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REVIEW PAPER

# Recycling municipal, agricultural and industrial waste into energy, fertilizers, food and construction materials, and economic feasibility: a review

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## Abstract

The global amount of solid waste has dramatically increased as a result of rapid population growth, accelerated urbanization, agricultural demand, and industrial development. The world's population is expected to reach 8.5 billion by 2030, while solid waste production will reach 2.59 billion tons. This will deteriorate the already strained environment and climate situation. Consequently, there is an urgent need for methods to recycle solid waste. Here, we review recent technologies to treat solid waste, and we assess the economic feasibility of transforming waste into energy. We focus on municipal, agricultural, and industrial waste. We found that methane captured from landfilled-municipal solid waste in Delhi could supply 8–18 million houses with electricity and generate 7140 gigawatt-hour, with a prospected potential of 31,346 and 77,748 gigawatt-hour by 2030 and 2060, respectively. Valorization of agricultural solid waste and food waste by anaerobic digestion systems could replace 61.46% of natural gas and 38.54% of coal use in the United Kingdom, and could reduce land use of 1.8 million hectares if provided as animal feeds. We also estimated a levelized cost of landfill solid and anaerobic digestion waste-to-energy technologies of \$0.04/kilowatt-hour and \$0.07/kilowatt-hour, with a payback time of 0.73–1.86 years and 1.17–2.37 years, respectively. Nonetheless, current landfill waste treatment methods are still inefficient, in particular for treating food waste containing over 60% water.

**Keywords** Solid waste · Value added · Economic feasibility · Sustainable development · Waste to energy

## Introduction

Waste is a byproduct of population increase, urbanization, and economic growth (Kaza et al. 2018). Approximately 2.59 billion tons of waste will be generated globally in 2030, which is predicted to reach 3.4 billion tons by 2050, doubling from 2016 and tripling by 2100 (Abdollahi Saadatlu et al. 2022).

The principles of waste classification are diverse, such as classification according to material, state, or source. This review discusses three types of waste that use the source of waste as a classification principle: municipal solid waste, agricultural solid waste, and industrial solid waste. Municipal solid waste is one of the most significant byproducts of the urban lifestyle and is growing faster than urbanization (Tun and Juchelkova 2018; Tawfik et al. 2022). Municipal solid waste typically includes similar waste from households, businesses and trade, office buildings, institutions, and small companies (Sipra et al. 2018). According to Mandal (2019), about 4.3 billion people are estimated to live in cities by 2025, producing 1.42 kg of municipal solid trash per person per day. Azam et al. (2019) pointed out that the disposal of domestic waste in the atmosphere can cause severe health and environmental problems.

Moreover, with a dramatic increase in population, food production will face severe challenges in the coming years (Myers et al. 2017). To meet the food needs of millions of people, livestock and crop production has increased significantly with intensive rearing and cultivation systems. However, this has further led to large amounts of agricultural

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waste (Tripathi et al. 2019). Agricultural solid waste mainly includes spoiled food waste from crops, orchards, vineyards, dairies, feedlots, farms, agricultural residues, and hazardous waste (Akinrinmade 2020). In contrast, improper disposal of agricultural waste generates greenhouse gases such as carbon dioxide, nitrous oxide, and methane, threatening humans and the natural environment (Kaab et al. 2019).

In addition, worldwide industrial solid waste generation is vast, with an increasing trend to meet humans' daily needs (Tyagi et al. 2018). Industrial solid waste usually comprises steel slag, tailings, fly ash, red mud, waste tire, rubber, and special wastes generated by industries, in addition to wastes from light and heavy manufacturing, fabrication, construction sites, power plants, and chemical plants (Li et al. 2021a). These wastes contain a large number of heavy metals and other hazardous substances, and if dumped or landfilled indiscriminately, will have a severe impact on the ecological environment; meanwhile, the dumping of these industrial solid wastes takes up a large number of scarce land resources (Kulkarni 2020).

Solid waste management approaches include waste identification, reduction, recycling, storage, collection, transfer and transportation, effective treatment and disposal, and reuse (Anand 2010; Saja et al. 2021). Among several management options, landfill is the most common waste disposal route globally due to the ease of implementation (Das et al. 2019). However, landfills take up many land resources and produce leachate and landfill gas that still negatively affect the atmosphere. About 3–4% of global greenhouse gases are generated due to irrational waste disposal (Abdollahi Saadatlu et al. 2022; Chen and Lo 2016; Mrozik et al. 2021). Landfilled-solid waste can be valorized and effectively utilized for value-added products (Dlamini et al. 2019). For instance, one ton of recycled mobile phones may typically provide 0.347 kg of gold, or 80% of the material's value (Dumlao-Tan and Halog 2017). Velvizhi et al. (2020) argued that most solid waste fractions could be converted into resources rather than polluting elements through value-added technologies, which can reduce resource consumption, protect the environment, and ease the pressure on waste disposal.

However, due to the lack of economic feasibility analysis of value-added technologies, many solid waste valorization technologies have not yet been fully promoted. They are still in the laboratory research stage. In addition, because of the different value-added technologies, application directions, fundamental factors, and parameters involved in various solid wastes, the same economic feasibility assessment method cannot be applied even for the same solid waste applications. This paper assesses the economic feasibility of value addition and application of municipal, agricultural and industrial solid waste in an attempt, as shown in Fig. 1, to (i) Promote the complete application of value-added reliable waste technologies to relieve pressure on solid waste disposal; (ii) Encourage recycling and reuse of solid waste; (iii) Mitigate the adverse environmental impacts of solid waste; (iv) Conserve natural resources and expedite the achievement of the 3R strategy—Reduce, Recycle, and Reuse. This review first summarizes the directions of value-added technologies and applications for municipal, agricultural and industrial solid wastes; analyses the environmental, economic and social impacts of their practical application through case studies; summarizes the methods for assessing the economic viability of solid wastes; and finally presents limitations and future perspectives on solid waste value addition and applications, economic viability and solid waste pretreatment.

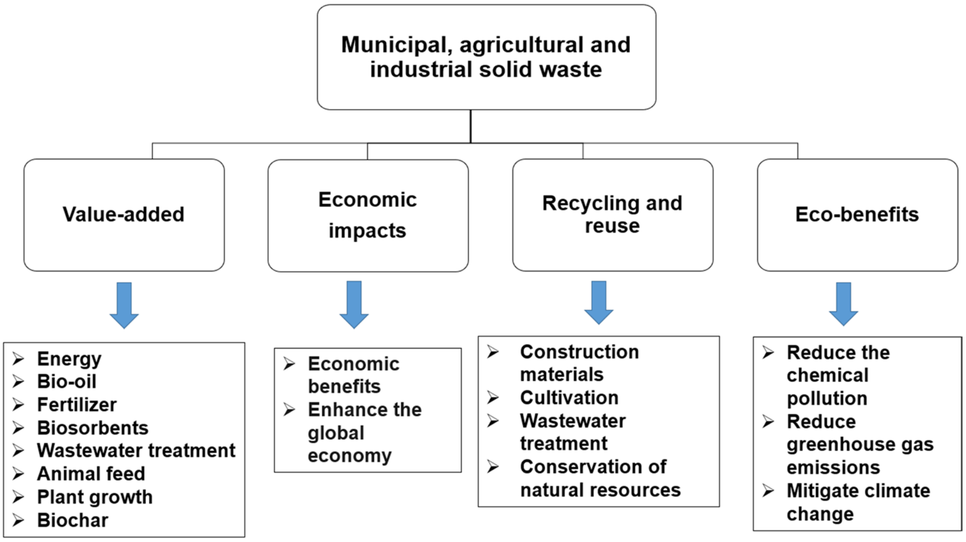

**Fig. 1** Valorization of solid wastes. Several solid wastes, including municipal, agricultural, and industrial, can be reused and recycled for many benefits. Value-added byproducts, eco-benefits, recycling, reuse, and economics are the cascade of waste valorization

## Municipal solid waste

Global urbanization increases the growth and complexity of municipal solid waste plastics, electronics, and related derivatives (Khan et al. 2022a). Municipal solid waste generally refers to products that are no longer useful and originate from the domestic and commercial sectors (Vergara and Tchobanoglous 2012). Differences in urbanization and cultural practices result in more complex content and composition of municipal solid waste (Zhu et al. 2021; Mian et al. 2017). Surveys in coastal China report that nearly half of the municipal solid waste typically disposed of in China goes to landfills and is incinerated, with only 3% being used for composting technology (Khan et al. 2022a), and that the efficiency of municipal solid waste use is much lower than in developed countries (Khan et al. 2022a). Therefore, improving municipal solid waste management systems and exploring more environmentally friendly, efficient, and affordable waste reuse technologies is essential.

The waste pyramid and integrated waste management are widely used as guiding principles for waste management (Vergara and Tchobanoglous 2012). A proper waste management system can reduce environmental pollution and solve energy issues, a worldwide challenge. Given the decisive status of today's ecological worldwide problems, reducing municipal solid waste generation at source is the most direct and effective means of doing so (Williams 2005). The conversion of municipal solid waste into alternative energy sources, such as waste-to-energy, is an inevitable route to waste applications (Huang and Fooladi 2021; Gopikumar et al. 2021). However, statistics show that reducing municipal solid waste is a challenge.

Figure 2 shows possible application directions for municipal solid waste in energy, electricity production, and fertilizer. In addition, the most recent examples of municipal solid waste applications under the above application directions, particularly in the waste-to-energy generation, which is the leading waste application direction for municipal solid waste, and the economic, environmental, and social impacts are summarized in Table 1.

Table 1 confirms the viability of municipal solid waste for different applications by summarizing and quantifying the economic, environmental, and social impacts. Waste recovery targeting municipal solid waste can provide the impetus for value addition and reuse of municipal solid waste. It significantly reduces greenhouse gas emissions, replaces traditional fossil energy sources, uses waste to produce methane for power generation and liquid fertilizer production, improves power generation efficiency and fertilizer production efficiency, reduces costs, effectively reduces total municipal solid waste, makes cleaner energy, and advances renewable energy development and clean energy recovery application options. This demonstrates the feasibility and effectiveness of adding value to and applying municipal solid waste management policy.

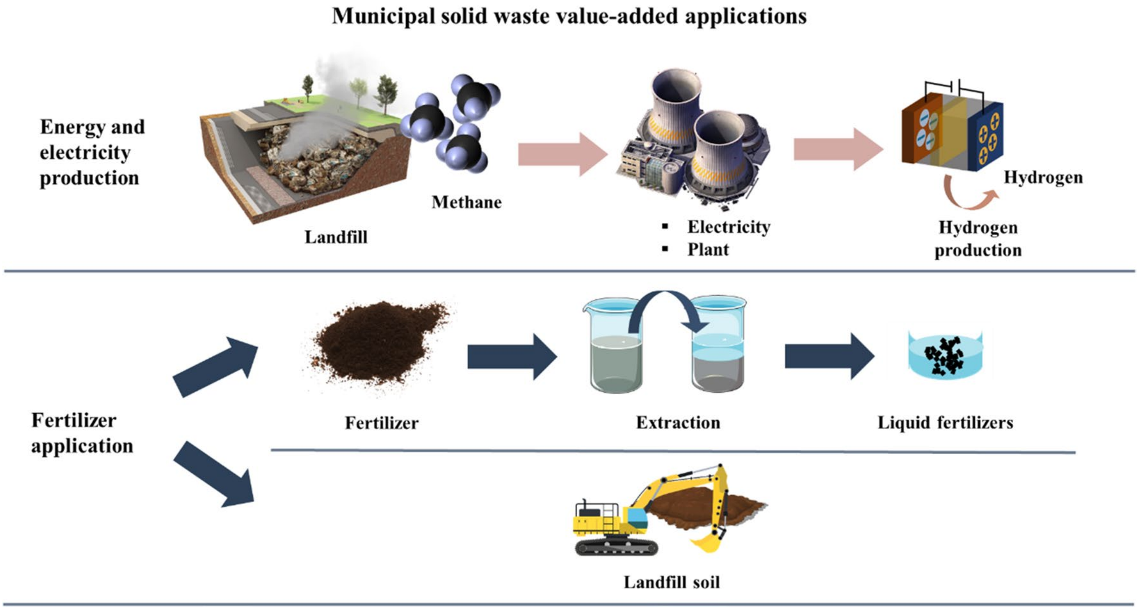

**Fig. 2** Municipal solid waste value-added applications. There are numerous uses for municipal solid waste, including energy, power generation, and fertilizer. Municipal solid waste can be converted into methane, which can then be used to generate electricity. Additionally, electricity generated from municipal solid waste can be used to produce hydrogen, a source of clean energy. The organic carbon from municipal solid waste can be extracted and used as fertilizers to improve soil fertility or buried to strengthen the soil

**Table 1** Examples of municipal solid waste application according to the different application directions. The economic, environmental, and social impact of municipal solid waste in producing energy, electricity, and fertilizer are briefly presented. Country or region refers to where the actual application was conducted for this municipal solid waste. Waste refers to the specific municipal solid waste used in a particular application case. The economic, environmental, and social impact refers, respectively, to cost savings performance, energy saving and emission reduction, and social behavior gain obtained from municipal solid waste value-added applications. " -" indicates not mentioned

| Type of waste | Country or region | Waste | Technology | Application direction | Application examples | Application impact | | | References |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Economic | Environmental | Social | |
| Municipal solid waste | Delhi, India | Biodegradable material (> 7%) | Landfill gas technology | Energy and electricity production | Collection of methane from landfills as feedstock for electricity generation | Captured methane can provide electricity for 8–18 million homes (2015) | Helping to reduce greenhouse gas emissions | Energy capture of methane to provide energy to nearby areas | (Ghosh et al. 2018) |
| Municipal solid waste | China | Biodegradable organic matter in municipal solid waste | Vertical gas extraction well system (low cost, most commonly used). Horizontal gas extraction well system (high efficiency, high cost, difficult to construct) | Energy and electricity production | Power generation and production of biogas (for vehicle and pipeline fuel) using landfill gas technology | The energy efficiency of biogas is equivalent to 228 kilotons of standard coal for energy production | Can replace 85.5% of electricity consumption or 25.3% of natural gas consumption (2015); can replace 90–220 kilotons of standard coal and reduce carbon dioxide emissions by 350–920 kilotons (2020) | Promoting sanitary landfills as an alternative to open-air refuse collection points; producing clean energy | (Fei et al. 2019) |
| Municipal solid waste | Eskisehir, Turkey | Organic, paper, glass, plastic, metal, ash, and others | Internal combustion reciprocating engines (more broadly, high generation efficiency, and low fuel operating costs) and gas turbines technology | Energy and electricity production | Generation of electricity at landfill sites by internal combustion engines and collection of landfill gas and methane | The net present value of the maximum electrical energy value is 109,070.1 gigawatt-hour; the minimum cost of electricity generation is only \$0.054/kilowatt-hour; the price of electricity from landfill gas is \$0.133/kilowatt-hour | Has a low global warming potential (conversion of methane to carbon dioxide when used as fuel in internal combustion engines) | Promotes renewable energy development; provides waste reduction and clean energy recovery alternatives | (Kale and Gökçek 2020) |

**Table 1** (continued)

| Type of waste | Country or region | Waste | Technology | Application direction | Application examples | Application impact | | | References |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Economic | Environmental | Social | |
| Municipal solid waste | Guangdong-Hong Kong-Macao Greater Bay Area, China | Food waste, paper, textiles, bamboo, wood, and ash | Landfill gas and incineration (steam generation) technologies | Energy and electricity production | Electricity production from waste through both landfill and incineration disposal | Estimated electricity generation from waste-to-energy plants is 7,140 gigawatt-hour (2019), which is 1.33% of local electricity consumption; electricity production efficiency is expected to be up to 30%; maximum potential electricity production from steam incineration is approximately 4.8–5.3 times greater than from landfill gas (assuming 15% efficiency) | Reduction in greenhouse gas emissions (maximum emission reductions of 18.4 million tons in 2030 and 45.5 million tons in 2060) | Reduction in the amount of waste disposed of to 90% | (Zhou and Zhang 2022) |
| Municipal solid waste | Saudi Arabia | Biomass from organic waste such as food waste, paper, cardboard, textiles, and wood | Anaerobic digestion and gas turbine technology | Energy and electricity production | Use of an efficient combined cogeneration cycle to produce electricity from methane produced by anaerobic digestion of solid waste, and use of electricity to produce hydrogen by electrolysis | The proton exchange membrane electrolyzer system is 3.0% more efficient than the alkaline electrolyzer system and produces 34.2% more hydrogen but at a 9.3% higher product cost | The proton exchange membrane electrolyzer system reduces carbon dioxide emissions by 3.3% compared to the alkaline electrolyzer system | Optimization of power generation systems; efficient production of hydrogen energy | (Cao et al. 2022) |

**Table 1** (continued)

| Type of waste | Country or region | Waste | Technology | Application direction | Application examples | Application impact | | | References |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Economic | Environmental | Social | |
| Municipal solid waste | Greece | Organic fraction (biowaste), paper and cardboard, plastics, metals, glass, wood, and others | Anaerobic digestion and sanitary landfilling for combined heat and power production using biogas | Energy and electricity production | Combined heat and power production using methane from the organic fraction of municipal solid waste through anaerobic digestion and sanitary landfill technology | The energy production value of anaerobic digestion technology is expected to be approximately 16–25% higher than that of sanitary landfilling technology | Reduce greenhouse gas emissions; reduce uncaptured methane emissions; reduce generated leachate production | Anaerobic digestion for the production of combined heat and power following law 2008/98/EC | (Mavridis and Voudrias 2021) |
| Municipal solid waste | India | 70% fine gravel, sand, silt, clay, 15–23% stones, brickbats, concrete fragments, 3–5% plastic, wood, textiles, and 0.9–6.5% others | Drying and sieving | Fertilizer applications | Use of soil-like material from landfills as fill (embankment, low-lying areas) and compost (horticultural, non-agricultural applications) | Reduces the need for fresh topsoil; can be used as earth fill for infrastructure projects (road and rail embankments, e.g.); low height large area fill for non-load bearing purposes (parks, golf courses); serving of low-lying areas and deep pits (mine pits) | It can be used as a low-nutrient compost in non-agricultural applications (including parks and non-food crops); enhances nutrient growth in virgin soils | Effective reduction in old waste deposits in landfill sites (< 4.75 mm soil-like material accounts for 40–70% of total excavated waste) | (Datta et al. 2021) |

**Table 1** (continued)

| Type of waste | Country or region | Waste | Technology | Application direction | Application examples | Application impact |  |  | References |
|---|---|---|---|---|---|---|---|---|---|
|  |  |  |  |  |  | Economic | Environmental | Social |  |
| Municipal solid waste | Mirandela, Portugal | The organic fraction of composted municipal mixed solid waste | Conventional solvent extraction and microwave-assisted extraction | Fertilizer applications | Liquid manure extraction from organic waste by conventional solvent extraction and microwave-assisted extraction techniques in aqueous and alkaline solutions | Traditional solvent extraction is four times less expensive than microwave-assisted extraction (complex equipment); fertilizer yields with alkaline extraction are ten times higher than water-based extraction, and the price is > €3/liter | Water-based extraction consumes 53–280 times more water and 12–18 times more energy than alkaline extraction and has a more significant environmental impact | Scale-up of organic waste liquid fertilizer production; facilitates waste management and disposal; provides a more favorable approach to liquid fertilizer production | (Fernández-Delgado et al. 2022) |
| Municipal solid waste | Dhanbad, India | Solid organic waste | New thermal digestion technology | Fertilizer applications | Organic fertilizer production from the organic fraction of solid waste using the new thermal digestion technology | Maximum weight loss and optimum nutrient retention with minimal energy (150 °C, 135 min); total macronutrients (sodium, phosphorus, potassium) in the digested solid organic waste are above the specified standards for organic fertilizers (> 1.2%) | Increased water holding capacity of organic fertilizer (43–55% increase in porosity) for plant growth; maximum nutritional value; > 90% seed germination | The effectiveness of thermal digestion in the rapid reduction in solid organic waste and nutrient cycling was demonstrated as a novel concept and research database for the clean and sustainable management of solid organic waste | (Kumar and Gupta 2021) |

## Municipal solid waste for energy and electricity production

Using municipal solid waste for waste-to-energy pathway is necessary for waste management and disposal (Jabeen et al. 2022). Landfill gas and anaerobic digestion are the primary methods for producing energy from municipal solid waste (Mlaik et al. 2019).

Landfill gas technology is one of the oldest and most commonly used technologies for electricity generation (Cudjoe et al. 2021a; Timilsina 2021). The landfill gas process for electricity generation comprises approximately 40% carbon dioxide and 60% methane with a high electrical and thermal energy content (Ayodele et al. 2017). Fei et al. (2019) found a maximum landfill gas value of 3.3 billion $Nm^3$ over 30 years in China, generating up to 7.5 billion kilowatt-hours of electricity. The minimum cost of landfill gas technology for electricity generation in Turkey is only $0.05/kilowatt-hour (Kale and Gökçek 2020).

Anaerobic digestion is capable of recovering high-quality methane, converting organic waste from municipal solid waste into electricity (Uddin et al. 2021) and high levels of heat (Ayodele et al. 2017), and solving energy problems while also obtaining compost and humus (Mlaik et al. 2019; Diaz et al. 2011). Not only is the waste recycling phase simplified (Khanal et al. 2021) and the landfill process simplified (Chen et al. 2010; Sikarwar et al. 2021), but it can also have a higher power generation capacity while producing fertilizer (Mlaik et al. 2019) and biogas (Fei et al. 2019) as a derivative. Farghali et al. (2022) estimated that using the anaerobic digestion of affordable wastes for biogas generation has the potential to decrease greenhouse gas emissions by approximately 4.36 gigatons of carbon dioxide equivalent, or 13% of worldwide greenhouse gas emissions from deforestation, evaded emissions management, crop burning, landfill gas, and fertilizer synthesis emissions.

Conversion of municipal solid waste to energy through a waste-to-energy pathway can produce renewable energy by capturing methane. For instance, Ghosh et al. (2018) showed that captured methane from Delhi landfills supplied 8–18 million houses with power in 2015. Similarly, Zhou and Zhang (2022) found that a waste-to-energy plant in Taiwan, China, generated 1.33% of local electricity consumption, with expected electricity production efficiency of 30%, corresponding to 31,346 and 77,748 gigawatt-hours by 2030 and 2060, respectively. Furthermore, Cao et al. (2022) suggested combined cogeneration of hydrogen from electrolysis and power from the anaerobic digestion process. In addition to renewable energy production, waste-to-energy generation has the potential to reduce greenhouse gas emissions (Huang and Fooladi 2021; Mavridis and Voudrias 2021; Osman et al. 2022a). Ayodele et al. (2017) reported the environmental performance of hybrid and landfill gas blending methods in the Nigerian region, with greenhouse emission reduction rates of 76–93% and 75–85%, respectively. In addition, using the waste-to-energy concept can save on fossil fuel combustion and significantly reduce the cost of electricity generation (Olujobi et al. 2022; Breunig et al. 2022). The minimum price of electricity generation is only $0.054/kilowatt-hour compared to $0.133/kilowatt-hour for landfill gas (Kale and Gökçek 2020), with a significant reduction in the total amount of disposed waste (Zhou and Zhang 2022). In addition, the waste-to-energy concept provides a way to recycle, reuse, and add value to waste (Fei et al. 2019; Patel et al. 2021), provides an alternative to clean energy recovery (Kale and Gökçek 2020), and facilitates the sustainable development of alternatives to fossil fuel combustion (Gil and Management 2022).

Both anaerobic digestion and landfill gas technologies have good environmental, economic, and social performance for electricity generation. However, Cudjoe et al. (2020) showed that anaerobic digestion has a higher and more economic potential for electricity generation than landfill gas in the study area (Cudjoe et al. 2020; Ogunjuyigbe et al. 2017). Huang and Fooladi (2021) investigated the power generation potential of landfill gas and anaerobic digestion technologies in Tehran and Beijing over 20 years. They found that the technologies generated 45.2% and 41.9% more electricity than landfill gas technologies in Tehran and Beijing, respectively, and that anaerobic digestion had the most substantial potential to mitigate global warming (Caiardi et al. 2022). Thus, anaerobic digestion has tremendous potential for producing power from municipal solid waste (Longsheng et al. 2022).

Landfill waste treatment methods currently face the challenge of inefficiency, particularly when treating food waste comprising over 60% of the water content (Zhou and Zhang 2022). One approach to solving this issue is by reducing the food waste content of waste incineration; for example, reducing the waste's water content by 9–44% significantly increased calorific value and, therefore, improved power generation efficiency (Yang et al. 2012).

In conclusion, using waste-to-energy is the best way to dispose of and add value to waste to meet the growing world population and the increasing volume of municipal solid waste. At the same time, the production of clean renewable energy as an alternative to fossil fuels creates a virtuous cycle in economic, environmental, and social terms, contributing to the development of sustainable cities and a global green future.

## Municipal solid waste for fertilizer application

Uses of inorganic nitrogen comprise about 50% of current agricultural production (Chehade and Dincer 2021); however, the heavy use of inorganic fertilizers poses climate and environmental concerns. For example, inorganic fertilizers contribute to large amounts of greenhouse gas emissions (Bhattacharyya et al. 2012; Wang et al. 2022) and eutrophication of the water environment (Walling and Vaneeckhaute 2020; Liu et al. 2021). On the other hand, organic fertilizers can improve organic carbon in the soil while providing sufficient nutrients to plants (Sharma et al. 2019). Therefore, replacing inorganic fertilizers with organic fertilizers is urgently needed to address current environmental issues.

Municipal solid waste can be used either to produce high-quality liquid fertilizers from organic waste or extract soil-like materials from organic waste for landfill and fertilizer use. Several recent studies have shown the possibilities of producing organic fertilizers from municipal waste (Yong et al. 2021; Rashid and Shahzad 2021; Roman et al. 2021). For example, Fernández-Delgado et al. (2020) proposed the extraction of organic carbon from municipal solid waste compost technology to produce 200 L of liquid fertilizer at €1/liter per 100 kg of dry compost. Campuzano and González-Martínez (2017) confirmed the possibility of extracting soluble organic substances from municipal solid waste's organic fraction and accelerating methane production.

Extraction technologies of high-value organic fertilizer from municipal solid waste are received more attention and innovation at a lower cost (Fernández-Delgado et al. 2022). Conventional solvent and microwave-assisted extraction are common for liquid fertilizers (Monda et al. 2017). The extraction of liquid fertilizers by alkaline traditional solvent extraction techniques is a simple, efficient, and environmentally friendly method (Fernández-Delgado et al. 2022; Gravert et al. 2021). In addition, traditional solvent extraction is a less energy-required intensive method, with a selling cost of €1/liter (Fernández-Delgado et al. 2022), and the fertilizer yield is ten times higher than that of water-based extraction (Yan et al. 2022).

Microwave-assisted extraction is considered a more environmentally friendly and green technology than conventional solvent extraction (Arpia et al. 2021). However, microwave-assisted extraction requires more complex conditions during the extraction process, such as higher temperatures, power, and limitations in the dielectric properties of solid materials (Kostas et al. 2017; Picot-Allain et al. 2021). Microwave-assisted extraction is comparable to conventional solvent extraction techniques when increasing the operating temperature and reducing the reaction time (Dao et al. 2020).

In general, the liquid fertilizers produced from municipal solid waste have much higher total macronutrients (sodium, phosphorus, potassium) than those specified for organic fertilizers, improve soil water-holding capacity (Leno et al. 2021), increase porosity (Khosravi et al. 2022), and benefit plant and crop growth (Kumar and Gupta 2021). The new thermal digestion is a new type of digestion that has been developed to make the application of organic fertilizers from the organic fraction of solid waste more efficient and environmentally friendly, hence achieving maximum weight loss of waste and optimum nutrient retention of fertilizer with minimal energy consumption within 135 min at 150 °C (Kumar and Gupta 2021).

In addition, soil-like material from municipal solid waste piles can be used as fill for road embankments and low-lying areas (Datta et al. 2021), compost for horticulture, and other non-agricultural applications (Sadeghi et al. 2022).

Through the adoption of this technology, the total amount of waste in landfills is significantly reduced, reducing the need for fresh soil and saving on landfill costs and waste management and disposal costs (Saravanan et al. 2022). Considering the possible presence of heavy metal ions in soil-like materials in waste piles (Gujre et al. 2021), their use for non-edible crops can reduce their risk and hazard while enhancing the nutrient content of virgin soil for non-agricultural applications (Datta et al. 2021; Bernat et al. 2022; Singh et al. 2021).

Although the feasibility of organic extraction from the municipal solid waste application has been verified, the technology's reliability and the liquid fertilizer quality still need to be supported by a lot of research data (Norouzi and Dutta 2022). In addition, applying municipal solid waste to extract organic liquid fertilizers still needs much exploration. Using other organic residues as raw materials also be explored as a breakthrough in advanced technology (Thanigaivel et al. 2022).

In conclusion, using more advanced technologies to extract high-quality liquid fertilizers from the organic fraction of municipal solid waste and using soil-like materials from municipal solid waste as compost for landfill and non-agricultural applications are excellent methods for the valorization of municipal solid waste. Such an approach in the direction of fertilizer applications provides a novel concept, innovative technology, and a reliable pool of examples for the clean and sustainable management of solid organic waste.

This section explains the latest directions in applying municipal solid waste in energy, electricity production, and fertilizer and demonstrates system feasibility. The reuse of municipal solid waste is not only outstanding for generating electricity from waste but also for the significant mitigation of the greenhouse effect and the production and substitution of new energy sources at a lower cost. In addition, municipal solid waste also performs well in the preparation of liquid fertilizers. Technological innovations have been applied to achieve minimal energy consumption to achieve maximum waste consumption and optimum nutrient retention, reduce production costs and increase the efficiency of fertilizer production. Furthermore, treated waste in landfill reduces the total amount of waste, reduce the use of fresh soil, and improve soil nutrients. It offers innovative solutions for clean energy recovery and renewable energy development applications, providing the latest technology and inexhaustible power for value-adding and application of municipal solid waste.

## Agricultural solid waste

Today's agricultural development is growing at a rapid pace due to the explosion of population growth worldwide (Otsuka and Fan 2021). Based on consumption patterns over the last 30 years, crop and food production must increase by more than 50% by 2050 and is expected to reach approximately 12 billion tons (Porter 2016). Agricultural production is no longer limited to feeding the population but is involved in producing livestock and industry (Helliwell and Burton 2021) and should consider conserving natural resources (Li et al. 2021b). As a result, it is anticipated that the demand for and production of agricultural products will continue to increase over time.

The rapid growth of agriculture and the higher demand for agricultural products is stressing and threatening the environment, climate, ecosystems, and human health (Duque-Acevedo et al. 2020; Cai et al. 2021). According to recent statistics, the world produces about 1 billion tons of agricultural waste yearly, and agriculture contributes about one-fifth of greenhouse gas emissions (Karić et al. 2022). The United Nations has echoed the global call for people to reduce fossil fuel use and greenhouse gas emissions and move toward zero solid waste (Duque-Acevedo et al. 2020; Commission 2012). In addition, the world is facing increasing energy scarcity today (Zhao et al. 2022; Pandey and Asif 2022). Applying agricultural waste to developing and using alternative energy sources is crucial for researchers in sustainable energy and green development (Chen et al. 2022).

Therefore, as shown in Fig. 3, the application directions for agricultural solid waste are summarized as industrial production, plant growth, soil improvement, animal feed, and biosorbents. Table 2 summarizes the latest examples of applications and technologies and the economic, environmental, and social impacts of the applications.

This table confirms the feasibility of reusing agricultural solid waste by quantifying the economic, environmental, and social aspects in different application directions. Valorizing agricultural solid waste strongly mitigates the global greenhouse effect, contributes to alternative energy sources, saves investment costs, increases crop yields and improves crop quality, and significantly contributes to innovation and development in managing agricultural solid waste and waste utilization technologies. This demonstrates the feasibility and needs for value addition and application of agricultural solid waste.

### Agricultural waste in industrial production

Bio-oil from rapid pyrolysis of agricultural waste and methane from anaerobic digestion is a critical resource used in industrial processes. Fast pyrolysis is the rapid thermal decomposition of organic matter without oxygen, resulting

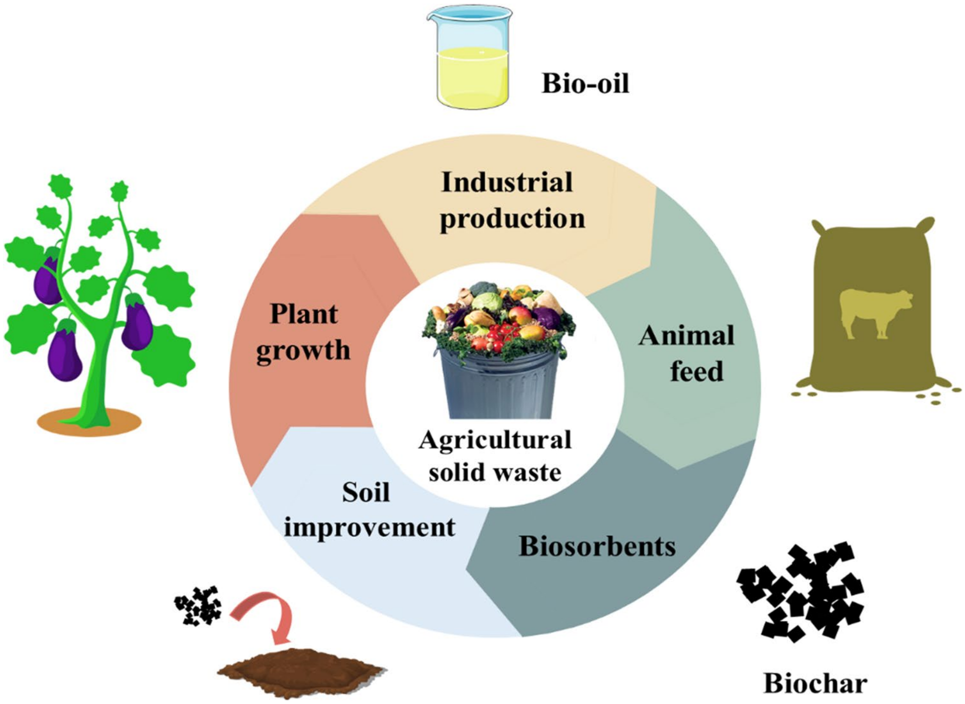

**Fig. 3** Value-added application scope of agricultural solid waste. This figure shows agricultural solid waste that can be valorized for industrial production, plant growth, animal feed production, soil improvement, and biosorbents. Bio-oil is representative of the leading industrial production directions. Through the production of biosorbents, organic carbon can be extracted and used for soil improvement. This facilitates the improvement of plant growth and the improvement of animal feed. Using treated agricultural waste as animal feed would assist in solving current high feed prices

**Table 2** Valorization directions of several agricultural solid wastes. Brief examples of agricultural solid waste in different application directions and data on economic, environmental, and social impacts are presented. Country or region refers to where the actual application study was conducted for this agricultural solid waste. Waste refers to the specific waste name of the agricultural solid waste used in this application case. The economic impact exemplifies the cost savings performance of a value-added agricultural solid waste application. In contrast, the environmental impact refers to this agricultural solid waste value-added application case's energy and emission reduction performance. Social influence refers to the gain from the value-added application of agricultural solid waste in terms of social behavior. "-" indicates not mentioned

| Type of waste | Country or region | Waste | Technology | Application direction | Application examples | Application impact | | | References |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Economic | Environmental | Social | |
| Agricultural solid waste | – | Agricultural residues | Processing of agricultural residues by rapid pyrolysis and rapid cooling at 450 °C to 500 °C | Industrial production | Rapid pyrolysis and cooling of agricultural residues to produce bio-oil | Bio-oil conversion from agricultural residues yields up to 80% oil, reducing the cost of oil for industrial use | – | – | (Guedes et al. 2018; Xiu and Shahbazi 2012) |
| Agricultural solid waste | - | Animal manure, straw | Digestion of organic matter in manure into simple organic matter and biogas products through anaerobic digestion units | Industrial production | Animal manure and straw are sampled and digested to produce biogas and methane that can be used as engine fuel | Reduced engine fuel costs | Reducing the environmental problems caused by the use of fossil fuels in engines | Achieved fossil energy substitution | (Demirbas 2007; Gao et al. 2019) |
| Agricultural solid waste | – | Woody biomass, such as coconut fiber and dead eucalyptus leaves | Woody biomass is charred by hydrothermal technology at 150–375 °C for 30 min | Soil improvement | Woody biomass treated with hydrothermal carbonization technology produces biochar for soil amendment | – | – | Increased area of usable soil | (Liu et al. 2013) |
| Agricultural solid waste | – | Onion, mint, coconut, everlasting fruit, corn cob | Treatment of flowerpots with a mixture of decomposed waste and finely powdered poly-chitosan | Plant breeding | Control of root-knot nematodes that are harmful to the plant | Reduces the cost of cultivation and improves the yield and quality of the plant's fruit | Reduced use of pesticides and fertilizers, reducing chemical pollution of soil and water | – | (Asif et al. 2017) |
| Agricultural solid waste | – | Walnut shells | Dried walnut shells | Plant breeding | Walnut shells have a repellent effect on the plant | – | Reduced root-knot nematode activity and chemical pesticide use | – | (Maleita et al. 2017) |

**Table 2** (continued)

| Type of waste | Country or region | Waste | Technology | Application direction | Application examples | Application impact | | | References |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Economic | Environmental | Social | |
| Agricultural solid waste | United Kingdom | Manufacturing or retail food wastes or agricultural co-products (such as beet tails or soybean meal) | Conversion to dry, wet pig feed; anaerobic digestion and composting | Animal feed | Processing of food waste into wet pig feed and dry pig feed | Reduction in land use by 1.8 million hectares; provision of feed to support 20% of European Union pork production | Biogas from this study was able to replace 61.46% of natural gas and 38.54% of coal use in the United Kingdom; using food waste for anaerobic digestion contributed 1.04 times more to carbon dioxide reduction than making dry feed | Improving farmers' profitability; improving meat quality and taste | (Salemdeeb et al. 2017) |
| Agricultural solid waste | Cyprus | Orange, mandarin, and banana peels | Microcosm set-up | Soil improvement | Agricultural waste application to soils improves soil fertility and reduces carbon dioxide and nitrous oxide direct gas emissions through effects on bacterial communities | Enhances soil fertility (increases organic carbon and nutrients and stimulates bacterial activity) | 5.3–10.2 times lower nitrous oxide emissions than ammonium nitrate applied to the soil | For the promotion and innovation of the management of peel-based agricultural waste | (Anastopoulos et al. 2019) |

**Table 2** (continued)

| Type of waste | Country or region | Waste | Technology | Application direction | Application examples | Application impact | | | References |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Economic | Environmental | Social | |
| Agricultural solid waste | Ho Chi Minh, Viet Nam | Plant debris, food waste, plant waste, and animal waste | Physical steam-assisted reforming (pyrolysis and gasification); chemical synthesis | Biosorbents | Biochar production from agricultural waste biomass as a raw material | Improves plant productivity (improves nutrients, water retention, increases bioactivity, neutralizes soil pH, metal supplements); increases agricultural profitability (promotes agricultural production, improves farm resilience) | Reduction in airborne greenhouse gas emissions; fluid retention (porosity to enhance water retention); carbon capture (sequestration); reduction in soil acidity | Ease of use; ecological integrity; public safety trustworthiness | (Van Nguyen et al. 2022) |

**Table 2** (continued)

| Type of waste | Country or region | Waste | Technology | Application direction | Application examples | Application impact |  |  | References |
|---|---|---|---|---|---|---|---|---|---|
|  |  |  |  |  |  | Economic | Environmental | Social |  |
| Agricultural solid waste | Ukraine | Walnut shells and apricot kernels | Aqueous ammonia soaking biomass processing technique | Biosorbents | Production of biosorbents and liquid fertilizers from non-wood biomass | The intermediate product has an exchange capacity of up to 70–90% compared to commercially available ion exchangers at a 5–10% price. Cost savings of 75–85% for the preparation of biosorbents compared to direct waste treatment;<br>the byproduct liquid fertilizer increases the growth intensity of wheat (40–75% increase in plant length and 20–30% increase in total weight) | Biosorbents for heavy metal ions (270 mg/g), uranium (-196 mg/g), various metal cations, and synthetic dyes | Fueling the development of waste-free technologies for large-scale chemical treatment of agricultural waste | (Yelatontsev 2023) |

in charcoal, bio-oil, and gaseous co-products (Kostas et al. 2020). Kostas et al. (2020) stated that the pyrolysis of agricultural residues at temperatures 450–500 °C resulted in condensable gaseous volatiles, which were rapidly cooled to obtain bio-oil. Dried agricultural residues can yield up to 80% bio-oil after pyrolysis (Bharathiraja et al. 2018). Anaerobic digestion is defined by Ighalo et al. (2022) as a process that speeds up the breakdown of organic matter in manure into simple organic matter and biogas products. The anaerobic reactor provides essential temperature conditions for the decomposition and digestion of agricultural residues to ensure bacterial activity and gas production (Singh et al. 2019a, b). Biomethane obtained from the anaerobic digestion of agricultural waste (for example, animal manure and straw) can substitute diesel fuel engines (Bisaglia et al. 2018). Waste disposal policies using biomethane increase resource demand (Patrizio et al. 2015; Scarlat et al. 2018). In addition, Bisaglia et al. (2018) demonstrated through comparative experiments between diesel and methane engines that the methane engine performs similarly to diesel engines under stable conditions.

This means that bio-oil and biomethane can be introduced into industrial production in large quantities, partially replacing fossil energy sources and reducing fuel costs. However, the quality needs from bio-oil to be improved (Xiu and Shahbazi 2012). Furthermore, the design of methane-depending engines is still in its infancy, as the performance of the engine equipment is more suited to diesel fuels, which may result in methane fuels not being well performed (Bisaglia et al. 2018). Hence, further exploration and research are needed.

## Agricultural waste for plant growth

Root-knot nematodes affect almost all crops worldwide, causing significant yield losses and reducing fruit quality (Forghani and Hajihassani 2020). However, the continued use of chemical nematicides increases environmental pollution and exacerbates human health problems (Khan et al. 2022b). Asif et al. (2017) verified the effectiveness of agricultural waste in controlling root-knot nematode. They found that eggplant treated with a combination of chitosan and mint showed a significant increase in yield, pollen fertility, and length. The root-knot nematode population of the treated plants was only one-third of the untreated plants.

Similarly, Khan et al. (2022b) suggested that using mint and onion enhanced the release of alkaloid metabolites, providing the plant with a defense against pathogens. In addition, Maleita et al. (2017) noted that the significant content of biocide naphthoquinone-based products in walnut shells, the main component of biocides against root-knot nematodes, resulting in a repellent effect of dried walnut shells, reducing nematode root penetration but not affecting plant reproduction. Thus, the biological role of agricultural waste in plant breeding for pest control can effectively avoid negative impacts on the environment and humans (Brigde and Starr 2007; Fabiyi et al. 2018).

In general, onion, mint, and walnut shells from agricultural waste are active and effective in controlling root-knot nematode damage to crops, preventing the quality and yield of fruit from negatively affecting the pest. Using agricultural waste as a biopesticide reduces the cost of cultivating plants and soil and water pollution by chemical pesticides, resulting in green agriculture (Campos et al. 2019).

## Agricultural waste for animal feed

In the United Kingdom, 234 kg of food is wasted per person annually, generating approximately 15 million tons of food waste per year (WRAP 2015). The conventional disposal of food waste can be very damaging and burdensome to the environment. For example, landfills and composting generate large amounts of greenhouse gases and lead to the eutrophication and acidification of ecosystems (Arafat et al. 2015; Moult et al. 2018). Therefore, there is an urgent need for more development and innovation in managing and disposal of food waste from agricultural solid waste. Worldwide, food waste can be used as animal feed, for example, in modern pig farming systems (Fausto-Castro et al. 2020). Approximately 42.5% and 35.9% of food waste are recycled as feed in Korea and Japan, respectively (Zu Ermgassen et al. 2016). Similarly, Salemdeeb et al. (2017) showed that using treated food waste as pig feed could support 20% of pork production in the European Union, thereby reducing land use by 1.8 million hectares.

In addition, the use of food waste from agricultural solid waste for the preparation of animal feeds is an outstanding contribution in terms of environmental and economic terms. For example, using food waste as animal feed can effectively reduce the total amount of food waste (Georganas et al. 2020) and significantly reduce the carbon emissions associated with food waste disposal in traditional landfills (Dorward 2012; Lee et al. 2017). The use of waste for animal feed preparation is an update and advancement in the management and disposal of agricultural solid waste, with implications for social hygiene (Eriksson et al. 2015), farmers' profitability (Filimonau et al. 2022), and livestock development (Singh and Kumari 2019) are of great importance. Thus, animal feed practitioners unanimously favor food waste as a research area for sustainable animal nutrition to advance animal husbandry (Mourad 2016).

On the other hand, using food waste in anaerobic digestion for biomethane production could replace 61.46% of natural gas and 38.54% of coal in the United Kingdom (Salemdeeb et al. 2017). However, using food waste for animal feed is more significant in terms of carbon dioxide reduction than composting and anaerobic digestion due to eliminating the cumbersome production phase of traditional feed (Awasthi et al. 2021a).

Although the preparation of animal feed from food waste in agricultural solids has been explored and confirmed with several environmental and public health benefits, its application's feasibility is currently not legalized (Yang et al. 2019; Rajeh et al. 2021). Scarce nations such as South Korea and Japan collected food waste and used it for animal feed production (Chen et al. 2015; Torok et al. 2021). Thus, legalizing the use of food waste as feed in animal husbandry requires local government and policy support (Zu Ermgassen et al. 2016). In addition to the political and infrastructural concerns, public concerns about using safe food waste as animal feed are still of particular concern (Shurson 2020). The food waste freshness and operational complexity of separate collection from other waste also hinder using food waste from agricultural solid waste for animal feed production (Salemdeeb et al. 2017). Therefore, separating food waste according to the animal feed grads and feedstocks for composting or anaerobic digestion can overcome poor quality or incomplete separation of collected food waste (Keng et al. 2020).

In conclusion, applying agricultural solid waste for animal feed production positively impacts environmental and social benefits. In particular, valorizing animal wastes as feed stands out regarding economic costs and is environmentally friendly. Several benefits can also be attained, such as low carbon, healthy animal feed at a lower production cost, indirectly reducing land use, considered waste resources, managing agricultural solid waste, and realizing value added from the waste.

## Agricultural waste for soil amendment

The management and collection of agricultural solid wastes and their amendment to soil is another development direction for the value-added solid waste application. Microorganisms' genetic engineering and bioremediation to improve soil are considered ecologically adaptive, non-toxic, environmentally friendly, and rational practices today (Santos et al. 2019). This practice does not cause secondary damage to the ecosystem (M. Tahat et al. 2020). The highly biodegradable nature of agricultural solid waste is favored waste recycling (Kainthola et al. 2019).

Application of peel waste from agricultural solid waste to soil can effectively improve soil fertility by increasing organic carbon content, improving porosity, increasing ion exchange capacity, increasing soil nutrients, and promoting bacterial activity in the soil (Weber et al. 2007; Mr et al. 2022; Almendro-Candel et al. 2018; Murtaza et al. 2019). In addition, using agricultural solid waste as an alternative to conventional fertilizers in soil amendment applications can significantly reduce greenhouse gas emissions of nitrous oxide and carbon dioxide (Rittl et al. 2018). For instance, Anastopoulos et al. (2019) investigated that applying organic waste of orange, mandarin, and banana peel resulted in 5.3–10.2 times lower nitrous oxide emissions than using ammonium nitrate in the soil. Numerous agricultural solid wastes have proven their technical feasibility in soil improvement (Wainaina et al. 2020; Duan et al. 2020). In addition, the agricultural solid waste amendment to soil significantly reduced conventional fertilizers' need and use (Kizito et al. 2019), thereby reducing costs, toxicity, and damage to ecosystems (Bekchanov and Mirzabaev 2018).

However, applying chemical fertilizers and pesticides is inevitable to meet the rapid global population growth and the massive demand for agricultural production (Yaashikaa and Kumar 2022). Therefore, the immediate improvement of the soil environment, nutrient enrichment, and increased crop yields through the widespread substitution of agricultural solid waste for traditional feedstuffs is currently unattainable. Hence, governments and relevant authorities must support agricultural solid waste application policy (Duan et al. 2020). More innovative exploration and technological applications for reusing agriculture waste to replace fertilizers as much as possible for soil improvement are needed (Usmani et al. 2020) to increase yields and productivity and to maintain the well-being of global human health and safety.

The conversion of agricultural waste to biochar for soil improvement is a hot topic today (Osman et al. 2022b). Biochar can be produced from the thermochemical conversion of waste using pyrolysis, hydrothermal carbonization, and gasification in an anoxic environment (Osman et al. 2022b). Biochar can be generated at 300–900 °C pyrolysis conditions at different time ranges (Osman et al. 2022b), while the hydrothermal carbonization technology converts waste biomass into hydrochar at 150–375 °C with a residence time of 30 min (Peng et al. 2016; Sharma et al. 2020). Biochar improves the soil's physical properties in terms of permeability, swelling, shrinkage, water-holding capacity, aeration, nutrient fixation, and soil preparation workability response to ambient temperature changes (Osman et al. 2022b). Biochar also reduces drought by increasing soil water content and reducing soil erosion (Oni et al. 2019; Sohi et al. 2010). Additionally, biochar prompts methane production during the anaerobic digestion of organic waste (Xiao et al. 2021).

In summary, increasing research is dedicated to technological advances and innovations in applying agricultural solid waste to soil improvement. Combining the management and application of agricultural solid waste in bioengineering reduces costs, improves soil fertility, and significantly mitigates the greenhouse effect and carbon emissions, contributing to sustainable and environmentally friendly agriculture development and advancement.

### Agricultural waste for biosorbents preparation

Treated agricultural solid waste can be used as biosorbents to treat wastewater (De Gisi et al. 2016) and contaminated soil (Abedinzadeh et al. 2020). The adsorption capacity of biosorbents is determined by the adsorbent's material composition, chemical properties, and activation capacity (Bernal et al. 2018). The ideal biosorbents should have high selectivity, high biosorption rates, increased storage capacity, and low cost (Crini and Lichtfouse 2018). Some of the peelings, husks, wood, and roots of plants from agricultural waste are commonly applied as raw materials for biosorbents to add value to agricultural waste (Karić et al. 2022). Specific example includes potatoes peels, citrus fruits, and bananas (El-Azazy et al. 2019; Meneguzzo et al. 2019), coconut husks and waste (Obeng et al. 2020), maize cobs (Luo et al. 2018), rice husks of rice straw (Shamsollahi and Partovinia 2019), and peanut hulls (Banerjee et al. 2019), among others. Thus, using effective biomass from agricultural waste to prepare novel biosorbents is a new direction of research to address water and soil pollution from an ecological perspective (Dai et al. 2018).

The main methods currently used to prepare biosorbents are high-temperature physical pyrolysis (Rosales et al. 2017) and hybrid processes by adding chemical reagents at lower temperatures (Janyasuthiwong et al. 2015). El-Azazy et al. (2019) used potato peel as a raw material to carbonize activated carbon at 500 °C for 30 min. Similarly, Lu and Guo (2019) used composite carbonized walnut shells to prepare biosorbents by combining a chemical activation reaction with immersion in concentrated sulfuric acid for 12 h and then exposure to temperatures below 55 °C.

Using agricultural solid waste for biosorbents preparation can effectively reduce greenhouse gas emissions in the air (Saad et al. 2010; Gwenzi et al. 2015) and achieve carbon capture and sequestration (Gwenzi et al. 2015). In addition, waste-based biosorbents in soils can significantly increase plant productivity. Biochar can be considered as a biosorbent to enhance soil water retention by increasing porosity (Van Nguyen et al. 2022), reducing soil acidity (Afroze et al. 2018), providing pH stability for plant growth, and replenishing metal elements (Van Nguyen et al. 2022; Schwantes et al. 2022). Thus, the recycling of agricultural solid waste for the preparation of biosorbents promotes agricultural production, contributes to the resilience of farmland, effectively increases farmers' profitability, and demonstrates outstanding environmental friendliness. Waste-based biosorbents have been used as cost-effective (Deniz and Kepekci 2016) biosorbents for heavy metal ions, uranium, various metal cations, and synthetic dyes from wastewater (Yelatontsev 2023; Moharm et al. 2022). Yelatontsev (2023) found that the preparation of biosorbents from walnut shells and apricot kernels was 75–85% cheaper than the direct treatment of agricultural solid waste and that the preparation of biosorbents resulted in the production of liquid fertilizer as a byproduct (Ververi et al. 2019), effectively increasing the growth intensity of crops such as wheat.

Although current biosorption from agricultural solid waste has better environmental and economic benefits and performance than conventional adsorbents on the market, the raw biosorption capacity of biosorbents is lower than that of commercial synthetic sorbents (Karić et al. 2022). However, pretreatment of agricultural solid waste under appropriate conditions can effectively improve the adsorption performance of biomass (Enaime et al. 2020). For example, adjustment of effluent pH can change the adsorption efficiency for anions and cations (Singh et al. 2015) or the tailoring and design of functional groups according to the affinity of the target pollutant (Godinho et al. 2019). Although further technological developments and research breakthroughs are still needed, efficient biosorbents based on agricultural solid waste can gain attention and widespread promotion on the road to a sustainable future.

In conclusion, the appropriate treatment of agricultural solid waste can be used to prepare biosorbents to treat wastewater and remediate contaminated soil with biochar. Moreover, this application direction of biosorbents is becoming increasingly mature, with better adsorption and waste treatment properties, higher environmental friendliness, lower prices, and longer-term social sustainability.

This section explains the feasibility of using agricultural solid waste in five recent applications: industrial production, plant growth, soil improvement, animal feed, and biosorbents. The reuse of agricultural solid waste can achieve several benefits. In economic terms, agricultural solid waste can increase crop yields and reduces costs. Environmentally, agricultural solid waste can replace fossil energy and reduces greenhouse gas emissions. Finally, in social terms, agricultural solid waste can promote and innovate the management of agricultural solid waste. Thus, agricultural solid waste is an impetus for new applications and technological updates in waste reuse.

## Industrial solid waste

With accelerated urbanization and industrialization, industrial solid waste prevention and control is under pressure worldwide. Industrial solid waste is not easily mobile and diffuse, fluctuates poorly and causes long-term pollution and damage to the ecological environment (Guan et al. 2019). Therefore, more efforts are needed to explore ways to manage industrial solid waste (Cetrulo et al. 2018; He 2017). In this paper, the reuse of industrial solid waste is classified according to its application directions in plant cultivation, construction materials, and natural resource conservation, as shown in Fig. 4.

The application directions of industrial solid waste and specific examples are demonstrated in Table 3. Whereby the application of industrial solid waste for plant cultivation can be achieved in two main ways, building water storage systems for plant pots and partially replacing commercial fertilizers for plant growth by increasing the nutrient content of plant fruits. For construction materials, industrial solid waste can be used as an additive to asphalt concrete and cement supplement to achieve cost reductions in construction materials and greenhouse gas emissions. In addition, industrial solid waste can be treated to make adsorbents, active agents, and zeolites to remove harmful metals to help meet wastewater discharge standards and can be used as silane carriers to treat soil and water bodies for spills to reduce the risk of oil.

Table 3 confirms the feasibility of reusing industrial solid waste by analyzing examples of different applications and summarizing the economic and environmental impacts. The new products obtained through the technical processing of raw industrial solid waste can be used for the conservation of natural resources, the cultivation of plants, and the preparation of construction materials, reducing the pollution and harm caused by industrial solid waste to the natural environment, reducing the cost of construction materials and improving the yield and quality of plant cultivation. In the direction of plant cultivation, industrial solid waste plastic sheets, tires, *Acacia* sawdust, beech sawdust, and dairy sludge contribute directly to the plant growth process through general assembly and simple treatment. In construction materials, industrial solid waste fly ash fibers and self-combusting gangue powder are added to the concrete as supplementary materials. In the area of natural resource conservation, industrial solid waste blast furnace sludge, slag, soot fly ash, black liquor lignin, red mud, old brown cardboard, oil plant waste, and lithium silica fines are used in different technologies to achieve the goal of mitigating water and soil pollution.

## Industrial waste for plant growth

In the context of plant cultivation, the reuse of industrial solid waste is mainly reflected in the construction of irrigation systems and the provision of fertilizer feedstock. Water is a limiting factor for desert plant survival (Zhou et al. 2017). In Kuwait, based on value engineering guidance and the serious challenge of severe water scarcity, an irrigation model similar to waterboxx but more cost-effective, using recycled plastic sheets and old tires as the primary materials, was proposed and implemented by researchers. Waterboxx is a self-irrigation system that collects and stores water and is also insulated from the natural environment and pests, ensuring that plants can grow properly in harsh desert environments (Haqq-Misra et al. 2022; Schotting 2009). Additionally, Al-Anzi (2022) conducted three years of plant rising tests to investigate how tire tanks compared to waterboxx regarding plant quality traits, microbial environment, and project costs. Tire tank also has a higher positive impact on creating a microenvironment for plants.

Most importantly, the project costs of the two irrigation systems in the test showed a significant difference, with the cost of the equipment being only a quarter of that of the waterboxx, despite the same inputs of seedlings, fertilizer, water, and labor. Suppose the tire water tank is put into the planting of desert plants. In that case, the superiority of the tire water tank will be evident in terms of equipment input alone, considering its durability and low cost. Notably, a limitation of the experiment was that it did not focus on the value of reusing waste tires for the environment, which could

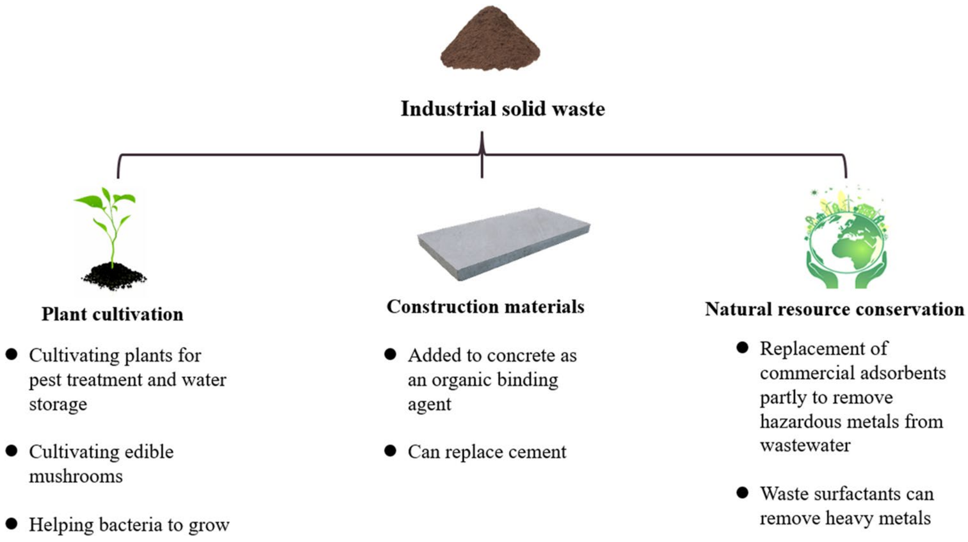

**Fig. 4** Value-added application of industrial solid waste. This figure demonstrates that industrial solid waste benefits value-added plant cultivation, construction materials, and natural environment protection. Industrial solid waste improves the soil environment and enhances plant cultivation. The waste can also improve the performance of concrete materials. The protection of the natural environment is mainly applied in the treatment of polluted wastewater

**Table 3** Industrial solid waste applications according to the different application directions. The uses of industrial solid waste in three application directions are briefly presented, with the economic and environmental impacts cited. The country or region is where industrial solid waste is studied for practical applications. Several economic and environmental positive social impacts can attain from industrial solid waste valorization application technologies. For example, plastic sheets, fly ash fiber, dairy-derived sludges, paper mill waste, oil plant waste, and others can be re-utilized in several value-added applications to achieve eco-friendliness, cost-effectiveness, pollution reduction, natural resources conservation, and construction improvement. "-" indicates not reported reference

| Type of waste | Country or region | Waste | Technology | Application direction | Application examples | Application impact | | References |
|---|---|---|---|---|---|---|---|---|
| | | | | | | Economic | Environmental | |
| Industrial solid waste | Kuwait | Plastic sheets and old tires | General assembling | Plant breeding | A system of underground planters with water storage capacity to control pests and collect and store water for plants that survive in harsh environments | Reduces the cost of plant survival in harsh environments by 43.84% compared to the waterboxx model | Rational and efficient use of water resources and increased plant survival in the desert | (Al-Anzi 2022) |
| Industrial solid waste | – | *Acacia* sawdust, beech sawdust | – | Plant breeding | Using industrial waste to grow mushrooms that produce protein for human consumption | Reduces the cost of fertilizer in the agricultural process | – | (Kumla et al. 2020) |
| Industrial solid waste | – | Sludge from dairy plants | – | Plant breeding | 60% of sludge from dairy plants can aid the rapid growth of rhizobia | Reduced production costs of biofertilizers | – | (Ahmad et al. 2019) |
| Industrial solid waste | – | Fly ash fiber | – | Construction materials | 4% fly ash fibers were added to the asphalt concrete as an organic binder ameliorative component | Reduced cost of concrete additives | Improves the durability of asphalt concrete pavements by increasing the strength and shear resistance of the mixture and the roughness of the mixture's coating | (Bieliatynskyi et al. 2022) |
| Industrial solid waste | – | Self-combusting gangue powder | – | Construction materials | Self-combusting gangue powder and recycled concrete powder as supplementary materials, partially replacing cement | Reduced concrete preparation costs | Reduces carbon dioxide emissions from concrete to the atmosphere by 22% | (Sun et al. 2021) |

**Table 3** (continued)

| Type of waste | Country or region | Waste | Technology | Application direction | Application examples | Application impact | | References |
|---|---|---|---|---|---|---|---|---|
| | | | | | | Economic | Environmental | |
| Industrial solid waste | – | Blast furnace sludge; slag and soot; fly ash; black liquor lignin and red mud | – | Conservation of natural resources | Commercial adsorbents can replace industrial solid waste to remove hazardous metals from wastewater after simple treatment, helping solid waste to meet discharge standards | Reduces the cost of commercial adsorbents for wastewater treatment in plants | Diminishes pollution of water resources | (Ahmed and Ahmaruzzaman 2016) |
| Industrial solid waste | – | Paper mill waste (old brown cardboard) | Solution impregnation of cardboard with two different alkoxysilane couplings | Conservation of natural resources | The surface coating is applied to waste materials and then used for oil spill clean-up of oil-contaminated soil, surface water, and groundwater | – | Reduces the risk of oil to soil and water | (Bayık and Altın 2018) |
| Industrial solid waste | – | Waste from oil plants | Sustainable carbon source from oil plant waste rich in lipids and other nutrients for the synthesis of biosurfactants | Conservation of natural resources | The microbial surfactants produced from oil plant-sourced waste significantly used to remove toxic heavy metals | Reduces the cost of waste disposal at oil plants | Reduced the pollution of soil and water resources by toxic heavy metals, with removal rates of 13.57%, 12.71%, 2.91%, 1.68%, and 0.7% for copper, lead, zinc, chromium, and cadmium in polluted water bodies, respectively | (Md Badrul Hisham et al. 2019; Sharma et al. 2021) |

**Table 3** (continued)

| Type of waste | Country or region | Waste | Technology | Application direction | Application examples | Application impact | | References |
|---|---|---|---|---|---|---|---|---|
| | | | | | | Economic | Environmental | |
| Industrial solid waste | – | Industrial waste lithium silicon powder | Preparation of NaP zeolite from lithium silica powder by a one-step hydrothermal process | Conservation of natural resources | Removal of divalent copper ions (Cu (II)) from aqueous solutions with synthetic NaP zeolite | Reduced plant wastewater treatment costs | After 3 cycles of zeolite adsorption and desorption, the number of copper ions adsorbed can reach 77.1 mg/g, reducing the number of copper ions in water resources | (Pu et al. 2020) |

also potentially build savings for governments to dispose of them. Furthermore, chemical fertilizers have been shown to cause radiological hazards (Elnagmy et al. 2018). Solid waste from industrial production can be used as organic fertilizer to grow mushrooms that produce protein for human consumption. Pardo-Giménez et al. (2020) noted that crude protein reached 15% and more dry weight in mushrooms grown using *Acacia* sawdust and beech sawdust as fertilizer. It is difficult to ignore that 60% of sludge from dairies can assist in the rapid growth of rhizobia, which delivers nitrogen to legumes to meet the growing needs of the crop (Ahmad et al. 2019). Using industrial solid waste as fertilizer will improve the edible value of mushrooms and the growth of legumes, reduce the cost of fertilizer, and provide a way to dispose of industrial solid waste.

Overall, industrial solid waste such as tire tanks and *Acacia* sawdust can contribute to the cultivation of plants in terms of water supply and auxiliary nutrient delivery, enabling the reuse of waste. At the same time, the use of tire water tanks contributes to the transformation of deserts into oases, and the use of *Acacia* sawdust achieves the goal of increasing the nutritional value of crops.

## Industrial waste for construction materials

Using industrial solid waste in construction materials is also a typical application. Asphalt concrete is the most common material used in pavement construction. Still, the durability of traditional asphalt concrete declines as the intensity of traffic and the frequency of extreme weather increases (Al-Osta et al. 2016). However, industrial solid waste fly ash fibers appear to improve this problem. For example, Bieliatynskyi et al. (2022) investigated the effect of fly ash fibers from thermal power plants in China on asphalt. They compared the fly ash fibers to conventional asphalt concrete without the additional fibers. The authors noted that using fly ash fibers as a component of an organic binder produced a chemical effect, which resulted in improved properties and structure of the asphalt. Experiments have shown that when fly ash fibers from thermal power plants are included in asphalt concrete at 4%, the strength, shear resistance, and coating roughness of the mixture are the best indicators in controlled experiments (Bieliatynskyi et al. 2022). As for concrete's greenhouse gas emissions, including industrial solid waste self-combusting gangue powder can also effectively mitigate the problem. Sun et al. (2021) mentioned that self-combusting gangue powder and recycled concrete powder could be used as supplementary materials to partially replace cement to reduce the cost of concrete preparation and reduce the carbon dioxide emissions of concrete to the atmosphere by 22%.

Overall, adding industrial solid waste-fly ash fibers and self-combusting gangue powder to the concrete as supplementary materials increases service life and reduces the preparation cost of the concrete. In addition, they reduce environmental hazards and achieve the reuse of industrial solid waste in construction materials.

### Industrial waste for natural resource conservation

Due to global water shortages caused by climate change, treating contaminated water sources has become a scorching topic (Wang and Yang 2016). Importantly, protecting water resources is also an essential direction for reusing industrial solid waste. Removal of heavy metals from wastewater is a means to protect water resources and is a necessary step in meeting discharge standards for wastewater. Several adsorbents derived from blast furnace sludge, slag, soot, fly ash, black liquor lignin, and red mud, as well as NaP zeolites prepared from lithium silica powder and biosurfactants synthesized from petroleum plant waste-rich in lipids and other sustainable carbon source nutrients are effective in removing toxic heavy metals such as copper, lead, zinc, chromium, and cadmium from wastewater (Md Badrul Hisham et al. 2019; Sharma et al. 2021). In addition, silanes from old brown cardboard can also treat oil spills in oil-contaminated water bodies and soils to avoid further pollution of natural resources (Bayık and Altın 2018). This means that many commercial sorbents will be replaced, and the cost of treating the effluent will decrease.

In summary, industrial solid waste-based adsorbents and surfactants effectively remove toxic heavy metals from wastewater. Industrial solid waste-based silanes can also adsorb leaked oil, both of which conserve natural resources and realize the value-added and application of industrial solid waste.

This section demonstrates that the reuse of industrial solid waste not only reduces the cost of waste disposal but also allows for the efficient use of its residual value for reuse. The above examples only summarize the reuse of industrial solid waste in agriculture, construction, and the conservation of natural resources. However, there is still a need for much research and study on more reuse directions and technologies.

## Economic feasibility and valuation method of value-added solid waste

A value assessment must accompany advanced and efficient solid waste application technologies to verify their value-added economic viability (Awasthi et al. 2021b; Razzaq et al. 2021; de Sá Moreira et al. 2022). This can provide a value assessment method and strong evidence support for government, authorities, and enterprises in solid waste management and reuse (Shah et al. 2022; Chaianong and Pharino 2022). Therefore, a methodological description and case studies on the value assessment of solid waste and economic feasibility analysis are discussed in this section. Table 4 summarizes the different economic parameters indicators, definitions, and calculation formulas used to estimate the economic effects of solid waste application technologies. While Table 5 lists the other economic parameters involved in evaluating the economic feasibility of solid waste in the cases of varying application directions, costs, estimates of revenues, and critical information about the economic benefits.

This table provides decision-makers involved in solid waste reuse with different economically viable options for estimating costs and benefits by summarizing other economic benefit methods and their calculation formulas. The identification of some economic indicators, such as techno-economic assessments, total life cycle cost, levelized cost of energy, payback time, internal rate of return, and net present value, could be the pointers to the sustainability, operability, and economic feasibility of these capital projects for solid waste recycling and disposal.

Tables 4 and 5 provide the methods used to measure the value and economic benefits of different categories of solid waste in various areas through a financial analysis of actual study cases under different solid waste application directions, estimating and summarizing the capital costs and benefit revenues of each case. This confirms the economic feasibility of managing and reapplying solid waste in a way that provides policymakers, project investors, and plant operators with a recently updated data reference.

The feasibility and significance of solid waste management and application need to be supported and validated from economic feasibility (Gopalakrishnan et al. 2021). According to Saqib et al. (2019), hydrothermal carbonization efficiently turns food waste from municipal solid waste into energy. They estimated the minimum selling price of hydrocarbon at $30, compared to the current market price of $85.68/ton using techno-economic assessments. This confirmed the energy recovery from food waste, and the advantages of cost savings were demonstrated. Similarly, Afroze et al. (2018) confirmed the effectiveness, economy, and stability of waste-to-energy generation using landfill gas technology to generate power from municipal solid waste with a levelized cost of $0.23/kilowatt-hour and a payback period of roughly 7 years. Compared to the previous system, Xue et al. (2022) created a revolutionary compressed air energy storage system that combines a waste-to-energy plant and a biogas plant. The system has a net present value of $120,520 and a decreased investment cost of roughly $188,764.61. Therefore, the economic and technical advantages of this technology can be widely used in future projects. The levelized cost of energy for anaerobic digestion and landfill gas technology for waste-to-energy is about \$0.04/kilowatt-hour and \$0.07/kilowatt-hour, respectively, and the payback time in Beijing is 0.73–1.86 years and 1.17–2.37 years, respectively (Huang and Fooladi 2021). Therefore, landfill gas and anaerobic digestion technologies are feasible technologies to obtain quick and stable benefits from waste reuse and better environmental benefits (Ng et al. 2021; Mondal et al. 2021). The study conducted by Fernández-Delgado et al. (2022) supported the viability of using the method to manufacture liquid fertilizer from municipal solid waste.

With a lower total investment cost for construction and production, a minimum production cost of €0.5/liter, a more extensive spread between the minimum selling price and the market price, and the ability to extract liquid fertilizers from the organic fraction of municipal solid waste under potassium hydroxide conditions, this method performs better on the market. In addition, producing solid biofuels from wood pellets of agricultural solid waste also stands out in value-added waste (Nabavi et al. 2020; Abdulyekeen et al. 2021; Abdullah et al. 2022). Nabavi et al. (2020) mentioned that the minimum production cost of wood pellets for fuel production at €104.29/ton and the internal rate of return could reach 45–124%.

Agricultural solid waste can also be used as a biosorbent to treat wastewater (Mishra et al. 2021). For example, Praveen et al. (2021) found that the removal of dyes from wastewater using peanut shells has the lowest cost of ₹0.91 has a high adsorption capacity, and the unloaded biochar can be safely discharged into the environment because biochar is stable (Guo et al. 2021). Furthermore, the construction and demolition of waste from industrial solid waste can be used for concrete block preparation (Abraham et al. 2022) with a minimum life cycle cost of 1.14, demonstrating the efficiency and sustainability of the material and reducing the environmental impact caused by industrial solid waste. Petrillo et al. (2022) also used life cycle cost to assess the economic feasibility of using cement and industrial solid waste to produce lightweight manufactured aggregates with a minimum production cost of only \$22, making lightweight manufactured aggregates a sustainable environmental option.

In the field of solid waste applications, environmental impacts and economic factors have driven the development of solid waste recovery and value-added technologies and the exploration of new solid waste applications directions in energy production, such as waste-to-energy (Afroze et al. 2018), thermodynamics (Mavridis and Voudrias 2021), and hydrogen electrolysis (Cao et al. 2022). Economic assessment methods can generally be used to calculate their financial indicators using payback time, levelized cost of energy, net present value, and internal rate of return methods.

The average cost established for the energy source to provide zero net present value is known as the levelized cost of energy (Pawel 2014). To be economically feasible, the solution's net current value, which is the difference between the project's cash inflows and outflows, must be positive (Fernández-Delgado et al. 2022; Afroze et al. 2018; Xue et al. 2022; Nabavi et al. 2020). Generally, solid waste conversion for energy production involves accounting costs, including raw material costs, utility costs, and operating labor costs (Saqib et al. 2019). Energy costs are estimated assuming reliable historical financial data and determining annual energy production (Rosa-Clot and Tina 2020). Additionally, a life cycle assessment, a technique to measure the environmental advantages of solid waste management and recycling operations, is frequently used in conjunction with the net present value and internal rate of return approaches (Pryshlakivsky and Searcy 2021). This technology has been widely implemented in the technical field of waste management and disposal. Examples include green waste management (Talwar and Holden 2022) and the incineration industry (Di Maria et al. 2021). Overall life cycle cost, which accounts for the total cost of owning and managing the project during the project's specified life cycle, is a crucial financial indicator for determining the economic sustainability of investment projects (Afroze et al. 2018; Abraham et al. 2022; Petrillo et al. 2022; Sharma and Chandel 2021).

Life cycle assessment and life cycle cost must be combined as supporting tools for solid waste recovery and management (Lu et al. 2021) to achieve sustainable green development and promote a circular economy, especially in developing countries (Ferronato et al. 2021). However, many advanced application directions are still in the exploration and development stage for solid waste value addition and application. No complete database provides the annual percentage or tax rate or calculates the operating cost (Mahmud et al. 2021; Kargbo et al. 2021). Therefore, for solid waste application directions focusing on technological exploration, only cost analysis is usually used to analyze their feasibility. For example, the cost of preparing a biosorbent using peels from agricultural waste, compared to the current market price of powdered activated carbon (Petrillo et al. 2022).

This section explains the analysis of value assessment methods and economic feasibility of solid waste in different application directions, demonstrating the possibility, reliability, and sustainable economic development of value-added solid waste through different economic parameters and aggregation of information on economic benefits. It provides a reference for waste management and reuse practitioners and the basis and inexhaustible motivation for the value-added utilization of solid waste.

**Table 4** Methods of economic feasibility and value assessment of solid waste. A brief description of the various economic parameters indicators applied to the economic evaluation of solid waste and general calculation formulas are described. Other economic parameters allow the determination of cost indicators for each value-added waste process that is mentioned. The table also presents the formulas that facilitate quantifying the results of calculating waste costs. This helps to analyze the cost value at each step of the process

| Number | Economic parameters indicators | Formulas | Definition | References |
|---|---|---|---|---|
| 1 | Techno-economic assessments | $\frac{C}{C_b} = \frac{I}{I_b}$<br>C: the cost in a given year; I: the inflation rate in the same year; Cb: the known cost for the year indexed as Ib | Techno-economic assessment is a method for analyzing the economic performance of an industrial process, product, or service. Techno-economic assessment is usually based on software modeling input parameters' technical and financial use to estimate capital costs, operating costs, and revenues | (Saqib et al. 2019; Ng et al. 2021; Santos and Hanak 2022) |
| 2 | Total life cycle cost | $\mathrm{TLCC}_{(i)} = \mathrm{C}_{\mathrm{inv}(i)} + \sum_{n=1}^{N} \frac{\mathrm{C}_{\mathrm{O\&M}(i)} + \mathrm{C}_{\mathrm{R}}}{(1+d)^{n}}$<br>$C_{inv}$: the sum of investment costs; $C_R$: annualized cost of residual landfill waste; $C_{O\&M(i)}$: operation and maintenance costs | Including the calculation of the total cost of owning and operating the project over the complete life cycle | (Afroze et al. 2018; Abraham et al. 2022; Petrillo et al. 2022; Sharma and Chandel 2021) |
| 3 | Levelized cost of energy | $\mathrm{LCOE}_{(i)} = \left( \frac{\mathrm{TLCC}_{(i)}}{\sum_{n=1}^{N} \frac{\mathrm{E}_{\mathrm{P}(i)}}{(1+d)^{n}}} \right)$<br>TLCC: the total life cycle cost of the project; d is the nominal discount rate; N: the economic life of the project; i is the type of anaerobic digestion technology | Levelized cost of energy is the minimum cost of an energy system to achieve break-even (United States dollar/kilowatt-hour) | (Huang and Fooladi 2021; Afroze et al. 2018; Cudjoe et al. 2021b; Mabalane et al. 2021) |
| 4 | Payback time | $PBP(i) = \frac{TLCC_{(i)}(USD)}{C_{saved}(i)(USD/year)}$<br>$\mathrm{TLCC}_{(i)}$: the total life cycle cost of the project; $C_{saved}$ (i): the cost savings; i: the technology type | It is the time to break even on project costs (years) | (Huang and Fooladi 2021; Fernández-Delgado et al. 2022; Afroze et al. 2018; Xue et al. 2022; Nabavi et al. 2020) |
| 5 | Net present value | $NPV_{(i)} = \sum_{n=0}^{N} \frac{F_n}{(1+d_r)^n}$<br>$F_n$: the net cash flow; $d_r$: the annual real discount rate | The difference between the present value of all expenses made during the system's lifetime and the current value of all revenues received during that time is known as net present value (the difference between cash inflows and cash outflows) | (Fernández-Delgado et al. 2022; Afroze et al. 2018; Xue et al. 2022; Nabavi et al. 2020) |
| 6 | Internal rate of return | $\sum_{n=0}^{N} \frac{F_n}{(1+IRR)^n} = NPV_{(i)} = 0$<br>$F_n$: the net cash flow; N: the total number of years in the study | When applied to the after-tax cash flows throughout the project, the nominal discount rate, known as the internal rate of return, has a net present value of zero. The internal rate of return should not be more than the target value or equal to zero for financially successful initiatives | (Fernández-Delgado et al. 2022; Afroze et al. 2018; Nabavi et al. 2020; Ayeleru et al. 2021) |
| 7 | Cost analysis | $C = C_C + C_o + C_{fh} + C_{ft}$<br>$C_C$: annualized capital expenditure; $C_o$: total annual operating cost; $C_{fh}$: the total annual cost of raw material harvesting; $C_{ft}$: the total annual cost of raw material transportation | Used in cost analysis for unit cost estimation | (Praveen et al. 2021) |

**Table 5** Application examples of solid wastes according to different application directions. The various economic parameters indicators and value assessment methods applied to solid waste in different application directions are briefly presented. The costs and critical benefits information in the study case are estimated and listed. The economic costs from different perspectives can be determined with other economic parameters. The financial parameters are compared with information on revenues and costs to determine the economic feasibility of each case."-" indicates not mentioned. '₹' refers to the Indian rupee currency

| Formula used | Application direction | Countries and regions | Cost | Income | Key information | References |
|---|---|---|---|---|---|---|
| 1 | Biomass/organic waste to energy (hydrothermal carbonization) | New Zealand | Cost of raw materials: $44,426,097,668; utility costs: $2,650,900; operating labor costs: $158,700 | $21,900,000/year (2000 tons per day) | Minimum price of $30 (market price is $85.68/ton); 30% tax rate; 10% annual interest rate | (Saqib et al. 2019) |
| 2, 3, 4, 5, 6 | Recovery of biogas from the organic fraction of municipal solid waste for power generation | Ibadan, Nigeria | levelized generation costs for anaerobic digestion technology: $0.0681–0.0336/kilowatt-hour; landfill gas technology: $0.2411–0.0350/kilowatt-hour | Net present value of anaerobic digestion: $834,120,000; net present value of landfill gas recovery: $489,260,000 | The levelized cost of energy is $0.23/kilowatt-hour. Payback time is approximately 7 years. Anaerobic digestion payback time, internal payback, and total life cycle cost are 5 years, 19.3%, and $413,680,000, respectively, while the landfill gas recovery technology is 7 years, 23.4%, and $288,050,000, respectively | (Afroze et al. 2018) |
| 4, 5 | Heating with waste-to-energy and using biogas combustion instead of a compressor for a gas turbine system | China | Total investment cost: $105,900; annual operating cost: $6,350; fuel cost: $56,650 | Total annual revenue: $89,340 | Total annual profit: $32,690; dynamic payback period: 4.35 years; net present value: $120,520 | (Xue et al. 2022) |
| 3, 4 | Municipal solid waste as feedstock for landfill gas and anaerobic digestion for waste-to-energy generation | Beijing and Tehran | – | – | The levelized cost of energy is about $0.04/kilowatt-hour for anaerobic digestion and $0.07/kilowatt-hour for landfill gas; the payback time for anaerobic digestion is 0.73–1.86 years in Beijing and 1.17–2.37 years in Tehran; the payback time for landfill gas is 1.34–3.43 years in Beijing and 2.08–4.2 years in Tehran. Payback time in Beijing is 1.34–3.43 years and in Tehran is 2.08–4.2 years | (Huang and Fooladi 2021) |

**Table 5** (continued)

| Formula used | Application direction | Countries and regions | Cost | Income | Key information | References |
|---|---|---|---|---|---|---|
| 4, 5, 6 | Extraction of liquid fertilizer from the organic fraction of municipal solid waste | Mirandela, Portugal | Production cost: €0.5/liter; annual production cost: €1,867,000 | Minimum price: €0.75/liter | The internal rate of return is the discount rate (10%). Liquid fertilizer production efficiency: 515 L/hour; maximum payback time: 7.1 years | (Fernández-Delgado et al. 2022) |
| 4, 5, 6 | Solid biofuel production from agricultural solid waste wood pellets | – | Production costs: €104, €108, and €107 /ton; energy production costs: €43.5/megawatt-hour (€25.9 and €22.3/megawatt-hour for gasoline and natural gas, respectively) | – | Internal rate of return: 124.3%, 41.3% and 45.8%; net present value: €7.8, €7.8 and €14,000,000; payback periods: 1.83, 3.53 and 3.23 years | (Nabavi et al. 2020) |
| 7 | Use of agricultural solid waste as a biosorbent for the treatment of dyes in wastewater | India | The cost of 1 kg of adsorbent was ₹45.4 (coconut shell), ₹42.5 (peanut shell), and ₹42.7 (rice shell), respectively | – | The average price of biochar is ₹185.5/kg (globally); the average cost of mixed biochar ranges from ₹5.6–943.60/kg (in India) | (Praveen et al. 2021) |
| 2 | Use of construction and demolition waste from industrial solid waste for concrete block preparation | India | – | – | Life cycle costs of 1.14, 1.14, 2.15, and 2.14 (without recycling) | (Abraham et al. 2022) |
| 2 | Preparation of lightweight synthetic aggregates from cement and industrial solid waste | Italy | Total cost at 5%, 15%, and 10% portland cement options are $30, $30, and $22, respectively | – | – | (Petrillo et al. 2022) |

## Perspectives

### Value addition and application of solid waste

The conversion of municipal food waste into value-added products holds excellent promise. However, appropriate technologies for effective conversion are still lacking, and the technical barriers are mainly due to the heterogeneity of the waste (Sindhu et al. 2019). Future researchers may need to adopt alternative research methods to circumvent the unreliable effects of waste heterogeneity. Pyrolysis units for decomposing municipal solid waste are expensive and require a lot of thermal energy. Hasan et al. (2021) suggested that integration into the pyrolysis unit can minimize this pyrolysis heating problem and make the system more environmentally friendly and energy efficient.

According to Gonzalez et al. (2022), the high ash level of agricultural solid waste soybean straw makes it difficult for biomass furnaces to operate. However, the following research may solve this issue by co-firing more biomass with lower ash contents. In addition, pretreatment of agricultural solid waste lignocellulose has the potential to produce a large variety of chemical and biochemical compounds that can be directly utilized as feedstock in the textile, materials, biomedical, and pharmaceutical industries. However, excessive water use, energy consumption, toxic reagents, and lignocellulose collection, transport, and disposal must be explored (Batista Meneses et al. 2022).

The waste generated from industrial processes has great potential for recovery, and the extraction of rare precious metals from waste is one of the ways to break the resource bottleneck (Wu et al. 2022). However, in extracting valuable metals from solid waste, care must be taken to avoid secondary contamination by controlling critical technical parameters, as many valuable metals might be lost, reducing newly valuable waste (Wu et al. 2022). In addition, industrial waste contributes significantly as a nutrient source for bacterial media and is favored by biomedical companies and scientists (Kadier et al. 2021). According to Haile et al. (2021), paper mill waste may be used to create engineering materials, including carbon fibers, bioplastics and fibers, cellulose nanocrystals, and biocomposites, with the potential to be crucial. Multifunctional bio-based goods for a wide range of conventional, high-performance, and intelligent applications may also be made from biomass or biomass waste for various engineering applications and biomaterials created using appropriate and practical methods (Akor et al. 2021).

Overall, future value-added applications of municipal solid waste will need to break through the limitations of technology and develop integrated solar heating systems. Agricultural solid waste also needs to explore new substances and technologies to avoid resource wastage in value addition and application. In addition, the existing value-added technology of industrial solid waste needs to strengthen the parameter control, and the application in the direction of bacterial culture needs to be studied.

### Methods for the assessment of economic feasibility

Since many reuse technologies for waste are currently at the development level, the technology readiness level assessment method was introduced based on information from policy implementers and developers to effectively assess and compare the type and scale of waste reuse technologies (Rybicka et al. 2016). For instance, Solis and Silveira (2020) have analyzed nine technologies for the chemical recycling of household plastics using a technology readiness assessment methodology, ultimately identifying three technologies based on significant research and development centers to explore economies of scale. The authors concluded that the technology readiness level assessment methodology might be used in the future to evaluate municipal, agricultural, and industrial solid waste reuse technologies as data for economic feasibility analysis. In addition, investing economic feasibility in value-added waste technologies can be determined by calculating the return on investment and net present value. Maroušek et al. (2020) estimated potato waste management based on a payback period and net present values to make economic feasibility judgments and eventually adjust to a technical setup close to the technical–economic optimum.

In conclusion, this part suggests that assessment methods such as technology readiness level, rate of return, and net present value can be introduced to conduct a comprehensive economic feasibility assessment of solid waste value addition and application.

### Solid waste pretreatment

Recycling and sorting is the first and critical step in the valorization and application of waste (Kaya 2016; Yang et al. 2022). Policies and facilities should improve waste's recovery rate and sorting accuracy (Khan et al. 2022a). First, the policy section on waste recycling and sorting should be as detailed as possible, down to the unit responsible for implementing the policy and the rules and regulations. The approach should also suit the characteristics of the region where waste is implemented. Second, waste recycling and sorting facilities should also consider the operators' age and height to make the facilities universal, simple, and efficient. In siting facilities, spatial analysis of geographic information systems can be used to screen and identify the most suitable areas or locations for recycling facilities (Khan et al. 2018). At the same time, governments, non-governmental, and other organizations should

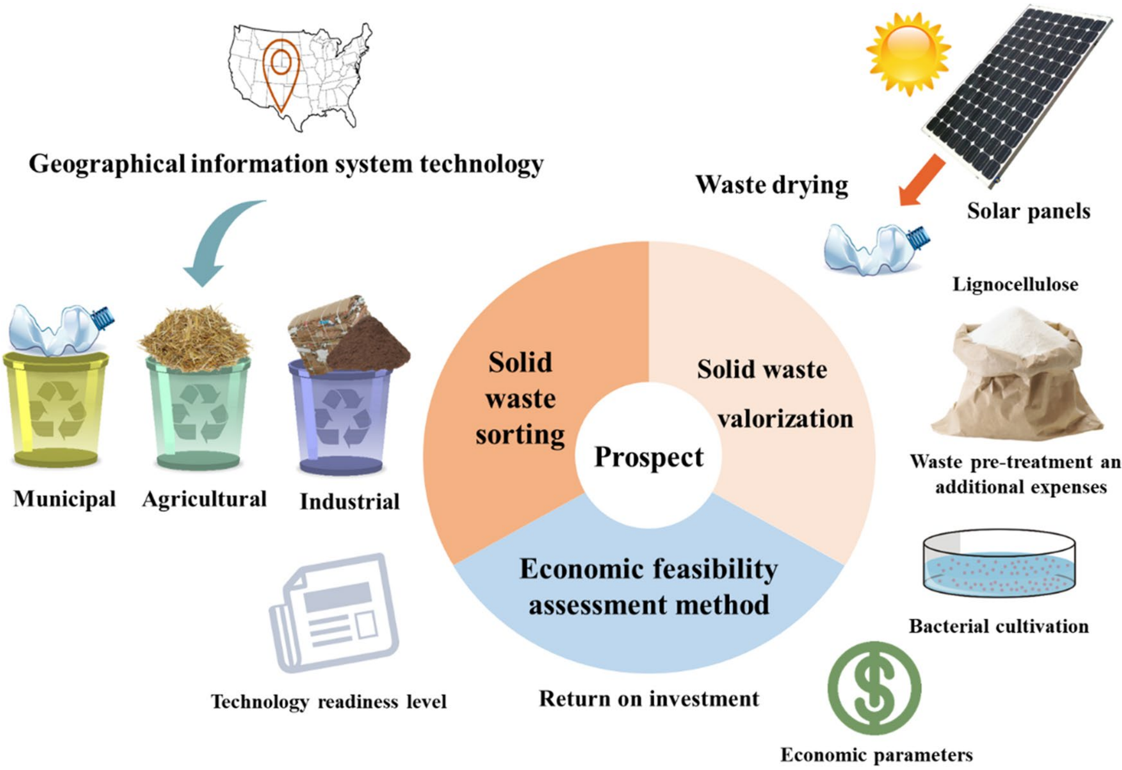

**Fig. 5** Enhanced recycling and sorting techniques for solid waste contribute to more efficient waste applications. In addition, there is a need to expand other directions of value-added solid waste applications, which improve the application rate of waste and provide avenues for excess waste. Among the economic feasibility assessment methods, the technology readiness level is considered a practical and comprehensive evaluation, considering more economic parameters to help decision-makers develop more effective cost analyses

focus on changing consumer waste behavior in the future (Bhattacharya et al. 2021).

Publicize the negative economic, environmental and social impacts of indiscriminate waste disposal and call for and guide consumers to recycle and separate their waste effectively. To achieve early results, consideration could also be given to adding the requirement to recycle and separate waste to the citizens' code of conduct to raise awareness of citizens' ownership. In addition, the government can also encourage businesses to develop recycling programs for sold goods linked to consumers' waste recycling behavior. Moreover, a detailed classification and characterization of a specific type of industrial solid waste could be conducted. Wiśniewska et al. (2022) indicated that green desulfurization of scrap tires is in line with the circular economy, and the production of rubber-based materials for high-value end ground tires markets will be developed because of current research trends. However, proper sorting and adequate characterization of scrap rubber before use can significantly improve the process reproducibility and the performance properties of the obtained rubber recycling products. In addition to this, Koskinopoulou et al. (2021) suggested that perhaps in the future, the implementation of autonomous robotic systems for waste recycling could be achieved with automatic sorting and physical sorting of recyclables according to material type. If artificial intelligence can be successfully spread to the waste recycling field, this will significantly improve the efficiency and accuracy of recycling and prepare the waste for reuse.

In conclusion, recycling sorting technology can improve the recycling rate of waste. The help of a policy system effectively facilitates the recycling of waste. Moreover, recycling according to the nature of specific waste will increase the accuracy of waste recycling.

This section summarizes the prospects for value-added solid waste applications, as shown in Fig. 5. This graph llustrates the solid waste value-added opportunities in terms of applications, economic feasibility assessment methods, and the sorting direction of solid waste recycling. It is determined how sorting technology for waste recycling can be improved. There is also a need to expand solid waste applications with added value. Some new evaluation methods and economic parameters can be added to increase the chances of economic viability.

## Conclusion

While accelerated global urbanization, technological innovations in agriculture, and the expansion of industrial automation have contributed to human development and progress, they have brought more solid waste, accelerating the environmental crisis and energy problems. This review analyzes and summarizes economically viable methods for valorizing solid waste from municipal, agricultural, and industrial sources based on the latest reusing and value-added technologies. Landfills are no longer the primary method of solid waste disposal; new ways of solid waste disposal have found a way to comply with sustainable green development. For instance, using solid waste as an alternative energy source for power generation is one of the most common ways of dealing with solid waste, achieving a positive impact on global warming. In addition, solid wastes can be used for fertilizer applications, plant breeding, construction material production, bio-oil, biomethane for engine fuel, biochar for soil remediation, biosorbents for wastewater treatment, animal feed, materials for water storage systems, and conservative natural resources. Thus, energy or byproducts can be obtained at a lower cost to maximize solid waste utilization and protect human health, the environment, and natural resources. More importantly, combining value assessment and economic feasibility analysis is vital to optimizing the economic benefits of solid waste reuse in different application directions, technological innovation, and future sustainable development and providing a library of methods for the economic assessment of participants in the field of solid waste.

Despite the significance of recycling waste to realize value, current policies and facilities for recycling and utilization of waste are not well developed, and there are significant limitations in the measures taken to reuse solid waste in several countries. Therefore, there will be more room for advancement in the future in the exploration of applications and technological innovation in solid waste recycling to maximize the value added and utilization of solid waste.

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## Declarations

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