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Review

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

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A B S T R A C T

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.

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-

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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.

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 &

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 waste	• With its abundant organic material and microbial flora, bio waste can be utilized directly for anaerobic digestion to generate biogas. By trans esterifying cattle oils and fats with alcohol, biofuel can be made immediately	• Anaerobic digestion requires a large tank and processing vessel, from which Fumes could result. • Recovering fats and oil from leftover meat necessitates pre-processing steps.	Nagai et al., 2001; Nouri et al., 2016; 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

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 et al., 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 et al., 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 et al., 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 et al., 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 et al., 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 et al., 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 et al., 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 et al., 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.

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 1000 L AD reactor to convert biodegradable food waste into biogas. A 10 kW 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.

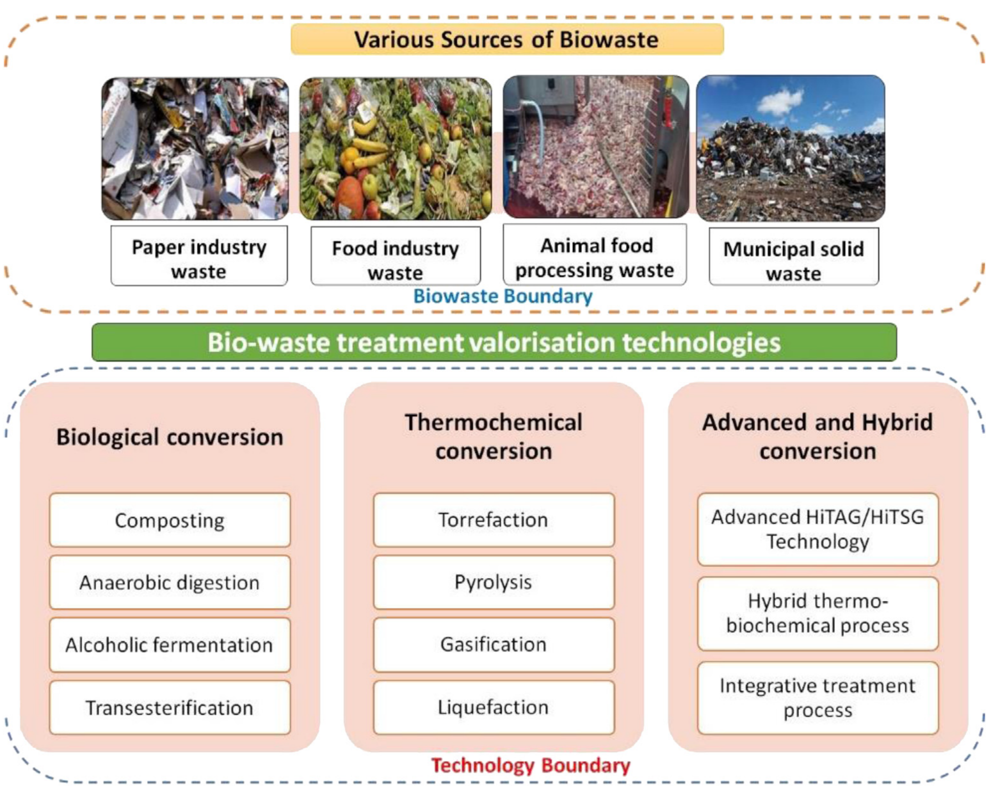

Fig. 1. Outline of potential origins of biowastes and available methods of valorization to obtain value-added products.

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.

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 et al., 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 et al., 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.

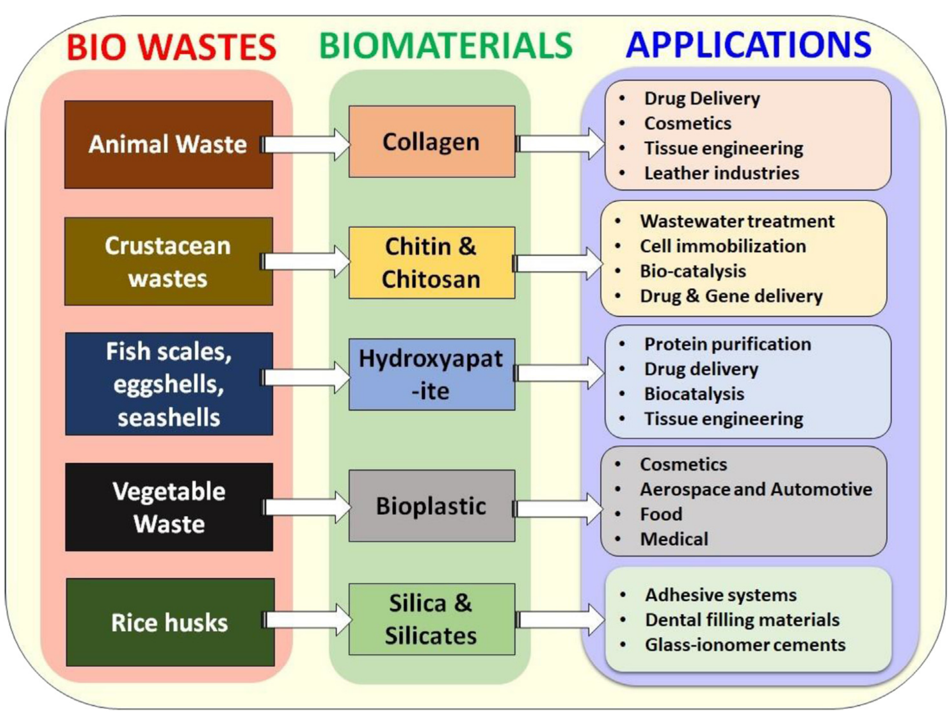

Fig. 2. Systematic look at how biowaste is turned into biomaterials and what it can be used for.

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 carboxymethylchitin (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 copolymerization 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 pretreatments 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.

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 3 h at 200 °C results in a stable carbon dot dispersion between 2 and 4 nm, an excitation peak at 365 nm, an emission peak at 444 nm, 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 0.23 nm (Ashokkumar et al., 2012). A similar technique, starting with orange seed coat debris, produced carbon dots with an average particle diameter of 2.9 nm 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 (2 kW). 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 20 nm were created; each was

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)
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)
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)
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 et al. (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 et al. (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 et al. (2020b)

Table 2 (*continued*)

S.L No	Name of biowaste	Prepared biomaterials	Key findings	Reference
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 et al. (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 et al. (2015)

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 4.61×10^{-1} 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, 12 h) before freeze-drying, the collagen fibrils rearranged with the nanocrystals to produce a sponge-like, extremely porous interconnecting substance (41 °C, 18 h) (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 et al., 2020; Kee et al., 2021; Srivastava et al., 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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