areview of torrefaction technology for upgrading lignocellulosic biomass to solid biofuels
BioEnergy Research, 14 (2021), pp. 645-669
Google Scholar ↗

Sathiskumar et al., 2019 S. Sathiskumar, S. Vanaraj, D. Sabarinathan, S. Bharath, G. Sivarasan, S. Arulmani, K. Preethi, V.K. Ponnusamy
Green synthesis of biocompatible nanostructured hydroxyapatite from *Cirrhinus mrigala* fish scale - a biowaste to biomaterial
Ceramics International, 45 (2019), pp. 7804-7810
Google Scholar ↗

Sedaghat et al., 2016 F. Sedaghat, M. Yousefzadi, H. Toiserkani, S. Najafipour
Chitin from *Penaeus merguiensis* via microbial fermentation processing and antioxidant activity
International Journal of Biological Macromolecules, 82 (2016), pp. 279-283
Google Scholar ↗

Sedaghat et al., 2017 F. Sedaghat, M. Yousefzadi, H. Toiserkani, S. Najafipour
Bioconversion of shrimp waste *Penaeus merguiensis* using lactic acid fermentation: An alternative procedure for chemical extraction of chitin and chitosan
International Journal of Biological Macromolecules, 104 (2017), pp. 883-888
Google Scholar ↗

Senaratne et al., 2006 L.S. Senaratne, P.J. Park, S.K. Kim
Isolation and characterization of collagen from brown backed toadfish (*Lagocephalus gloveri*) skin
Bioresource Technology, 97 (2006), pp. 191-197
Google Scholar ↗

Shankar Tumuluru et al., 2011 J. Shankar Tumuluru, S. Sokhansanj, J.R. Hess, C.T. Wright, R.D. Boardman

Review: A review on biomass torrefaction process and product properties for energy applications

Industrial Biotechnology, 7 (2011), pp. 384-401

Google Scholar ↗

Shen, 2017 Y. Shen

Rice husk silica derived nanomaterials for sustainable applications

Renewable and Sustainable Energy Reviews, 80 (2017), pp. 453-466

Google Scholar ↗

Shen et al., 2015 Y. Shen, L. Jarboe, R. Brown, Z. Wen

Athermochemical-biochemical hybrid processing of lignocellulosic biomass for producing fuels and chemicals

Biotechnology Advances, 33 (2015), pp. 1799-1813

Google Scholar ↗

Shenoy et al., 2022 M. Shenoy, N.S. Abdul, Z. Qamar, B.M. Al Bahri, K.Z.K. Al Ghalayini, A. Kakti

Collagen structure, synthesis, and its applications: A systematic review

Cureus, 14 (5) (2022), Article e24856

Google Scholar ↗

Shukla et al., 2022 S.S. Shukla, R. Chava, S. Appari, A. Bahurudeen, B.V.R. Kuncharam

Sustainable use of rice husk for the cleaner production of value-added products

Journal of Environmental Chemical Engineering, 10 (2022), p. 106899

Google Scholar ↗

Sionkowska et al., 2015 A. Sionkowska, J. Kozłowska, M. Skorupska, M. Michalska

Isolation and characterization of collagen from the skin of *Brama australis*

International Journal of Biological Macromolecules, 80 (2015), pp. 605-609

Google Scholar ↗

Song et al., 2013 C. Song, H. Yu, M. Zhang, Y. Yang, G. Zhang

Physicochemical properties and antioxidant activity of chitosan from the blowfly *Chrysomya megacephala* larvae

International Journal of Biological Macromolecules, 60 (2013), pp. 347-354

Google Scholar ↗

Srivastava et al., 2023 R.K. Srivastava, N.P. Shetti, K.R. Reddy, M.N. Nadagouda, M. Badawi, A. Bonilla-Petriciolet, T.M. Aminabhavi

Valorization of biowastes for clean energy production, environmental depollution and soil fertility

Journal of Environmental Management, 332 (2023), p. 117410

Google Scholar ↗

Stąsiek and Szkodo, 2020 J. Stąsiek, M. Szkodo

Thermochemical conversion of biomass and municipal waste into useful energy using advanced HiTAG/HiTSG technology

Energies, 13 (2020), p. 4218

Google Scholar ↗

Tahir et al., 2006 R. Tahir, K. Banert, S. Sebti
Natural and synthetic phosphates: New and clean heterogeneous catalysts for the synthesis of 5-arylhydantoins
Applied Catalysis A: General, 298 (2006), pp. 261-264

Google Scholar ↗

Taiwo et al., 2016 A.M. Taiwo, A.M. Gbadebo, J.A. Oyedepo, Z.O. Ojekunle, O.M. Alo, A.A. Oyeniran, O.J. Onalaja, D. Ogunjimi, O.T. Taiwo
Bioremediation of industrially contaminated soil using compost and plant technology
Journal of Hazardous Materials, 304 (2016), pp. 166-172

Google Scholar ↗

Tyagi and Kumar, 2021 B. Tyagi, N. Kumar
Bioremediation: Principles and applications in environmental management
G. Saxena, V. Kumar, M.P. Shah (Eds.), Bioremediation for environmental sustainability, Elsevier, Amsterdam (2021)

Google Scholar ↗

Umesh et al., 2021 M. Umesh, D.D. Choudhury, S. Shanmugam, S. Ganesan, M. Alsehli, A. Elfasakhany, A. Pugazhendhi
Eggshells biowaste for hydroxyapatite green synthesis using extract piper betel leaf - evaluation of antibacterial and antibiofilm activity
Environmental Research, 200 (2021), p. 111493

Google Scholar ↗

Uzoejinwa et al., 2018 B.B. Uzoejinwa, X. He, S. Wang, A. El-Fatah Abomohra, Y. Hu, Q. Wang
Co-pyrolysis of biomass and waste plastics as a thermochemical conversion technology for high-grade biofuel production: Recent progress and future directions elsewhere worldwide
Energy Conversion and Management, 163 (2018), pp. 468-492

Google Scholar ↗

Vaibhav et al., 2015 V. Vaibhav, U. Vijayalakshmi, S.M. Roopan
Agricultural waste as a source for the production of silica nanoparticles
Spectrochimica Acta Part A: Molecular and Biomolecular Spectroscopy, 139 (2015), pp. 515-520

Google Scholar ↗

Veeruraj et al., 2012 A. Veeruraj, M. Arumugam, T. Ajithkumar, T. Balasubramanian
Isolation and characterization of drug delivering potential of type-I collagen from eel fish Evenchelys macrura
Journal of Materials Science: Materials in Medicine, 23 (2012), pp. 1729-1738

Google Scholar ↗

Wang et al., 2021 H. Wang, K. Yan, J. Chen
Preparation of hydroxyapatite microspheres by hydrothermal self-assembly of marine shell for effective adsorption of Congo Red
Materials Letters, 304 (2021), p. 130573

Google Scholar ↗

Watson et al., 2018 J. Watson, Y. Zhang, B. Si, W.T. Chen, R. de Souza
Gasification of biowaste: A critical review and outlooks
Renewable and Sustainable Energy Reviews, 83 (2018), pp. 1-17
Google Scholar ↗

Xu et al., 2019 C. Xu, M. Nasrollahzadeh, M. Selva, Z. Issaabadi, R. Luque
Waste-to-wealth: Biowaste valorization into valuable bio(nano)materials
Chemical Society Reviews, 48 (2019), pp. 4791-4822
Google Scholar ↗

Yunus Khan et al., 2018 T.M. Yunus Khan, I.A. Badruddin, R.F. Ankalgi, A. Badarudin, B.S. Hungund, F.R. Ankalgi
Biodiesel production by direct transesterification process via sequential use of acid-base catalysis
Arabian Journal for Science and Engineering, 43 (2018), pp. 5929-5936
Google Scholar ↗

Zahouily et al., 2005 M. Zahouily, W. Bahlaouan, B. Bahlaouan, A. Rayadh, S. Sebti
Catalysis by hydroxyapatite alone and modified by sodium nitrate: A simple and efficient procedure for the construction of carbon-nitrogen bonds in heterogeneous catalysis
ARKIVOC (Gainesville, FL, United States) NO VOL. NO. (2005), pp. 150-161
2005
Google Scholar ↗

Zhang et al., 2018 J. Zhang, X. Kan, Y. Shen, K.C. Loh, C.H. Wang, Y. Dai, Y.W. Tong
Ahybrid biological and thermal waste-to-energy system with heat energy recovery and utilization for solid organic waste treatment
Energy, 152 (2018), pp. 214-222
Google Scholar ↗

Cited by (4)

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2024, Bioresources and Bioprocessing

Biomaterials technology and policiesin the building sector: a review ↗

2024, Environmental Chemistry Letters

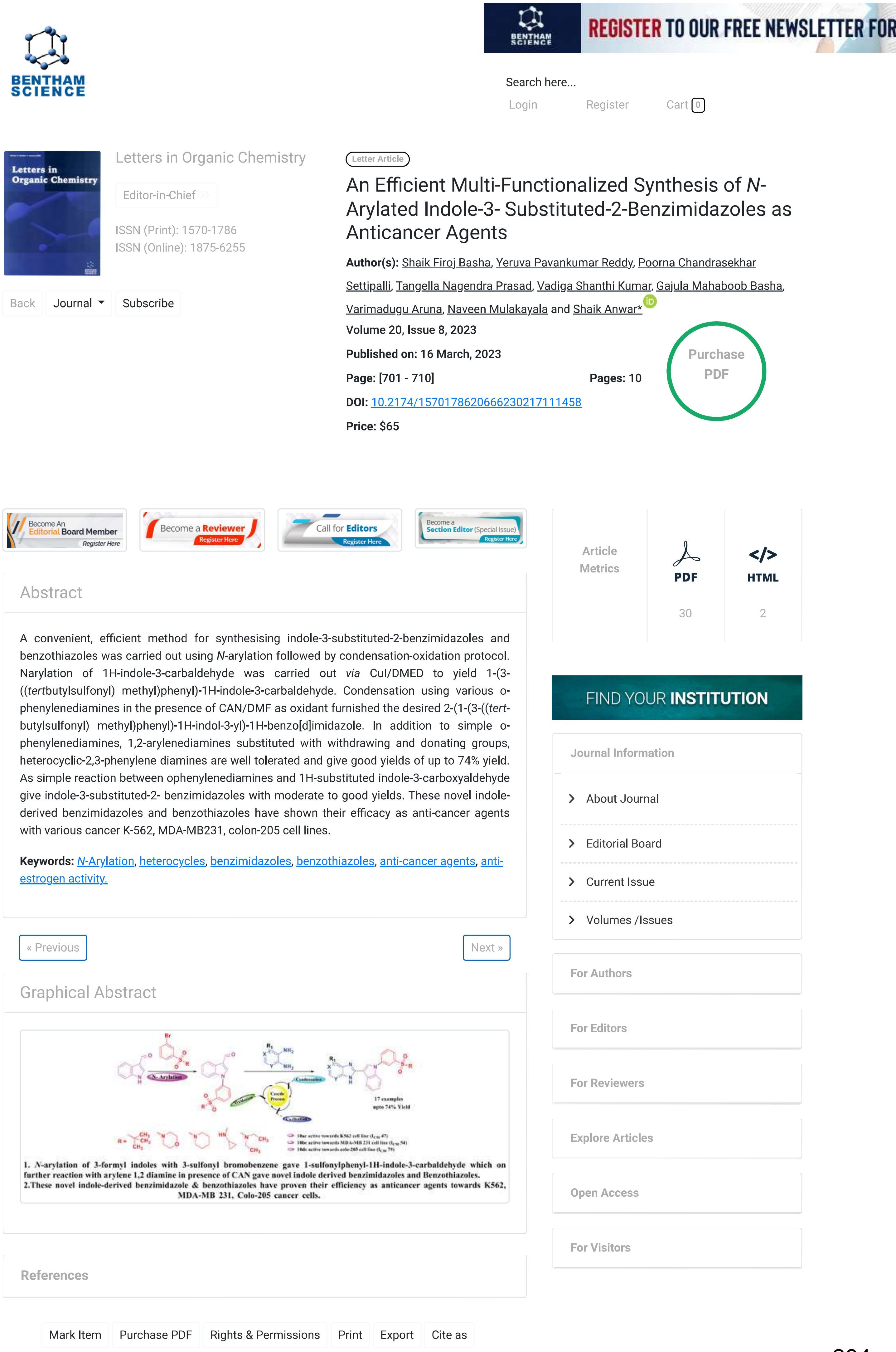
Extracting valuable compounds from shrimp shell waste: recovery of high-quality as calcium-centric resources for hydroxyapatite production ↗

2024, Journal of the Australian Ceramic Society

Selective Collection and Management of Biowaste from the Municipal Sector in Poland: A Review ↗

2023, Applied Sciences (Switzerland)

[1] These authors contributed equally to this work and were treated as joint first authors.



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An Efficient Multi-Functionalized Synthesis of *N*-Arylated Indole-3- Substituted-2-Benzimidazoles as Anticancer Agents

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Abstract

A convenient, efficient method for synthesising indole-3-substituted-2-benzimidazoles and benzothiazoles was carried out using *N*-arylation followed by condensation-oxidation protocol. Narylation of 1H-indole-3-carbaldehyde was carried out *via* CuI/DMED to yield 1-(3-((*tert*butylsulfonyl) methyl)phenyl)-1H-indole-3-carbaldehyde. Condensation using various o-phenylenediamines in the presence of CAN/DMF as oxidant furnished the desired 2-(1-(3-((*tert*-butylsulfonyl) methyl)phenyl)-1H-indol-3-yl)-1H-benzo[d]imidazole. In addition to simple o-phenylenediamines, 1,2-arylenediamines substituted with withdrawing and donating groups, heterocyclic-2,3-phenylene diamines are well tolerated and give good yields of up to 74% yield. As simple reaction between ophenylenediamines and 1H-substituted indole-3-carboxyaldehyde give indole-3-substituted-2- benzimidazoles with moderate to good yields. These novel indole-derived benzimidazoles and benzothiazoles have shown their efficacy as anti-cancer agents with various cancer K-562, MDA-MB231, colon-205 cell lines.

Keywords: *N*-Arylation, heterocycles, benzimidazoles, benzothiazoles, anti-cancer agents, anti-estrogen activity.

Graphical Abstract

1. ***N*-arylation of 3-formyl indoles with 3-sulfonyl bromobenzene gave 1-sulfonylphenyl-1H-indole-3-carbaldehyde which on further reaction with arylene 1,2 diamine in presence of CAN gave novel indole derived benzimidazoles and Benzothiazoles.**
2.These novel indole-derived benzimidazole & benzothiazoles have proven their efficiency as anticancer agents towards K562, MDA-MB 231, Colo-205 cancer cells.

References