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The present and proposed sustainable food waste treatment technology in Indonesia: A review

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A B S T R A C T

Domestic waste is dominated by food waste (FW) in Indonesia. Indonesia has committed to advancing FW management based on The National Strategy Policy Guidelines (Presidential Regulation 97/2017), aiming for a 30% reduction and 70% waste handling by 2025. However, the current FW regulations and treatments are insufficient to reach these targets. This paper aims to quantify the potential FW generation and provide integrated government regulation and technical recommendations on the current technology to enhance the applicability of FW treatment in Indonesia. The proposed treatment technology is discussed within the context of technical, economic, and environmental concerns. The current practical FW treatments include composting and landfill, with landfill having the highest environmental impact. Black soldier flies and thermal treatments are new technologies considered promising by Indonesia's Waste to Energy regulations. However, FW treatment technical considerations are expected to developing on different scales. Therefore, the environmental impact of current treatments must be considered. It is crucial to analyze specific FW treatment recommendations in terms of product and residuals to improve environmental impact assessment quality.

1. Introduction

The global population is expected to grow to 9.3 billion by 2050, creating a 50%–70% increase in food demand. Approximately one-third of the edible food produced for human consumption is lost or wasted yearly, which equals around 1.3 billion tons (Bond et al., 2013; FAO, 2020, 2011). Food waste (FW) contributes to the food crisis as an increased amount of food needs to be produced to feed the global population. If FW is reduced, food will be more accessible, and access to nutrition will increase for individuals.

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Economic resources could be saved by reducing FW by decreasing operational food costs and improving reliability and resistance to other factors, such as climate change. Furthermore, reducing FW will increase incomes due to a more stable food supply and provide adequate nutrient-rich food for consumption, particularly in developing countries (FAO, 2014; Mzumara et al., 2018; Thyberg and Tonjes, 2016). FW significantly impacts the environment, generating 4.4 $GtCO_2$ eq annually, or approximately 8% of the total anthropogenic GHG emissions based on carbon footprints (FAO, 2015). Therefore, reducing FW could significantly alleviate hunger, increase incomes, climate change reduction, and enhance food security.

Indonesia is the second-largest FW producer globally, estimated to create 300 kg of FW per capita per year. Indonesia also has the third-highest incidence of stunted children at 36.4%, followed by Nigeria at 32.9% (The Economist Intelligence Unit, 2017). To improve and secure food security in Indonesia, it is essential to reduce the amount of FW generated by the system. The potential impact on global warming resulting from FW in Indonesia over the last 20 years is estimated at 1,702.9 Mton CO_2-Ek, equivalent to 7.29% of the average GHG emissions in Indonesia for the last 20 years (Ministry of National Development Planning of the Republic of Indonesia, 2021a).

Previous studies have not properly analyzed Indonesia's current FW treatment, regulations, technical terms, and environmental impacts (see supplementary material). The National Strategy Policy Guidelines (Presidential Regulation 97/2017), which is abbreviated as Jakstranas, has set a 30% waste reduction target from the source and a 70% waste treatment target by 2025. However, achieving the waste treatment target remains distant. In 2022, Indonesia achieved 25.3% waste reduction and 49.2% waste treatment (Ministry of Environment and Forestry of the Republic of Indonesia, 2022). This study focused on accelerating the achievement of the 70% waste treatment target by 2025, analyzing the existing state of FW generation in Indonesia, and forecasting FW treatment through current and future FW treatment implementations.

The objectives of the present study are (i) to quantify the potential FW generation in Indonesia, (ii) to provide information and recommendations regarding the current government regulations to enhance the implementation of FW treatment, and (iii) to discuss the current and proposed FW treatments in Indonesia regarding their technical challenges, economic considerations, and environmental impact.

2. Review methodology

This study analyzed a comprehensive Scopus literature database listing important keywords related to FW literature. The researchers used the Scopus database as it is considered a reliable source of scientific, academic publications. The keyword "food waste" in the title, abstract, and authors was used to obtain the necessary data. During the selection round, we assessed the titles and abstracts of FW management and treatment studies conducted in Indonesia.

Data collected from regulations, annual state and local government reports, and various theses represent the local data and discussions regarding regulations, quantification, and current FW treatment in Indonesia. Solid waste management performance data from Indonesia was obtained from the open-access website SIPSN (National Waste Management Information System). However, several cities had not thoroughly reported the quantity and composition of waste based on the information from SIPSN. Therefore, recent data from 2020 has been approximated using more comprehensive and recent data.

This review focuses on the current condition and initiatives regarding FW treatment in Indonesia, as shown in Fig. 1. Section 1 of this review provides an overview of the definition, current situation, and influence factors regarding FW generation. Section 2 discusses and analyses Indonesia's SWM development and regulations. Section 3 analyzes the current and proposed FW treatment systems with technical, economic, and environmental impact consideration (BSF, AD, Composting, Thermal, RDF, landfilling and Hydrothermal) in Indonesia.

3. Food waste and Indonesia

3.1. Definition of food loss and waste in Indonesia

Food loss refers to the reduction in edible food mass that occurs within the supply chain that creates edible food for human consumption. Food loss occurs at the production, post-harvest, and processing stages of the supply chain. Food loss during retail and consumption is referred to as FW (FAO, 2013, 2011; Parfitt et al., 2010). In Indonesia, the definition of FW based on regulations Law No. 18 from 2008 (Government of Indonesia, 2008). FW management in Indonesia focuses on FW generated in the distribution and consumption stages, while food loss is considered appropriate in the context of agro-industrial waste. In this study, the definition of FW is waste involved in the distribution and consumption stages (Ministry of National Development Planning of the Republic of Indonesia, 2021a).

3.2. Food waste generation in Indonesia

Regarding the characteristics of MSW, in 2019–2020, FW generation in Indonesia was approximately 40%, being 40.34% in 2019 and 40.23% in 2020. The three most significant waste contributors are FW, plastic, and wood and paper. Plastics accounted for 15.9% of waste in 2019 and 17.29% in 2020, while wood and paper accounted for approximately 16% in

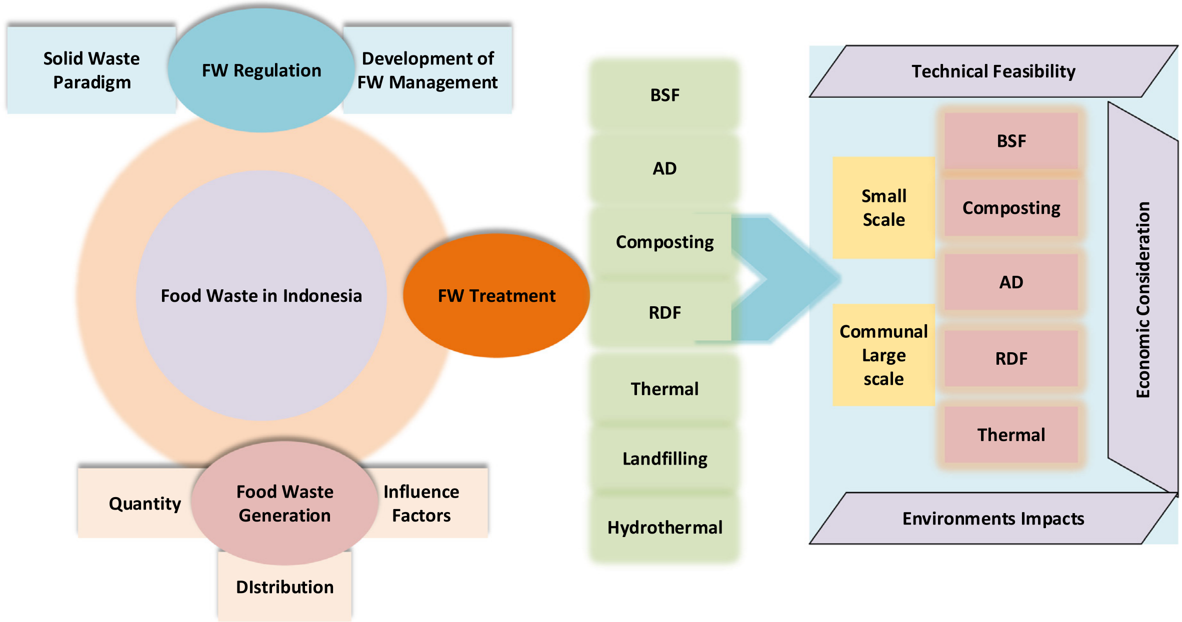

Fig. 1. Scope of this study.

2019, and ±11% in 2020 (Ministry of Environment and Forestry of the Republic of Indonesia, 2020a). FW is a significant waste contributor in Indonesia. Previous research has found that in Indonesia, solid waste is primarily comprised of FW (Dhokhikah et al., 2015; Khair et al., 2019; Nikmah and Warmadewanthi, 2013; Suhartini et al., 2022).

The percentage of FW in MSW varies across regions, ranging from 11.93–57.08% in 2020, as shown in Fig. 2 (Ministry of Environment and Forestry of the Republic of Indonesia, 2020a). Indonesia has six major islands that comprise several provinces. From West to East, these are Sumatera (10 provinces), Java (6 provinces); Kalimantan/Borneo (9 provinces); Sulawesi (6 provinces); Nusa Tenggara and Bali (3 provinces), and Maluku and Papua (6 provinces). FW is more common in metropolitan cities, such as DKI Jakarta (JKT) and East Java (EJ), which have FW rates of 45.43% at 46.43%, respectively. Several tourist cities, such as DIY Yogyakarta (YG), East Kalimantan (EK), and South Sulawesi (SS), have FW rates of 57.08%, 50%, and 45.37%, respectively. The amount of waste generated in 2020 was 67.8 million tons, and FW is predicted to account for 20.8 million tons/year (Ministry of Environment and Forestry of the Republic of Indonesia, 2020b,a). This is in line with estimates that total FW generation is 23–49 million tons/year, equivalent to 115–184 kg/capita/year (Ministry of National Development Planning of the Republic of Indonesia, 2021a). Most waste is generated in the consumption stage, ranging from 5–19 million tons/year. It is believed that 80% of consumption waste originates from households, with the remaining 20% created in the non-household sector. Leftover edible food accounts for 44% of all FW (Ministry of National Development Planning of the Republic of Indonesia, 2021a). This research employs national-level data, that not consider the socio-cultural nuances of individual regions thus requiring a more specific analysis in detailed stage.

3.3. Factors influencing the generation of food waste

FW generation can be influenced by age, perception, income, number of household members, and children (Szabó-Bódi et al., 2018). The variation in the food supply chain and demographic, social, educational, economic, and environmental factors impact FW in Indonesia. Families with fewer members produce more waste per capita than larger households (Mertenat et al., 2019; Sugiyarto, 2021). Customer behavior has been thoroughly investigated in FW studies. Human life patterns (Zhang et al., 2019), consumer habits (van Herpen et al., 2019), behavior, knowledge (Laso et al., 2021; Lemy et al., 2021), and culture (Elimelech et al., 2018; Padeyanda et al., 2016) all substantially impact FW reduction. Perceptions between employers and domestic household helpers could impact awareness regarding fluctuating FW quantity (Lemy et al., 2021; Soma, 2020, 2017). Without intervention, Indonesia's FW generation is predicted to reach 344 kg/capita/year by 2045. However, this could be reduced to 166 kg/capita/year with the implantation of specific strategies (Ministry of National Development Planning of the Republic of Indonesia, 2021b).

4. Progress of food waste management and regulation

The annual population growth in Indonesia is considerably high (1.12%). This will lead to a significant increase in FW generation within 10 years (Central Bureau of Statistics of Indonesia, 2020; World Bank, 2021) Therefore, Indonesia must

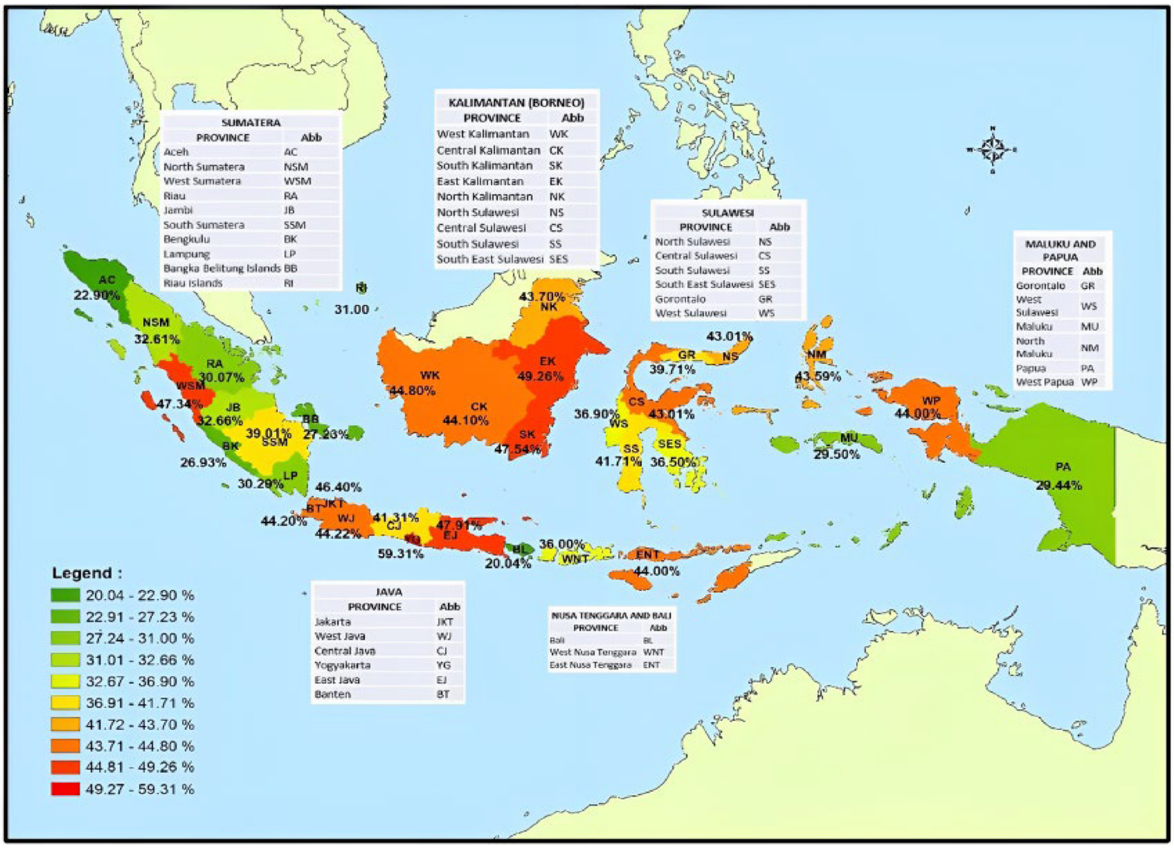

Fig. 2. Percentage of Food Waste in total MSW in each province in Indonesia (2020).
Source: Adapted from Ministry of Environment and Forestry of the Republic of Indonesia (2020c).

develop greater FW management, with the President stating during a Plenary Cabinet Meeting on June 20, 2022, that *"Indonesia has to anticipate the threat of food, energy, and financial crises. Therefore, we need the synergy and collaboration of all relevant stakeholders"* (Cabinet Secretariat of the Republic of Indonesia, 2020).

Indonesia has undergone a paradigm shift in regard to solid waste management (Fig. 3). Before Law 18 was enacted in 2008, Indonesia was using "end a pipe solution" where waste is not a resource and has no natural resource efficiency, and there is a tendency to overexploit natural resources (Government of Indonesia, 2008). The enactment of LAW 18/2008 and the 3Rs (Reduce, Recycle, Reuse) (2008–2015) have reduced the pollutant load associated with waste by changing behaviors and reducing waste at the source. Since 2015, Indonesia has implemented extended producer responsibility (EPR) and circular economy (CE) initiatives to enforce producer commitments, particularly regarding recycled packaging (Coordinating Ministry for Maritime and Investments Affairs, 2021). EPR refers to the responsibility of producers in regard to packaging management and regulation, particularly for packaging that cannot be recycled (Ministry of Environment and Forestry of the Republic of Indonesia, 2021a). CE implementation in the FW management includes managing packaging, product and materials in use, and regenerating natural systems (KPMG, 2020). In recent years, the Indonesian government has begun to develop technologies that enhance the implementation of CE, such as: AD, BSF, RDF, and composting technologies. This study incorporates a comprehensive analysis of the implementation of CE, that the discussion of each FW processing technology is integrated with technical, economic, and environmental impact considerations.

The basic framework of waste management and related FW policies was summarized by examining government documents on waste management in Indonesia, as shown in Fig. 4. Indonesia initiated solid waste management in their Long-Term Development Plan (RPJP 2005–2025), LAW No. 17/2007, and National Medium-Term Development Plan (RPJMN 2020–2024). This was followed by government and presidential regulations. The presidential regulation was developed specifically by the Ministry of Environment and Forestry and was related to guidelines, roadmaps, and environmental performance ratings. This regulation is an upstream (top-down) initiative by the government to clarify targets and achievements in solid waste management. Furthermore, the Ministry of Home Affairs stipulated solid retribution regulations, and the Ministry of Public Works provided technical guidelines regarding solid waste management infrastructure. These two regulations are downstream regulations to provide steps for solid waste technical management.

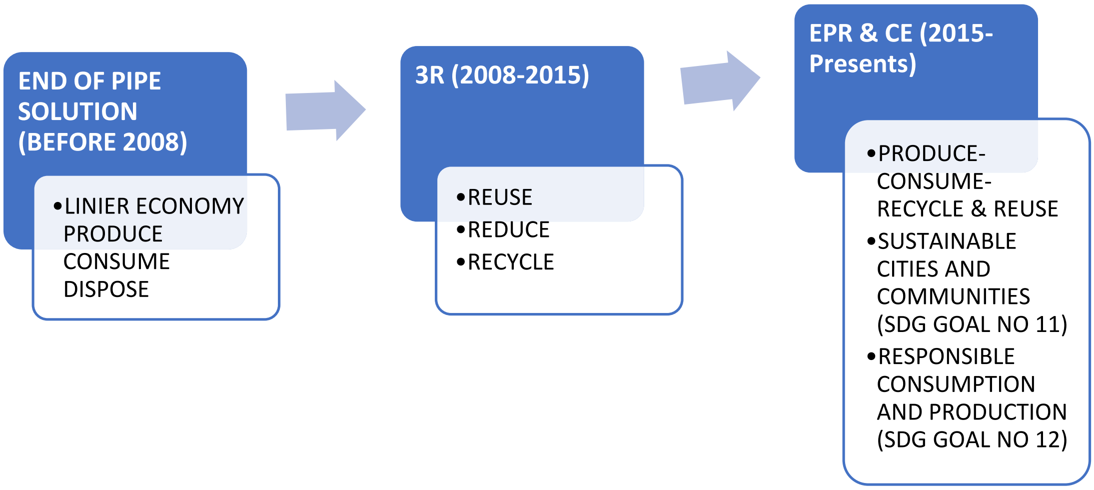

Fig. 3. The transition of the Solid Waste Paradigm in Indonesia.
Source: Adapted from Ministry of Environment and Forestry of the Republic of Indonesia (2021a).

As part of this, Indonesia has committed to mainstreaming its SDG goals, targets, and indicators in the RPJMN for 2020–2024. The plan is divided into 5-year medium-term development plans with various development priorities. The RPJMN for 2020–2024 (Presidential regulation 18/2020) has several FW management-related priorities. The third national priority is increasing food consumption availability, access, and quality, while the fifth is improving the national food system governance. The long-term development strategy has led to the creation of the current medium-term development plan.

The first waste management initiatives in Indonesia were LAW No. 18/2008 (Government of Indonesia, 2008) and government regulation No. 81/2021 (Government of Indonesia, 2021a). They enforce manufacturers to reduce and recycle their waste and/or biodegradable packaging. Furthermore, they stated that producers must minimize waste in their product supply chain. FW is a potential resource that could be utilized as renewable energy and enhance economic value. However, these regulations did not explicitly define the potential of FW resources. Furthermore, the FW reduction targets must be explained further for each supply chain.

FW minimization was cited in Ministry of Environment and Forestry regulation No. 75/2019, which is a 10-year waste reduction roadmap for producers in Indonesia's food and beverage service industry sector, including manufacturing, food and beverage services, and retail (Government of Indonesia, 2019a). This regulation states that minimization, recycling, and reuse could reduce product and packaging waste across 2020–2029. This regulation is targeted at food packing only, with no mention of minimizing FW products. The Indonesian Government's initiatives to manage FW were expanding to include more industries and companies in the Ministry of Environment and Forestry regulation No. 1/2021 (Goverment of Indonesia, 2021). The importance of solid waste, specifically FW, is significantly related to increasing industry performance.

The presidential regulation No. 97/2017 (Government of Indonesia, 2017) and the Ministry of Environment and Forestry regulation No. 10/2018 (Government of Indonesia, 2018) form the Jakstranas. It also guides developing regional policies and strategies at the provincial and district levels to explain waste reduction characteristics. FW should be part of the waste reduction from the source target. The Acceleration of Construction of Solid Waste Processing Installations into Electrical Energy Based on Environmentally Sustainable Technology, initiated in presidential regulation No. 35/2018, is a technical initiative to accelerate waste processing into renewable energy (Government of Indonesia, 2018). Waste has been discussed as energy waste; however, waste processing technology only involves thermal processing technology and refused-derived fuel (RDF). FW processing has not been separated as there are no specific terms for managing FW (i.e., food waste treatment). Indonesia has initiated presidential regulation No. 86/2019, which focuses on food safety requirements to meet food safety and quality standards for human consumption; however, it does not mention FW (Government of Indonesia, 2019b).

The downstream initiatives include the Ministry of Home Affairs regulation No. 7/2021 and Ministry of Public Works regulation No. 3/2013. These initiatives define the solid waste management infrastructure and domestic waste retribution (Government of Indonesia, 2021b, 2013). Organic waste management typically involves sorting and composting. FW separation and pre-treatment can increase the efficiency and recovery value of FW (see supplementary material).

The Indonesian Government is concerned about its waste problem and has explored other options for minimizing FW disposal in landfills. Recognizing the increase in waste generation and the changing composition of waste, the government began to promote 3R in 2008 to increase material recovery and reduce the waste disposed of in landfills. Several regulations have focused on the recovery management of domestic solid waste, including the Waste to Energy

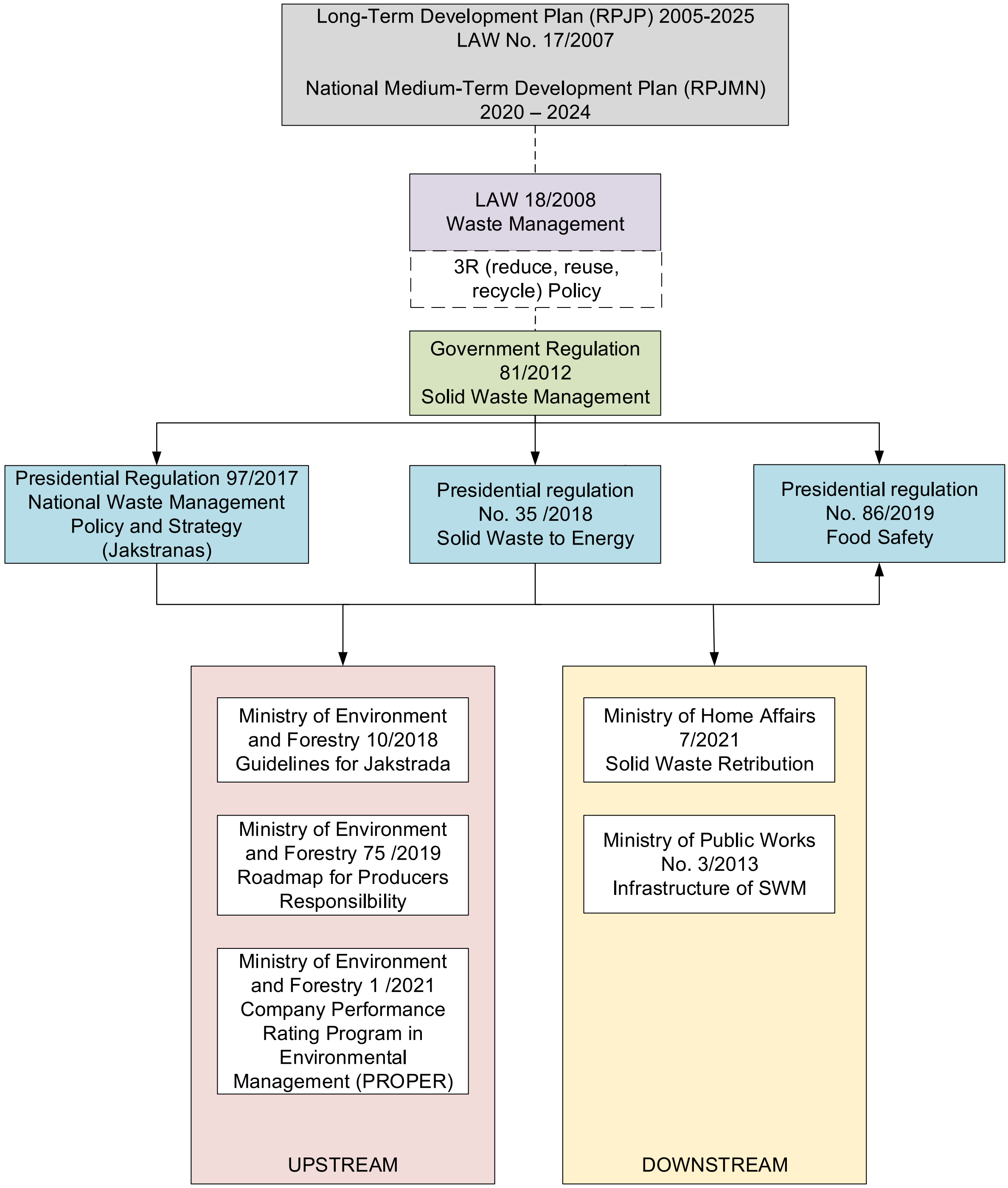

Fig. 4. Regulation related to food waste management in Indonesia.

(WTE) program, whereby waste is transformed into useful substances or into fuel via RDF or in thermal processing, Presidential regulation No. 35/2018; however, the direct use of FW in this program is not clearly defined (Luthfia et al., 2020; Sudibyo et al., 2017). While the government has made significant progress in terms of waste management rules, they are still somewhat antiquated and do not address the present amount of FW output, as they do not directly address minimizing waste management from consumer sources or waste handling.

Several statements have highlighted the urgency of FW management in regard to its impact on climate change, which has resulted in the adoption of a CE and low-carbon development in Indonesia (Luthfia et al., 2020; Ministry of

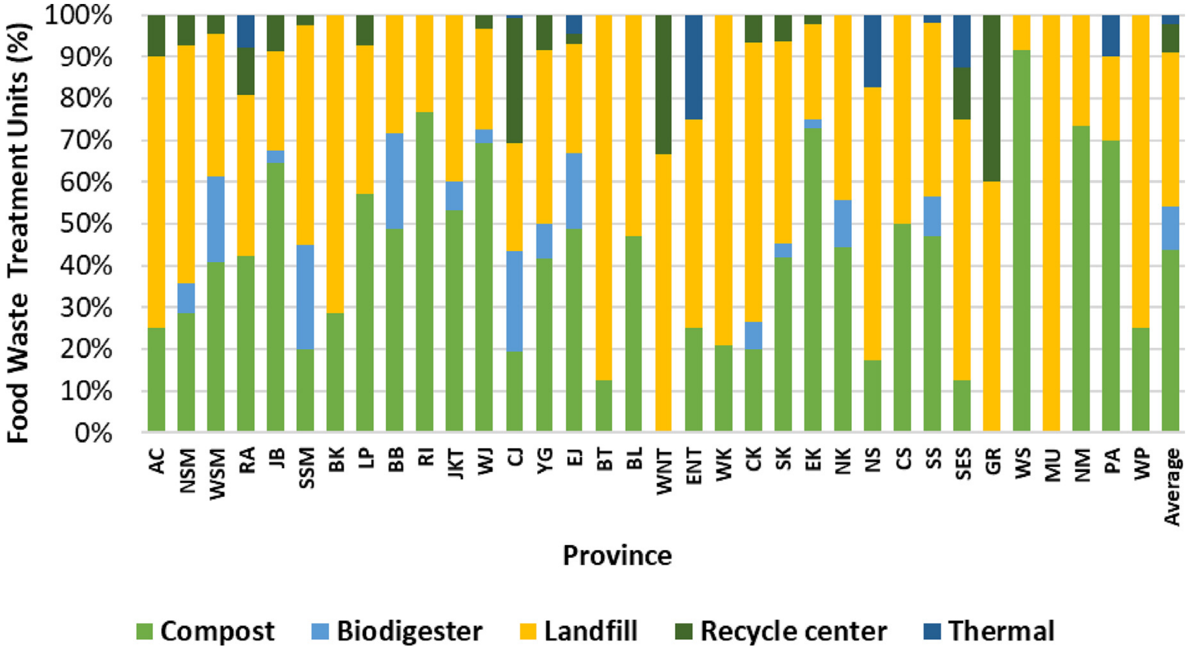

Fig. 5. Current food waste treatment in each province in Indonesia (2020) (Ministry of Environment and Forestry of the Republic of Indonesia, 2020d).

National Development Planning of the Republic of Indonesia, 2021a; Suhartini et al., 2022). Indonesia has committed to combating climate change in its long-term visions (Visi Indonesia 2045; Long-Term Strategy on Low Carbon and Climate Resilient Development 2050). Specifically, Indonesia has set a 2050 reduction target of 3.45% regarding the impact of climate change on national GDP. Indonesia aims to achieve this by increasing the resilience of four necessities: food, water, energy, and environmental health. Three target areas and extending the adaptation strategy into the Updated Nationally Determined Contributions (NDC) focus on the contributions of the economy, social and livelihood, ecosystem, and landscape (Government of the Republic of Indonesia, 2021).

Domestic solid waste is a priority sector for reducing greenhouse gas emissions. Significant amounts of methane gas from landfill waste contribute to the greenhouse gas effect. In addition, open burnings and illegal waste disposals still occur, and no methane utilization is associated with landfills (Auvaria, 2013; Government of the Republic of Indonesia, 2021; Lumban, 2017; Rachim, 2017). Therefore, FW will become the focus of the government's attention in Indonesia's Long-Term Strategy for Low Carbon and Climate Resilience 2050 (Government of the Republic of Indonesia, 2021).

5. Current food waste treatment technology in Indonesia

Regarding solid waste management achievements, Indonesia reported 25.3% waste reduction and 49.2% waste handling in 2022 (Ministry of Environment and Forestry of the Republic of Indonesia, 2022). The Indonesian government has introduced several terms for waste processing sites. Waste processing units involved in food waste processing include composting, biodigester, landfill, recycling centers, and thermal treatment units. In this study, composting is specific to the communal compost plant. Biodigester refers to a waste processing digester unit that uses an anaerobic process. Landfills are waste processing units managed by the Indonesian government. In this study, landfills included open dumping, secure landfills, or sanitary landfills. Most landfills in Indonesia are open dumping or controlled landfills (Ministry of Environment and Forestry of the Republic of Indonesia, 2020d).

Fig. 5 demonstrates the condition of FW treatment in Indonesia in 2020 based on the number (unit) of food waste processing units throughout Indonesia. The composting units are compost plants managed by the government or non-governmental organizations that focus only on managing organic waste. Recycling centers have a separation process for FW processing that usually involves a manual composting process and black soldier flies (BSFs). Thermal treatment involves incineration, gasification, and pyrolysis. Landfill technology is still used for FW management in Indonesia.

Surprisingly, some areas only have landfill for waste management, such as Maluku (MU). However, some areas have composting plants, biodigesters, landfill, and recycling centers, such as EJ and Central Java (CJ). Different technologies are distributed in Fig. 5, where the colors represent FW technology variants in each province. The landfill system is distributed among all Indonesian compared to biodigester, thermal, and recycling centers. This condition shows that FW processing conditions in Indonesia are dominated by composting followed by landfilling. The acceleration of FW processing into energy should accelerate the implementation of processing technology on a small scale from community participation (Colón et al., 2010; Keng et al., 2020) or large/communal scale from government support (Lokahita et al., 2019).

5.1. Black soldier larvae

The BSF (*Hermetia illucens*) is widely distributed globally in tropical and warm temperate areas. They are voracious consumers of decomposing plant and animal matter, such as rotting fruits, vegetables, food items, cow and chicken mounds, and other animal waste. These insects' oviposition and larval growth are greatly impacted by several conditions, such as temperature, relative humidity, light sources, and other waste-related characteristics, including moisture content and pH. (Hopkins et al., 2021; Singh and Kumari, 2019) Substrate characteristics become essential in the decomposition process of BSFs. FW is a suitable material for processing by BSF larvae, including fruit peel mixed with goat manure, agriculture, cafeteria, and domestic waste (Fitriana et al., 2021; Ichwan et al., 2021; Indri et al., 2021; Sanjaya et al., 2019; Widyastuti et al., 2021). As a tropical country, Indonesia has an optimum temperature for BSF-related FW processing. However, it is crucial to maintain appropriate circumstances, including meal components, a suitable temperature, humidity, and acidity, for BSF larvae to survive and develop (Ojha et al., 2020)

In the 2020–2021, the Surabaya City government developed four food waste processing units using BSF in Jambangan, Wonorejo, Bratang, and Menur. The Jambangan Recycling Center (PDU) was initiated as a collaboration between the Ministry of Environment and Forestry and the Surabaya City Environment Service (DLH). From 2020–2021, PDU processed 50 tons of household FW, while the Wonorejo BSF processing unit processed 40–50 tonnes of FW from the nearest canteen food waste. The Bratang and Menur units can process 1–7 tons/year of canteen FW. The products produced from this process include maggots (pupae) and compost from the residual process (Environment Berau of Surabaya, 2021). The Jambangan and Wonorejo units have a BSF waste reduction performance of 84% and 54%, respectively (Zahra, 2022). Other research indicates that utilizing FW from domestic waste (household) and Cafetaria as a substrate could reduce 70%–75% of waste (Cheng et al., 2017; Fitriana et al., 2021; Ibadurrohman et al., 2020; Priyambada et al., 2021). There are several obstacles associated with managing BSF processing units in Indonesia, such as a lack of resources and funds and the collection of FW from households. Not all residents are aware that they need to separate their organic and inorganic wastes, making FW collection more challenging (Environment Berau of Surabaya, 2021).

BSFs contain a respectable amount of crude protein (40%–54%) and dry fat (15%–49%), and their essential amino acid composition is comparable to fish meal (Ebeneezar et al., 2021). BSF research conducted on canteen waste in Indonesia found that the product nutrient composition comprised 45%–50% protein and 24%–50% fat (Ichwan et al., 2021). Similar research using FW from cafeterias indicated a product composition that contained 29.1% protein and 11.86% fat within 12 days of bioconversion (Ibadurrohman et al., 2020). The residual process of BSF creates a high amino acid product that could produce high-quality compost (Kim et al., 2021; Mertenat et al., 2019; Indri et al., 2021). Moreover, BSF technology contributes less to global warming than other conventional composting techniques (Salam et al., 2022) (see supplementary material).

5.2. Anaerobic digestion

Anaerobic digestion (AD) technology can produce energy from organic materials. AD provides ideal heat- and oxygen-free conditions that enable microorganisms to thrive and decompose organic matter into biogas and nitrogen-rich fertilizers (Lukitawesa et al., 2020; Sandriaty et al., 2018; Sumantri and Hadiyanto, 2020; Zhang et al., 2020). AD has several economic and environmental benefits in addition to reducing the waste sent to landfills. According to estimates, large-scale AD applications could deliver operational benefits and efficiency improvements, such as reducing landfill costs and imparting economic benefits through the generation of power, heat, and fertilizer (Hobbs et al., 2021; Tiong et al., 2021; Waris et al., 2021; Zhang et al., 2020).

Previous AD research in Indonesia has involved pilot or laboratory studies. Biogas units in Indonesia typically process waste with the addition of a bacterial starter/inoculum, usually from cow manure, tofu wastewater, or palm oil mill effluent (POME) (Tiong et al., 2021). Monitoring anaerobic co-digestion involves using operational control parameters, such as pH, alkalinity, and process performance, which are characterized by volatile solids, biogas production, and methane content. FW utilization from canteens and cafeterias creates volatile solids (VS) with a conversion efficiency of 90%–96% (%WW, on a wet basis) (Sandriaty et al., 2018; Tassakka et al., 2019), while the recommended conversion efficiency of organic materials to VS is 83%. These characteristics are crucial because they enable the conversion of FW into useful products, such as energy recovery (Helenas Perin et al., 2020). In Indonesia's climate, AD plants have a hydraulic retention time (HRT) of 20–130 days, depending on the substrate, reactor, and operational system (Sandriaty et al., 2018; Saragih et al., 2019; Waris et al., 2021). Methane yields could generate 0.30 L CH_4/g COD removed with POME (Tiong et al., 2021). Substrates from canteens that use high fat, oil, and grease levels could produce 127 to 485 $\pm$ CH_4/kg of VS per day (Tassakka et al., 2019; Wulansari and Kristanto, 2016).

One of Indonesia's ADs for FW treatment projects is the Integrated Resource Recovery Center (IRRC) in Malang Regency, East Java developed by the United Nations Economic and Social Commission for Asia and the Pacific (UNESCAP) in collaboration with Waste Concern. An IRCC is a plant where 80%–90% of FW can be handled in a decentralized, cost-effective manner for small and medium-sized communities. Such plants utilize traditional market waste as a substrate and cow manure as inoculum at a ratio of 1:1. The construction of IRRCs typically includes an AD, sludge drying bed, compostor, and generator (Farahdiba et al., 2021b; Suhartini et al., 2022). IRRC Malang District (Farahdiba et al., 2021a).

Biodigester processing has been growing in Indonesia since 2020. In 2020, managed waste reached 300 tons/year and will increase to 3800 tons/year in 2022. This process has produced animal feed, compost, and produce up to 1000 tons of raw energy materials each year (Ministry of Environment and Forestry of the Republic of Indonesia, 2022, 2021b, 2020a). However, in the Indonesian national database, the production of specific substrates is not explained in detail.

5.3. Composting

Composting is a method of handling environmental waste that involves the biological decomposition of organic substances (Cai et al., 2022). Compost can be created using aerobic windrow composting, which involves stacking long rows of biodegradable materials. This process works well for larger-scale processes when mechanical pile rotation is required and is frequently used in agricultural treatment plants (Abu et al., 2021; Keng et al., 2020; Saer et al., 2013). Most communal compost plants in Indonesia involve aerobic composting with manual aeration, where the garbage is stacked and turned manually.

The Indonesian government and community widely use composting for FW management. In 2021, waste reached 300,000 tons/year, and generated compost products reached 192,000 tons/year with a residual yield of the animal feed product is 38,236 tons/year. Large/communal scale composting applications typically use the open windrow method and are managed by the local government. An example of a composting process in a metropolitan city is Surabaya. Surabaya has 26 compost plants that utilize wooden twig waste from the city parks and food waste from households and traditional markets (see supplementary material) (Environment Berau of Surabaya, 2021). Composting is associated with several environmental issues, such as soil acidification, odor, and ground and surface water contamination from the release of leachate, as well as potential health impacts from drinking contaminated water. Composting can help improve waste disposal conditions and reduce MSW carbon emissions by 20%–25% (Salam et al., 2021).

5.4. Thermal treatment

The process of generating heat from waste material is known as thermal oxidation, which includes incineration. In this process, the steam engine boiler receives the heat. Waste containing hydrocarbons is burned during incineration, converting the hydrocarbons to water, carbon dioxide, and other pollutants. Prior to developing an effective combustion process, it is essential to comprehend a material's fundamental elements to establish its carbon, hydrogen, oxygen, nitrogen, sulfur, and ash makeup (Lokahita et al., 2019). Thermal waste processing can reduce large amounts of waste quickly and convert it into electrical energy that can be used by the community (Kadang and Sinaga, 2020).

In February 2016, the Indonesian government released a presidential regulation on the acceleration of WTE development in seven cities. WTE was defined as a power plant that uses thermal processing technology to convert MSW, such as FW, yard waste, and plastic waste, into sustainable energy by gasification, incineration, or pyrolysis. Thermal waste capacity in Indonesia reached 26947,95, 11913,60, and 3160,90 tons/year from 2021–2022, respectively (Ministry of Environment and Forestry of the Republic of Indonesia, 2022) (see supplementary material). It is thought that gasification is more reliable for many areas due to its reduced impact compared to landfilling, incineration, and pyrolysis (Budiono, 2021; Gunamantha, 2010; Muliawati, 2018; Rachim, 2017).

5.5. Landfilling

Disposing of FW in landfills is typically considered the most environmentally damaging option and, therefore, is the lowest method in the FW management hierarchy. This waste management system is often considered the most polluting and significantly contributes to global warming and acidification (Lumban, 2017; Nikmah and Warmadewanthi, 2013).

5.6. Refuse-derived fuel

As organic and plastic materials make up more than 50% of Indonesia's solid waste, there is enormous potential for recovering RDF (Lokahita et al., 2019). Indonesia has three RDF project units: Medan City, Depok City, and Cilacap City. The units in Medan City and Cilacap are private partnerships with the local government, while the unit in Depok City is managed by the local government. These three projects are estimated to have processed up to 57,874 tons/year of waste between 2021–2022 (Ministry of Environment and Forestry of the Republic of Indonesia, 2021b). The Cilacap unit has the highest processing capacity, capable of processing 150 tons of waste per day and producing approximately 54.89 tonnes of RDF, or around 36.09% (Goverment of Cilacap District, 2023). RDF technology is associated with refined implementation and is thought to have accelerated the implementation of national strategic projects in line with Indonesia's WTE target (The Government of Indonesia, 2018).

Compared to other biomass conversion technologies, such as pyrolysis and gasification, RDF technology requires a substantial investment, which often limits its utilization in waste management (Anasstasia et al., 2020). However, RDF products demonstrate an expense advantage relative to rice husks and satisfy the required minimum calorific value criteria, obtaining technical recognition (Paramita et al., 2018). This economic aspect must be analyzed further to clarify the required investment and economic value associated with FW utilization.

5.7. Hydrothermal treatment

The year 2017 marked the commencement of operations of a comprehensive Hydrothermal facility in Indonesia, designed to process non-segregated municipal solid waste. Unsorted, highly organic garbage is fed into the reactor and exposed to steam at a pressure and temperature of 2.5 MPa and 220 °C for 30 min. Hydrochar, a powder-like substance, is one product obtained from this process. It was estimated that the Hydrothermal might use approximately 15% of the powder is utilized as fuel for the boiler during the hydrothermal treatment process and sell the remaining portion as an alternative to coal.

Data on gas emissions from the boiler demonstrate low air pollution (Marzbali et al., 2021; Saqib et al., 2019). Many FW utilizes hydrothermal technology due to the diversity of current research. The applicability of this technology on an industrial scale is promising. However, the current study primarily concentrates on laboratory size (Hantoro et al., 2020; Putra et al., 2021; Sulaeman et al., 2021; Vlaskin et al., 2017). According to a sensitivity analysis, the most significant influencing variables are the financial costs associated with material collection and transportation (Mazumder et al., 2022). Therefore, the entire system should be assessed from a technological and economic standpoint, given the industrial viability of hydrothermal processing.

Several technologies can process input waste as wet or dry organics. The efficacy of these treatments depends on specific conditions, including air supply, reaction conditions, volume reduction, and time detention. The product of each technology is considered an advantage for further application and residual as environmental impact potential. The reliability of these technologies is related to the economic consideration and technical feasibility of their small/ large-scale application potential. RDF and Thermal treatment consider in large-scale applications because of the high investment and operational cost. AD, composting, and BSF comprise technology adopted in small/large scales with relatively easy operations and more affordable costs. Hydrothermal treatment is a suitable FW treatment. Nevertheless, considerable capital investment in equipment and infrastructure is required due to the high levels of maintenance required (see supplementary material).

6. Food waste treatment recommendations in Indonesia

Fig. 6 details the recommendations for FW processing in Indonesia. The waste reduction target is the main focus for reducing FW generation. FW generated at the waste source is transported to the temporary processing site (TPS) or temporary processing site (TPS3R) or goes straight to landfills. Processed food waste is transported to TPS3R. Transferring the waste source to TPS or TPS3R requires transportation to a communal waste processing site.

Households or communities manage several regional-scale composting and BSF processing units (on-site systems). Waste can be processed directly by the household or at the nearest processing site. The communal processing sites (off-site system), including TPS3R, can also function as a recycling center with compost processing, BSF, and thermal processing units. FW must be sorted and segregated before entering primary processing, except if entering the thermal processing unit. Any residual FW that cannot be reused can be immediately transported to landfill. Any products from FW processing can be resold or reused.

6.1. Technical feasibility

Collecting FW is a significant problem, requiring extra transportation and microbial growth control (Fig. 6). Before FW is moved to a centralized treatment facility, bacterial growth is easily encouraged during the separation, collection, and preservation procedures, as bacteria are abundant in water and organic materials. Therefore, the way FW is preserved is crucial for preventing contamination and odor during transit and treatment (Guan et al., 2021). Waste must be gathered and sorted in accordance with the specifications of the facility to run effectively. Every home and community requires suitable trash cans, and both urban and rural regions require proper collection and hygienic waste segregation procedures. Furthermore, both skilled operators and laborers are required for the functioning of these plants (Karmakar et al., 2023). The large range of target and non-target substances associated with different waste sources and the process costs associated with large-scale commercialization and high productivity could be challenging (Abu et al., 2021; Ahamed et al., 2016; Laurent et al., 2014).

6.2. Economic challenges

Indonesia's average national budget for waste management in 2022 was only 0.51% of the total budget (Ministry of Home Affairs, 2022). Due to insufficient funding for recycling, some developing nations have attempted to introduce a system for managing FW in their legislative frameworks. However, budgeting remains a significant problem in developing countries for handling waste (Lohri et al., 2017; Pham et al., 2015; Suhartini et al., 2022).

Sustainably managing FW has become a significant priority in developing countries. FW is significantly higher during processing, decreasing the use of sophisticated food preservation methods, including inadequate government regulations and immature supply chains. In developing countries, FW is primarily landfilled or utilized as animal feed (Lohri et al., 2017). The applicability of FW recycling in developing countries is highly limited due to weak recovery methods.

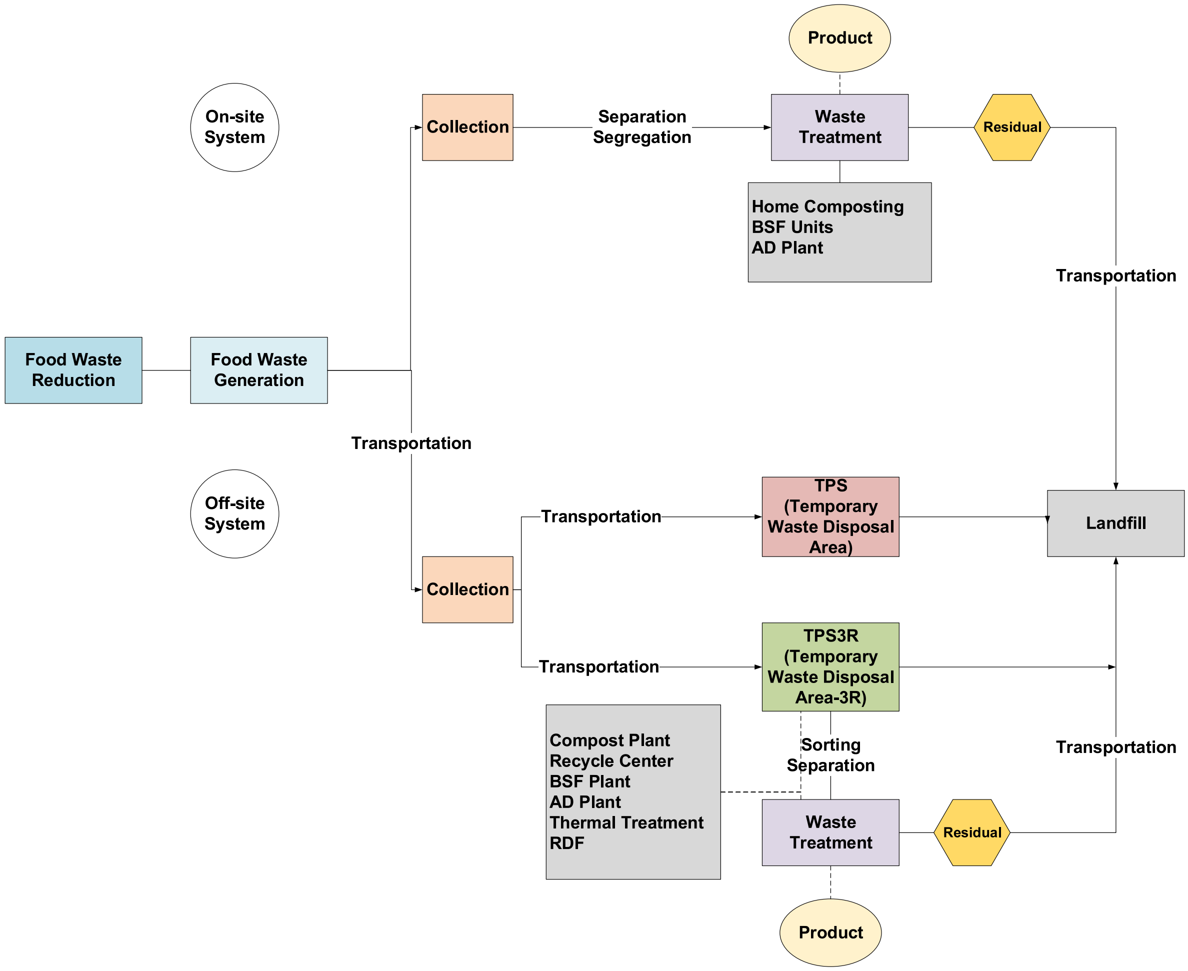

Fig. 6. Food waste handling recommendation in Indonesia.

Furthermore, there are no recycling requirements for the general public and no appropriate incentives to encourage individuals to recycle FW in these countries (Dora et al., 2021; Oelofse, 2014). The cost of trash collection, transportation, equipment design, operations, and maintenance should be considered when considering FW processing technologies (Fig. 6). Several techniques are more suitable for low-capacity, significantly polluting treatments with high energy yields that lower the operational cost (Wang et al., 2022). Indonesia needs to develop indigenous technologies that can specifically respond to the requirements of Indonesia's FW. Additional technological drawbacks involve elevated operational expenses and the dearth of proficient operators and technicians (Karmakar et al., 2023).

6.3. Environments impacts

Fig. 6 proposes community-wide home composting and BSF could further reduce the environmental impact associated with FW. On-site systems are very beneficial for managing FW as they do not require resources for transportation and waste storage facilities and minimize the production of hazardous contents, including waste leachate, from FW. Moreover, technology comparison is required by using the life cycle of FW processing. Life cycle assessments can be used to determine the best technology for different processing scenarios (Ahamed et al., 2016; Angelo et al., 2017; Beretta et al., 2017; Edwards et al., 2018; Iswara et al., 2020).

Proper waste management and treatment for FW with high moisture (80%–90%) and organic matter (approximately 90%) content may reduce GHG emissions and enable bioenergy production. AD technology is frequently cited as a more energy- and emission-beneficial treatment technique for FW than the conventional methods of waste disposal (Bernstad and La Cour Jansen, 2012; Mondello et al., 2017; Thyberg and Tonjes, 2017; Zhang et al., 2020).

Previous research on the environmental impact assessment of waste processing units in Indonesia has determined each processing technology's potential for environmental impact across different scenarios. AD can produce high acidification and eutrophication, while composting has the potential for higher eutrophication (Ula et al., 2021). Different thermal treatments were analyzed, including incineration, gasification, pyrolysis, and RDF. Most studies reported that gasification is the most appropriate technology due to its lower environmental impact than landfilling, incineration, and pyrolysis (Budiono, 2021; Gunamantha, 2010; Muliawati, 2018; Rachim, 2017). RDF is considered to be a more ecologically sustainable alternative to open dumping and incineration (Anasstasia et al., 2020), and it can reduce CO_2 emissions by 178–330 times (Suryawan et al., 2021). Landfill, which is the most common solid waste treatment in Indonesia, has the highest environmental impact (Auvaria, 2013).

7. Practical applications and future research prospects

This study has highlighted the importance of analyzing food waste generation data, considering FW treatment in technical feasibility, environmental impact assessment, and economic considerations. The study involves use of national data, moreover further analysis of data at a more detailed stage is necessary to uncover all the complexities of the issue. Environmental impact assessments need to be conducted to identify the environmental effects of food waste management strategies. Life cycle assessments are a useful tool to evaluate the environmental impacts of each FW treatment. Scenarios can assist in identifying the most environmentally friendly alternative by enabling visualize and predict the potential effects of different food waste management systems. The implementation of sustainable food waste management strategies can not only reduce environmental impact and promote sustainability but also create economic opportunities by promoting circular economies.

8. Conclusions

Approximately 20.8 million tons/year of FW potential in various regions contributes. Indonesia has to accelerate its progress to achieve its 70% waste treatment target by 2025. Acceleration of this target requires integrated regulation, initiatives, and comprehensive FW technology. However, no concrete regulations or incentives exist to accelerate FW reduction and handling. Small and large-scale technology management must be considered from a technical, environmental, and economic standpoint. Application of BSF, AD, composting, thermal treatment, and RDF promise FW treatment technologies with lower environmental impacts. Environmental impact assessments could be made more profound by carrying out integrated assessment studies. E-supplementary data for this work can be found in the e-version of this paper online.

CRediT authorship contribution statement

Aulia Ulfah Farahdiba: Conceptualization, Investigation, Resources, Writing – original draft. **I.D.A.A. Warmadewanthi:** Writing – review & editing. **Yunus Fransiscus:** Investigation, Writing – review & editing. **Elsa Rosyidah:** Data curation, Visualization. **Joni Hermana:** Supervision, Writing – review & editing. **Adhi Yuniarto:** Supervision, Validation.

Declaration of competing interest

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

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Appendix A. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.eti.2023.103256.

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