# Food waste to bioenergy: Current status and role in future circular economies in Indonesia

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**Abstract.**

Like many countries, Indonesia generates large quantities of food waste. Food waste is poorly managed due to inadequate treatment practices, which has a harmful impact on the environment. This paper demonstrates the high potential for food waste valorization in Indonesia and outlines the optimal valorization pathways to inform future decision-making surrounding the management of this waste. This paper also compares various conversion technologies for transforming food waste into liquid, solid, and gaseous biofuels. The challenges and opportunities for wider implementation are also considered, including the integration of supply chains and the logistics of food waste management, the technological feasibility, and the persistent behaviors surrounding food waste and energy in Indonesia. The economic and environmental benefits, the perspectives of improved food waste management practices and sustainable fuels, as well as the policy landscape surrounding waste and sustainable energy are also explored. The challenges of scalability and commercialization are also highlighted in this paper. This review demonstrates the best pathways from food waste valorization to bioenergy, including biogas or biodiesel integrated with a black soldier fly larvae (BSFL) composting system. Despite the scale of resources in Indonesia, the pathways and technologies for processing food waste are lacking. Further in-depth studies are required to demonstrate the sustainability and feasibility of food waste transformation into bioenergy to realize its high value.

**Keywords:** Bioeconomy; conversion technology; environmental protection; food waste; food waste for bioenergy

**List of Abbreviation**

| | |
|---|---|
| 3R | Reduction, Reuse, And Recycle |
| AD | Anaerobic Digestion |
| ADF | Acid Detergent Fiber |
| AP | Acidification Potential |
| BIOMIRU | *Biogas Mini Rumahan* |
| BMP | Biochemical Methane Potential |
| BSFL | Black Soldier Fly Larvae |
| CBP | Consolidated Bioprocessing |
| CHP | Combined Heat and Process |
| COD | Chemical Oxygen Demand |
| CSTR | Continuous Stirrer Tank Reactor |
| CMUP | Combined Mechanical-Ultrasonic Pre-Treatment |
| CV | Calorific Value |
| DT | Dry Torrefaction |
| EP | Eutrophication Potential |
| EPS | Extracellular Polymeric Substances |
| FAME | Fatty Acid Methyl Ester |
| FAO | Food and Agriculture Organisation |
| FVW | Fruit and Vegetable Waste |
| FW | Food Waste |
| GHG | Greenhouse Gases |
| GWP | Global Warming Potential |
| HHV | High Heating Value |
| HMF | Hydroxymethylfurfural |
| HoR | House of Representatives |
| HOT | Hydrothermal Oxidation |
| HRT | Hydraulic Retention Time |
| HSW | Household Solid Waste |
| HT | Human Toxicity |
| HTL | Hydrothermal Liquefaction |
| IUPTL | Electricity Supply Business License |
| LAB | Lactic Acid Bacteria |
| LCA | Life Cycle Assessment |
| LPG | Liquefied Petroleum Gas |
| MA | Microwave-Assisted |
| MEMR | Ministry of Energy and Mineral Resources of Republic of Indonesia |
| MEP | Marine Eutrophication Potential |
| MSW | Municipal Solid Waste |
| NDC | Nationally Determined Contribution |
| NDF | Neutral Detergent Fiber |
| NEP | National Energy Policy |
| NRE | New And Renewable Energy |
| OFMSW | Organic Fraction of Municipal Solid Waste |
| ODP | Ozone Layer Depletion |
| OLR | Organic Loading Rate |
| ORP | Oxidation-Reduction Potential |
| PEG | Polyethylene Glycol |
| PF | Photo Fermentation |
| PLTBg | Biogas Power Plant |
| PLTBm | Biomass Power Plant |
| PLTSa | MSW Power Plant |
| PT. PLN | The State Electricity Company |
| S | Sonicated Pre-treatment |
| SBHR | Sonicated Biological Hydrogen Reactor |
| SDS | Sodium Dodecyl Sulphate |
| SHF | Separated Hydrolysis Fermentation |
| SS | Sewage Sludge |
| SSF | Simultaneous Saccharification and Fermentation |
| TD | Tofu Dregs |
| TEP | Terrestrial Eutrophication Potential |
| TRL | Technology Readiness Level |
| TS | Total Solids |
| UA | Ultrasonic-Acid Pre-Treatment |
| UASB | Up-Flow Anaerobic Sludge Blanket |
| UB | Ultrasonic-Base Pre-Treatment |
| UH | Ultrasonic-Heat Pre-Treatment |
| US | Unsonicated Pre-Treatment |
| VFA | Volatile Fatty Acid |
| VS | Volatile Solids |
| WtE | Waste to Energy |
| WT | Wet Torrefaction |
| ww | Wet Weight |

## 1 Introduction

An over-reliance on fossil-based energy sources (i.e. coal and petroleum) leads to global climate change challenges. Increasing costs and risks surrounding fossil-based energy security have negative impacts on socio-economic and political aspects (Lin et al., 2013; Mahmood et al., 2016). Global population growth is also driving an increase in energy demand (Franco et al., 2017; Pérez-Lombard et al., 2008). Like many developing countries, Indonesia is experiencing the impacts of climate change and needs to identify sources of affordable, clean energy to support sustainable economic development (Khalil et al., 2019; McNeil et al., 2019). With the House of Representatives (HoR) approval, the Indonesian Government has established a National Energy Policy (NEP), regulated by Government Regulation Number 79 of 2014. This policy sets out biomass and waste as renewable energy resources to realize energy independence and improve security within Indonesia (Ministry of Energy and Mineral Resources/MEMR, 2016). Therefore, various supports (i.e. policy targets for renewables, financial instruments for investment, and trainings) are required for promoting wider implementation and operation of biomass valorization (Safril et al., 2020). Indonesia is also rich in other new and renewable energy (NRE) resources, as shown in Table 1 (MEMR, 2017). These NRE resources are still not fully utilized due to various constraints such as high investment costs, the remote location of potential resources, and lack of regulatory support. Bioenergy production from waste biomass has great potential in Indonesia due to the abundance of resources, such as municipal solid waste (MSW), in particular, food waste.

Table 1. Type of new and renewable energy in Indonesia

| Type | Capacity | Potential (MW) | Installed capacity (MW) |
|---|---|---|---|
| Geo thermal | - | 29,544 | 1,438 |
| Hydro | 75,091 MW | 45,379 | 8,671 |
| Mini-microhydro | - | 19,385 | 2.601 |
| Biomass | 32,654 MW | - | 1,626 |
| Solar | 4.80 kWh/m$^2$/day | - | 91.1 |
| Wind | 970 MW | - | 1.96 |
| Uranium | 3,000 MW | - | 30 |
| Shale Gas | 574 TSCF | - | - |
| Coal methane | 456.7 TSCF | - | - |
| Ocean Wave | 17,989 MW | - | - |
| Ocean thermal energy | 41,012 MW | - | - |
| Tidal energy | 4,800 MW | - | - |

Source: MEMR (2017)

Global MSW production is estimated to comprise 40-70% degradable organic matter, of which food waste is the main component (Ali et al., 2017; Caicedo-Concha et al., 2019). Global food waste production increases by approximately 1.3 billion tons (or one-third of the total food production) annually (Xu et al., 2018). On average, developed countries produce 100-170 kg of food waste per capita per year (Dung et al., 2014), while developing countries produce 80-90% of food waste (Food and Agriculture Organisation/FAO, 2011). Ong et al. (2018) reported that, in Indonesia, food waste is the second-largest waste stream after organic waste (i.e. food processing industrial waste, agricultural waste, etc.), which contributes about 22.2% of the total MSW (190 thousand tons in 2014). According to the FAO (2019), approximately 13 million tons of food waste are disposed of in Indonesia annually, thus making it the second-largest producer of food waste globally. Within Asia-Pacific countries, Indonesia generates over 30 million tons of food waste per annum. This is the highest generation globally and almost double that of the second-highest producer (Japan), as shown in Figure 1 (Kiran et al., 2014).

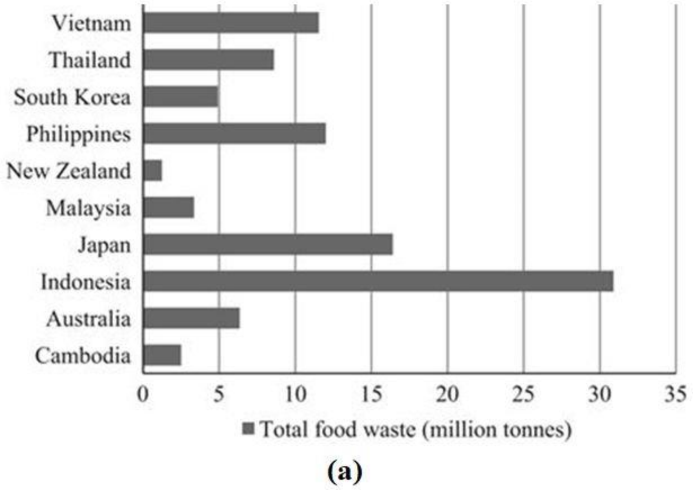

**Figure 1.** Production of food waste in Asian and Asia-Pacific countries (Adapted from Kiran et al. (2014))

Globally, food loss and food waste from various food products are generated from each stage of the food value chain (including agricultural or animal production, post-harvest handling, storage, processing, distribution, consumption, etc.), as can be seen in Figure 2. In many developing countries, premature agricultural harvesting systems may lead to increased food waste. FAO (2011) stated that 42% of fruits and vegetables and up to 30% of grains produced across Asia and the Pacific region are wasted or lost before reaching the consumer. Curry and Pillay (2012) reported that approximately 40% of food waste was derived from industrial and household activities. Household food waste consists of vegetables and other food ingredients that are not cooked and must be disposed of. Food waste can also be derived from leftovers in commercial activities such as restaurants, canteens, etc. In the case of Indonesia, Soma (2017a) found that food consumption behaviors and food production supply chains contribute to food waste. Other factors contributing to food waste generation may include: the relatively low level of public environmental knowledge and awareness of the severity of the waste problem, challenging socio-economic conditions, and behaviors and perceptions surrounding the 3R programs (Dhokhikah et al., 2015); employment, income, number of household members, eating out culture, buying best offer behaviors, and beliefs (Mattar et al., 2018); lack of food waste technology, unsustainable food consumption behaviors, lack of food waste management, and lack of communication or socialization (Kasavan et al., 2019).

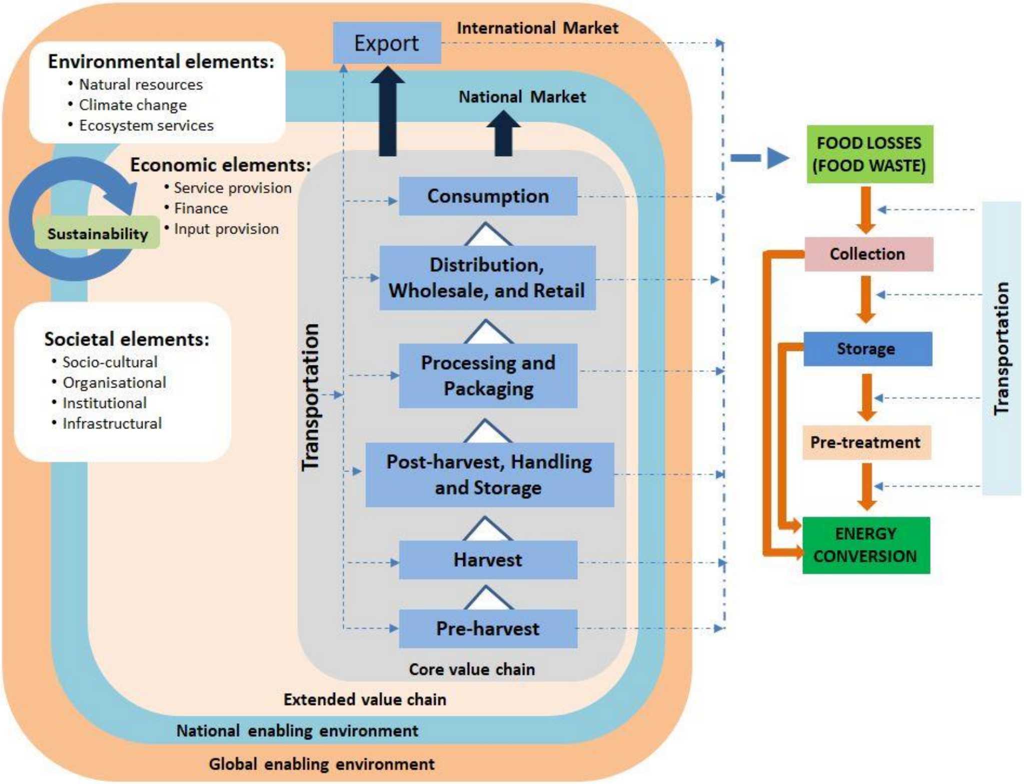

**Figure 2.** Schematic of food losses and food waste from the food value chain (Adapted from Iakovou et al. (2010); Gold and Seuring (2011); and FAO (2011) )

Currently, the collection and processing of food waste in Indonesia are not optimal, with the majority being disposed directly to open dumps and landfills. Only a small proportion is collected and utilized for animal feed and composting (Soma, 2017b). Various problems have arisen from the practice of open dumping such as pests, odours, and harmful emissions to land, air (particularly methane and carbon dioxide), and water (via leachates) (Sudibyo et al., 2017, De Clercq et al., 2017); leading to further climate change problems (Slorach et al., 2019). The landfills are not considered to be economically feasible as it is cost-intensive (i.e. cost of land, cost of equipment, etc.), require large areas of land, and may have detrimental impacts on the environment (i.e. carbon emissions, leachate, and odor problems) (Shen et al., 2013). The Indonesian Government, through the Government Regulation No. 81 Year 2012, supports household solid waste management (including food waste) via reduction, reuse, and recycle (3R) scheme, as well as other regulations which endorse the reduction of waste at sources (Dhokhikah et al., 2015). There are many challenges surrounding food waste management practices in Indonesia, including a lack of financial support, poorly managed or inadequate facilities and resources, and lack of support from the municipality (Soma, 2017a).

Composting of food waste offers a sustainable treatment pathway, and the Indonesian Government developed an initiative to promote this in 2008 as part of the Solid Waste Management Act 18/2008 (Damanhuri et al., 2014). However, the initiative to date has not been successful due to a lack of infrastructure for processing, marketing, and utilization of the resultant composts (Damanhuri et al., 2014; Soma, 2017a). Composting is not always a suitable option for food waste due to its high salinity content (Chan et al., 2016; Wang and Zeng, 2018). According to Meng et al. (2015a), transforming food waste into syngas using incineration was not feasible due to high initial investment costs and high energy requirements to evaporate the large amounts of water content in food waste.

There are several examples of small- and domestic-scale applications: household composting units, small-scale composting units, vermicomposting systems, and anaerobic digestion. Sekito et al. (2019) reported that the production of organic waste (mainly food waste from hotels or households) in Gili Trawangan (Indonesia) was about 6.0 tons/day. The composting of this waste can generate approximately 2.77 tons of compost/day, with a total income estimated at 11,974 USD/month. Composting was one of the alternative strategies of solid waste management practices in Gili Trawangan, considering the high demand for compost as organic fertilizer. Ibadurrohman et al. (2020) reported that bioconversion of the University canteen's food waste using *Hermetia illucens* (or black soldier fly/BSF) larvae were an attractive option. This technology can reduce 75% of waste with additional production of 800 g larvae biomass per 4 kg of food waste. The larva contains a high concentration of protein (29.1%) and fat (11.9%), which can be used as animal feed. In Indonesia, several projects have received governmental support for the development of food waste for bioenergy production. One example is the small-scale BIOMIRU project (*Biogas Mini Rumahan*) which was initiated under the BIRU program (http://www.biru.or.id/) (BIRU, 2021) and RUMAH ENERGI (http://www.rumahenergi.org/) (Rumah Energi, 2021). Various studies have emphasized that food waste has the potential to be converted to sustainable bioenergy and bioproducts (Dung et al., 2014; Karmee, 2016; Thi et al., 2016; Kiran et al., 2014)

Food consumption and food waste generation are increasing as the global population increases (Wang et al., 2018a). Some food waste can be reduced (as awareness of the problem increases and behaviors change); however, unavoidable food waste from crop waste, spoilage, or inedible parts of plants and animals will remain an issue. In Indonesia, high quantities of unavoidable food waste are generated from traditional markets (Hartono et al., 2015; Pasang et al., 2007); from spoilage of food products due to lack of refrigeration storage systems (Soma, 2018; Waisnawa et al., 2018); or incorrect refrigeration methods (Parizeau, 2020; Soma, 2020). Food waste has an impact on health, creates malodours, and attracts pest. To lessen the impacts of this waste on the environment and on communities, Indonesia needs to identify more sustainable practices to capture, mobilize, and valorize organic waste materials. According to Papargyropoulou et al. (2015), to develop sustainable waste management systems that for mitigating the climate change impacts and reducing impacts on communities, the challenges and opportunities in various aspects (i.e. technical, economic, political, and social) need to be addressed. Therefore, this review paper evaluates food waste to bioenergy valorization pathways, intending to identify the most technically and economically viable approaches and consider the overall environmental sustainability of each approach. This paper outlines the challenges and opportunities of scaling up and commercializing food waste to bioenergy processes in Indonesia.

## 2 Food waste – characteristics and compositions

Food waste is derived from various sources such as vegetable and fruit waste from markets, households, and restaurants (Xu et al., 2018). It is highly heterogeneous and contains complex components and high concentrations of organic material (Suhartini et al., 2019). Several studies state that the composition of food waste varies in terms of its organic compositions such as  protein, carbohydrates (i.e. starch, cellulose, hemicellulose, and lignin), fats, and organic acids (Meng et al., 2015a; Xu et al., 2018). Various studies have measured composition of food waste and confirmed its variability, as shown in Table 2. Factors such as seasonality, socio-cultural influences and behaviors (i.e. the household's consumption and spending on food), geographical location, and market trends can impact the availability and composition of food waste (Khair et al., 2019; Soma 2020).

Table 2. Characteristics of food waste and the analytical measures from various studies

| Parameters | Browne and Murphy (2013) | | Xiao et al. (2013) | | Tampio et al. (2015) | | (Zhang et al., 2017a) | | Xiao et al. (2018) | | Shi et al. (2018) | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Value | Analytical measurement | Value | Analytical measurement | Value | Analytical measurement | Value | Analytical measurement | Value | Analytical measurement | Value | Analytical measurement |
| TS (% ww) | 29.40 | APHA method (2540 G) | 17.20 | APHA method (2540 G) | 24.86 | SFS 3008 | 22.10 | APHA method (2540 G) | 10.69 | APHA method (2540 G) | 25.94 | APHA method (2540 G) |
| VS (% ww) | 28.02 | | 16.70 | | 23.11 | | 20.40 | | 10.06 | | 24.59 | |
| MC (%ww) | 71.60 | | 82.80 | | 75.14 | | 78.90 | | 89.31 | | 74.06 | |
| VS (%TS) | 95.30 | Calculation VS divided by TS multiplied with 100 | 95.60 | Calculation VS divided by TS multiplied with 100 | 92. 60 | Calculation VS divided by TS multiplied with 100 | 92.20 | Calculation VS divided by TS multiplied with 100 | 94.11 | Calculation VS divided by TS multiplied with 100 | | |
| pH | 4.10 | Digital pH meter | | 4.10 | Digital pH meter | Digital pH meter | 5.92 | Digital pH meter | 4.18 | Digital pH meter | | |
| Crude fat/lipids (%TS) | 19.00 | na | | | | a Soxcap-Soxtec-Analyser13.01 | 31.80 | na | 13.01 | Amethanol-chloroform extraction and weigh metho | 10.60 | APHA method |
| Crude protein (%TS) | 18.10 | na | | | 21.89 | Duma's method using Leco FP 428 nitrogen analyser. Multiplying the N% by a factor of 6.25 | 15.50 | TKN multiplied with factor of 6.25 | 22.94 | traditional Folin-phenol method | 15.1 | |
| Carbohydrate (%TS) | 59.00 | na | | | 112.7 (g/kgTS) | Inverted with 1 N HCl (50 °C, 12 h) | 41.60 | na | 56.85 | phenol-sulfate examination method | - | |
| C (%TS) | 49.58 | Ultimate analysis using element analyser (CE 440 Model) | 50.00 | Elemental analyzer (Elementar Analysensysteme Gmbh vario EL III CHNS-model) | - | | 50.84 | Elemental analyzer (Vario EL/micro cube, Germany) | - | | 51.10 | elemental analyzer (CE-440, EAI CO., USA) |
| H (%TS) | 7.32 | | 21.50 | | - | | 7.20 | | - | | 7.40 | |
| N (%TS) | 3.53 | | 2.80 | | - | | 1.80 | | - | | 3.40 | |
| S (%TS) | | | 0.29 | | - | | 0.24 | | - | | - | |
| O (%TS) | 34.88 | By difference of 100 minus C, H, N and S concentration | 25.41 | By difference of 100 minus C, H, N and S concentration | - | | 32.03 | By difference of 100 minus C, H, N and S concentration | | | 37.4 | |
| Cellulose | | | | | 5.15 | The difference | 4.70 | Automatic | | | 17.70 | APHA |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| (%TS) | | | | | | between ADF and lignin | | cellulose analyzer | | method |
| Hemicellulose (%TS) | | | | | 5.62 | The difference between NDF and ADF | 10.05 | (A200i, ANKOM, America) | 21.30 | |
| Lignin (%TS) | | | | | 0.66 | | 2.12 | | 9.00 | |
| C/N ratio | 14.20 | Calculation | 17.86 | Calculation | 15.30 | Calculation | 28.20 | Calculation | 17.50 | Calculation |

Note: TS is total solids, VS is volatile solids, ADF is acid detergent fiber, NDF is neutral detergent fiber

## 3 Trends and potential use food waste for bioenergy

Many studies have illustrated that food waste has great potential for generating various high value-added products such as fuels and chemicals. Their production involves biological, chemical, or thermochemical pathways (Elkhalifa et al., 2019; Karmee, 2016; Kiran and Liu, 2015). Various studies have also highlighted the potential use of food waste to produce bioenergy (i.e. biogas, bioethanol, solid fuel pellets, biochar, briquettes, bio-oils, etc.) both in Indonesia and globally, as explained in detail in the following section. Figure 3 maps out current sources of food waste, as well as current potential pathways and outcomes of food waste. Effective geo-spatial mapping of these pathways could support the planning of supply chains and logistics, as well as the optimal location of conversion plants in the future. The comparison of conversion technologies and the estimated energy recovery for each bioenergy route can be seen in Table 3.

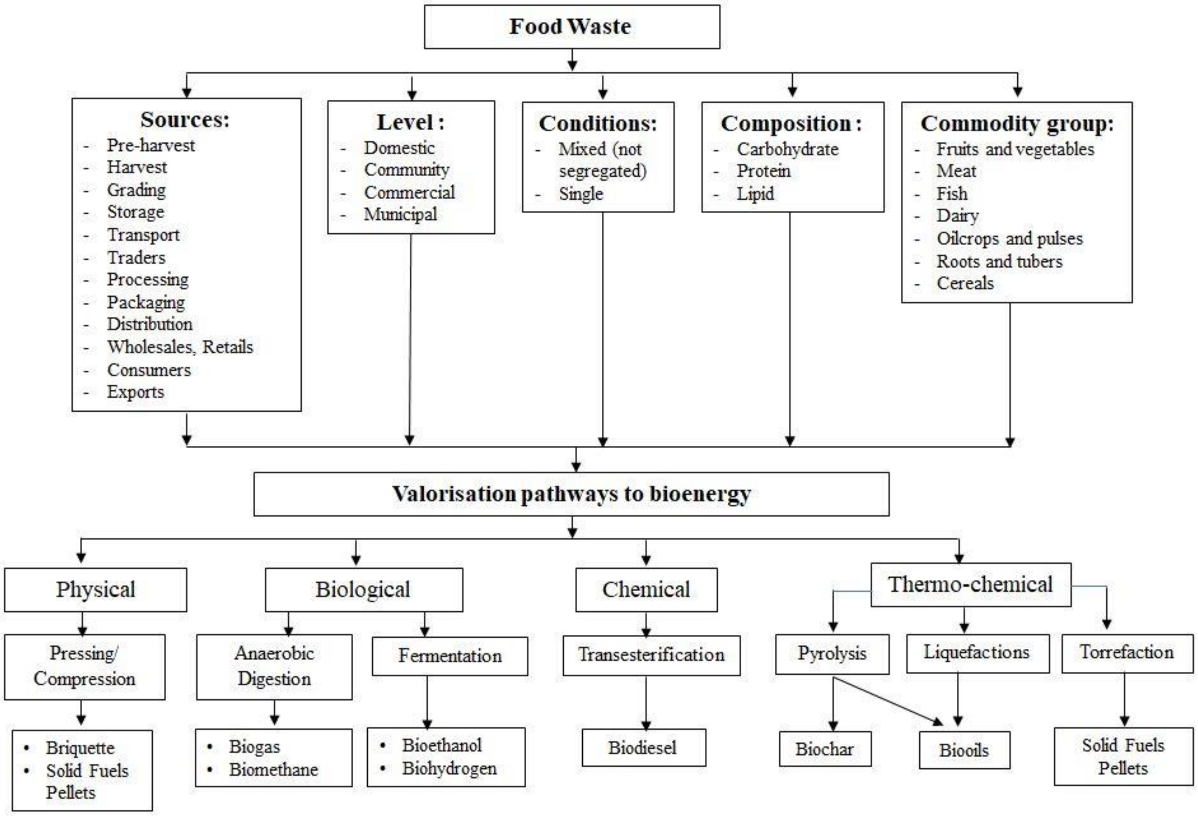

**Figure 3.** Food waste valorisation pathways for bioenergy production

Table 3. Comparison of conversion technology for bioenergy production from food waste

| Conversion technology | Technology Readiness Level (TRL)* | Estimated energy recovered per 1000 kg food waste** | Advantages | Disadvantages | Refs |
|---|---|---|---|---|---|
| Pressing or compression for briquette | 8 - 9 (Clare et al., 2015; Garcia-Nunez et al., 2016) | Calorific value of 10.3-16.6 GJ/kg food waste (Srivastava et al., 2014) | • cost-effective and low investment<br>• low energy consumption<br>• simple and easy operation and maintenance<br>• good adaptability for any biomass or waste<br>• resulted briquette or fuels pellets are easy to handle, transport and store<br>• can be applied with and without external binding agents | • need longer time for the drying process<br>• increased production cost<br>• invariability in size and length<br>• noise pollution (i.e. high noise production) | (Brunerová et al., 2017; Hu et al., 2014; Sawadogo et al., 2018; Srivastava et al., 2014) |
| Anaerobic digestion for biogas | 8-9 (Ardolino et al., 2020; Lytras et al., 2021; Neuling and Kaltschmitt, 2017) | 592 m$^3$ $CH_4$/kg VS (Tian et al., 2021) | • can handle high moisture content biomass such as food waste<br>• produce high biogas or methane yields<br>• reduces GHG emissions, thus mitigating climate change<br>• biogas or methane can be converted into heat and electricity<br>• produce biofertilizer<br>• generate small footprint<br>• well-established and commercial process<br>• can be operated without pre-treatment<br>• can be operated as a single- or do-digestion system | • emission, if any, contains sulphur-organic compounds<br>• high capital for operation and transportation<br>• the salt content in food waste may inhibit microorganism<br>• need longer time for processing (time-consuming)<br>• control of foaming is needed<br>• prune to operational challenges include VFA accumulation, low buffer capacity, and process instability | (Javkhlan Ariunbaatar et al., 2014; Elkhalifa et al., 2019; Karmee, 2016; Nayak and Bhushan, 2019; Xu et al., 2018) |
| Fermentation for bioethanol | 4 - 9 (Dey and Bhaskarwar, 2021; Neuling and Kaltschmitt, 2017; Rathnayake et al., 2018) | 295 m$^3$/kg food waste (Ebner et al., 2014) | • low cost<br>• lower GHG emission by 80%<br>• higher bioethanol yield if using simultaneous saccharification and fermentation (SSF)<br>• no capital and operational expenditures are required for enzyme production if using consolidated bioprocessing (CBP) | • the salt content in food waste may inhibit microorganism<br>• need longer time for processing (time-consuming)<br>• pre-treatment of food waste is required for releasing fermentable sugar<br>• high cost if using enzymatic pre-treatment<br>• end-product inhibition can minimize bioethanol yield | (Hafid et al., 2017b; Karmee, 2016; Kiran and Liu, 2015; Nathao et al., 2013; Nayak and Bhushan, 2019) |
| Fermentation for | 4-7 (Brown et al., | 295 m$^3$ $H_2$/kg VS (Han et | • high energy recovery if using dark | • the salt content in food waste may | (Kim et al., 2009; |

| | | | | | |
|---|---|---|---|---|---|
| biohydrogen | 2020; Garcia-Nunez et al., 2016; Neuling and Kaltschmitt, 2017) | al., 2016b) | fermentation for biohydrogen production<br>• environmentally friendly route if does not require external energy<br>• high carbohydrate content, total chemical oxygen demand (COD), and VS concentration of food waste lead to a faster $H_2$ production rate | inhibit microorganism<br>• need longer time for processing (time-consuming)<br>• the existence of indigenous non-$H_2$ producers (in particular, lactic acid bacteria/LAB) inside food waste may inhibit $H_2$ yield<br>• $H_2$ production from food waste still needs in-depth studies for economic efficiency | Kiran et al., 2014; Karmee, 2016; Yun et al., 2018) |
| Transesterification for biodiesel | 8-9 (Brown et al., 2020; Neuling and Kaltschmitt, 2017) | Transesterification alone:<br>BSFL composting with transesterification: 13.71 L (Guo et al., 2021). | • high production efficiency (up to 98%) of biodiesel<br>• use of US-assisted transesterification reduce energy consumption and reaction time<br>• enzyme-based transesterification is environmentally friendly<br>• catalyst-based transesterification is widely used and can recover unreacted feedstock<br>• by-product (i.e. glycerol) can be valorized into other high-value products<br>• high lipid content in food waste potentially to be converted and non-competitive with edible foodstuffs | • need lipid extraction process steps, and rather difficult to achieve complete lipid extraction<br>• pre-treatment of food waste is required<br>• high cost if using enzymatic pre-treatment<br>• conventional transesterification process requires high energy and time-consuming reaction process | (Bhatia et al., 2021; Carmona-Cabello et al., 2019; Karmee, 2016; Nayak and Bhushan, 2019; Shahzad et al., 2017) |
| Pyrolysis bio-char or bio-oils | 5-8 (Clare et al., 2015; Dupont and van Hullebusch, 2018) | Pyrolysis alone:<br>181 kg bio-oils and 97 kg biochar (Liang et al., 2015)<br>Integrated AD with pyrolysis: 130 kg bio-oils and 160 kg biochars (Opatokun et al., 2017) | • can be used for any biomass<br>• produces process gas (i.e. syngas) potential for energy production<br>• no other combustion products associated with burned waste<br>• requires less reaction time<br>• resulted biofuels has good physical and chemical characteristics | • high operational and production cost<br>• needs complex instrument<br>• high energy needs<br>• need drying process of food waste<br>• complex operational and maintenance<br>• recovery of condensate is required<br>• need efficient remediation for the syngas from food waste | (Bhatia et al., 2021; Elkhalifa et al., 2019; Grycová et al., 2016; Kim et al., 2020; Nayak and Bhushan, 2019) |
| Liquefactions for bio-oils | 3-8 (Brown et al., 2020; Perkins et al., 2019) | 329 kg bio-oils (W.H. Chen et al., 2019) | • requires less reaction time<br>• hydrothermal liquefaction (HTL) can be used for wet biomass (i.e. high moisture content) without the drying process<br>• HTL is well suited for food waste | • high operational and production cost<br>• high capital expenditure<br>• high energy needs<br>• conventional liquefaction requires drying pre-treatment | (Aierzhati et al., 2021; Chen et al., 2019a; 2020; Nayak and Bhushan, 2019) |

| | | | | | |
|---|---|---|---|---|---|
| | | | and saving energy<br>• resulted in high bio-oil yields | • upscaling HTL technology is still limited<br>• requires catalytic pre-treatment for higher yield | |
| Torrefaction for solid fuel pellet | 4-7 (Dupont and van Hullebusch, 2018; Garcia-Nunez et al., 2016) | 190 kg solid fuel pellet (Goyal et al., 2018) | • can generate biochar that comparable to coal<br>• can generate bio-oil that rich in chemical compounds<br>• wet torrefaction (WT) can be used for wet biomass (i.e. high moisture content) without the drying process<br>• WT can be used for any biomass<br>• dry torrefaction (DT) generates higher mass yield, energy yields, and energy efficiency<br>• WT generates biochar/solid fuel pellets with higher energy density, calorific value, and fixed carbon content<br>• better for handling, transportation, and storage of fuel<br>• protein content in food waste can act as a binder to increase strength<br>• the most efficient routes when using low temperature generate more fixed carbon lead to an increase in high heating value (HHV) | • high capital expenditure<br>• high operational and production cost<br>• needs complex instrument<br>• high energy needs<br>• need drying process of food waste<br>• need binding materials to enhance the process<br>• DT has poor pelletability<br>• WT requires post-treatment of wastewater<br>• WT has clogging issues from inorganic precipitates | (Chen et al., 2021; 2019a; He et al., 2018; Rago et al., 2018; Recari et al., 2017; Zhai et al., 2018) |

Notes: *Classification of TRL are based on Zabaniotou and Kamaterou (2019) , as follows: TRL1 is basic; TRL2 is applied research; TLR3 is critical function or proof of concept established; TRL4 is laboratory testing or prototype validation; TRL5 is prototype system verified; TRL6 is pilot-scale demonstration; TRL7 is system incorporated in commercial design; TRL8 is system complete and qualified; and TRL9 is system proven and full commercial deployment.

### *3.1 Biogas*

Biogas is a gas mixture of methane ($CH_4$), carbon dioxide ($CO_2$), and trace gases, generated from the decomposition of organic matter by methanogenic bacteria under anaerobic conditions (Pullen, 2015; Taricska et al., 2009). The process, also known as anaerobic digestion (AD), generates biogas (as an energy source) and organic residues/digestate (as a sustainable biofertilizer) (Ibrahim et al., 2015). Biogas contains 50–70% $CH_4$ and 30–50% $CO_2$ with a calorific value of 21–24 MJ/Nm$^3$ (Indrawan et al., 2018). According to Porpatham et al. (2008) and Chandra et al. (2011), the energy density of biogas depends on the concentration of methane ($CH_4$). The higher the methane content, the greater the energy content of biogas. Methane is a colorless, odorless, and flammable gas, which can be used as fuel for power plants, space heaters, water heaters, and cooking (Li et al., 2018). Biogas can also be converted into electrical energy by using a combined heat and process (CHP) unit, which greatly reduces carbon emissions to the atmosphere and contributes to protecting the environment (Patrizio et al., 2015; Hamzehkolaei and Amjady, 2018).

The composition and characteristics of food waste make it an ideal feedstock for AD (Lin et al., 2013; Meng et al., 2015b; Suhartini et al., 2019, 2020). AD is a more sustainable approach to processing food waste compared to other waste treatment methods (such as landfills which require a vast amount of energy and wide coverage of land area) (Leung and Wang, 2016). AD also mitigates methane emissions to the atmosphere (which occurs during open dumping and landfills) by processing the biomass within a closed reactor (Javkhlan Ariunbaatar et al., 2014). In addition, biomethane can replace fossil-derived fuels and thereby reduce $CO_2$ emissions (Xu et al., 2018).

Curry and Pillay (2012) reported that, in Canada, AD of food waste could potentially produce 367 m$^3$ of biogas per ton of Volatile Solid $(VS)_{added}$ (or approximately 239 m$^3$ of methane), with an energy content of 6.25 kWh/m$^3$ of biogas. The study found that AD of food waste may reduce the cost of waste disposal to landfills and carbon emissions. Tassakka et al. (2019) also reported that food waste has a methane potential of 0.127 m$^3$/kg VS at organic loading rate (OLR) of 10 kg VS/m$^3$/day with VS destruction (an indicator of organic degradation) of 92.2% after 134 days in a semi-continuous mesophilic AD system. Dung et al. (2014) evaluated the bioenergy potential of food waste from 15 developed and 6 developing countries using different methods. From a total food waste of 406.9 Mt/year, their study demonstrated a high biomethane production of 379,796 GWh/year using a single-stage AD process and 102,137 GWh/year using a 3-stage fermentation process.

Fisgativa et al. (2016) also studied the effect of food waste characteristics on biogas and methane production. The study indicated that physicochemical characteristics (such as VS, chemical oxygen demand/COD) and biochemical characteristics (such as carbohydrate, protein, and lipids) influence the AD process's efficacy and efficiency. Their study revealed that high carbohydrates and low pH levels might inhibit the stability of the AD process due to high acid production. Such conditions may inhibit methanogens, which results in low biogas or methane production. Meng et al. (2015a) reported that the AD of food waste yields high biogas and methane both in single- and co-digestion AD systems. However, when a co-digestion feedstock of 'floatable oil' was added at higher concentration (40-50 g/L), inhibition and instability of the AD process were observed, illustrated by a reduction in biogas production. Other studies have also highlighted the impact of food waste characteristics on overall methane potential, as shown in Table 4.

Table 4. Summary of previous studies on biogas of food waste

| Class of food waste | VS (%WW) | Scale | Operational system | Temp. (°C) | HRT (days) | Biogas Production ($m^3$/ kg VS) | Methane Yield ($m^3$ $CH_4$/ kg VS) | Refs. |
|---|---|---|---|---|---|---|---|---|
| Mixed fruit-vegetable wastes | - | Laboratory | - | 27-31 | 14 | - | 0.387 | (Sitorus et al., 2013) |
| Food waste from cafeteria | 27.54 | Laboratory | Batch, BMP test | 35-36 | 31 | - | 0.014 | (Wulansari and Kristanto, 2016) |
| Food waste from canteen | 24.83 | Laboratory | Batch , BMP test | 37 | 30 | - | 47.38 | (Suhartini et al., 2019) |
| Food waste: tofu dregs (TD) = 50 : 50 | 18.55 | | | | | - | 30.72 | |
| Food waste from canteen | - | Pilot (0.5 $m^3$) | Semi-continuous | 25-45 | 134 | 0.179 | 0.127 | (Tassakka et al., 2019) |
| • Pineapple waste | 15.34 | Laboratory | Batch, BMP test | 37 | 30 | 0.817 | 0.402 | (Suhartini et al., 2020) |
| • Vegetable waste | 7.11 | | | | | 0.800 | 0.420 | |
| • Orange peels | 18.83 | | | | | 0.771 | 0.366 | |
| • Apple peels | 21.29 | | | | | 0.702 | 0.407 | |
| • Jackfruit straw | 14.06 | | | | | 0.677 | 0.324 | |

Note: HRT is hydraulic retention time, BMP is biochemical methane potential

In Bandung City, Indonesia, in 2010, household food waste was investigated for its biogas potential (as an alternative for LPG for cooking fuel). The results showed that the conversion of food waste into biogas was not economically favorable. This was mainly due to the low separation of bio-slurry for biofertilizer (which resulted in high operational cost) and the low quality of the fuel produced. The success of these projects may rely on creating market incentives for the resulting biofertilizer, enhanced biogas utilization within communities, and increased community acceptance of the technology itself (Amir et al., 2016). Other studies have reported that fruit and vegetable waste (FVW) offers good potential for biogas production (Suhartini et al., 2019; 2020). Wulansari and Kristanto (2016) found that food waste from the University cafeterias has a methane potential of 0.140 $m^3$/kg VS under batch operation. However, when trialed under semi-continuous conditions, volatile fatty acid (VFA) inhibition was observed after 55 days of operation, causing a huge loss of methane production. Whereas Sitorus et al. (2013) reported that food waste, mainly composed of mixed FVW, has a methane yield of 0.387 $m^3$/kg $VS_{added}$ (with a methane content of 65%). The study showed that AD offered a good potential to convert food waste to bioenergy with the estimated energy value of 20-25 MJ/$m^3$.

The aforementioned findings clearly show that food waste can be converted into biogas. Co-digestion of food waste with other biomass feedstock may also provide an attractive approach to enhance biogas and methane production, particularly where organic waste is available and underutilized (e.g. sewage, animal manure, etc.) (Chiu and Lo, 2016; Oladejo et al., 2020; Sandriaty et al., 2018). Zhang et al. (2014) advised on several pre-treatment options (i.e. physical, thermo-chemical, biological, or combined pre-treatments) and co-digestion of food waste with other biomass substrates to enhance the AD performance, hence improving the production of biogas or methane.

### *3.2 Bioethanol*

Bioethanol or ethanol is short for ethyl alcohol ($C_2H_5OH$) and is often referred to as grain alcohol, a colorless liquid with a distinctive odor (Taherzadeh et al., 2013). According to Demirbaş (2005), bioethanol can be produced from a sugar fermentation process using the help of microorganisms. In industry, bioethanol is used as a raw material for industrial alcohol derivatives, a mixture for alcohol, a base material for the pharmaceutical industry, and a mixture for fuels. The bioethanol production process is clearly described by Taherzadeh et al. (2013) and Karmee (2016); with the mechanism explained by Dasgupta et al. (2017). In general, the steps of bioethanol production from food waste include pre-treatment, hydrolysis, fermentation, and distillation. The hydrolysis step can be carried out using a chemical or enzymatic precursor to enhance the sugar available for fermentation steps. The fermentation process can be performed using yeast, bacteria, or fungi under aerobic or anaerobic conditions, and a separate or simultaneous hydrolysis process (Suhartini et al., 2022).

Bioethanol is a promising source of energy that is sustainable and environmentally friendly (Domínguez et al., 2017). Globally, bioethanol dominates the renewable energy supply in the transportation sector (Khatiwada and Silveira, 2017). The use of bioethanol can significantly reduce GHG emissions by up to 86% compared to fossil fuels (Wang et al., 2015). It is considered a clean energy source because its combustion does not increase the amount of $CO_2$ in the atmosphere and can be produced from organic waste or biomass (Zhang et al., 2018). Utilizing waste as a feedstock offers a sustainable approach to bioethanol production due to its availability, low price, and relatively high sugar content (Zhang et al., 2017b). However, various factors may affect the efficacy of bioethanol production from waste, including particle size of the feedstock and the type of microorganisms used in the process (i.e. free or immobilized microorganisms) (Germec et al., 2019); fermentation technology (i.e. biofilm reactor) and methods (i.e. repeated-batch fermentation, separated hydrolysis fermentation/SHF, simultaneous saccharification and fermentation/SSF) (Germec et al., 2015; Saini et al., 2015); operational conditions of fermentation (i.e. pH, time, temperature) (Adaganti et al., 2014; Saini et al., 2015); culture media composition, pre-treatment, and enzyme addition (Saini et al., 2015). The presence of inhibitory or rate-limiting compounds (i.e. furans) can reduce the efficacy of the process, therefore detoxification through the addition of activated carbon can be employed (Germec et al., 2015).

Many studies have emphasized that food waste, in particular, can be used as feedstock for bioethanol due to its rich organic materials (Hafid et al., 2017a, 2017b; Kiran and Liu, 2015). Karmee (2016), however, stated that direct conversion of food waste into bioethanol was challenging due to the complex carbohydrate structure of food waste. Therefore, pre-treatment is often necessary to ensure optimal bioethanol yields. Kiran and Liu (2015) studied fungal pre-treatment to effectively enhance bioethanol production from food waste. Ma et al. (2017) reported that fungal pre-treatment enhances the fermentation of food waste into bioethanol. Hafid et al. (2017a) also found that acid pre-treatment of food waste resulted in a significant increase in fermentable sugar production during the hydrolysis process, thus leading to a higher bioethanol yield. A summary of previous studies focused on food waste valorization into bioethanol is shown in Table 5.

Table 5. Summary of previous studies on bioethanol of food waste

| Class of food waste | Pretreatment/ Hydrolysis | Fermentation | | | | | Ethanol Conc. (g/L) | Ethanol yield (g/g) | Refs. |
|---|---|---|---|---|---|---|---|---|---|
| | | Method | Microorganism | Duration (h) | Temp. (ºC) | Vessel type | | | |
| Mixed food waste from cafeteria | Fungal mash from waste cakes | SHF | Commercial dry baker's yeast *S. cerevisiae* | 32 | 30 | Bioreactor 1 L | 58 | 0.50 | (Kiran and Liu, 2015) |
| Food waste from canteen | Fungal mash from food waste with 10% (v/g) of *Aspergillus oryzae* as inoculum | SHF | *Zymomonas mobilis* | 15 | 30 | 5 L reactor with 3 L working volume | 71.8 | 0.51 | (Ma et al., 2017) |
| Food waste from food courts | Sequential acid-enzymatic pretreatment | SHF | *S. cerevisiae* | 24 | 30 | 250 mL flask | 10.92 | 0.42 | (Hafid et al., 2017a) |

### *3.3 Biodiesel*

Biodiesel is an alternative liquid fuel with lower emission levels than diesel. The nature of feedstock used to produce biodiesel will impact its chemical structure and emission characteristics. Consumption of biodiesel has been increasing in recent years, and the feedstock for biodiesel production has been diversified. Biodiesel can be produced from animal fats, algal oil, and vegetable oil (such as soybean oil, palm oil, rapeseed oil (canola), jatropha oil, and yellow grease) (Kim et al., 2018). Types of feedstock are also considered to influence the cost-effectiveness of biodiesel production (Gülşen et al., 2014). Food waste with high lipid content offers good potential as a feedstock for biodiesel production. Waste is considered more sustainable than purpose-grown biofuel crops as it does not compete for natural resources such as land, water, and soil (Karmee, 2016). However, lipid extraction from food waste remains a technical challenge in biodiesel production (Barik et al., 2018).

The transesterification process, which generates biodiesel (using biological or chemical techniques), forms mono alkyl esters by converting fats and oils into alcohol and esters (Kumar et al., 2020). A catalyst or solubilizer is added to initiate the esterification and transesterification process (Pruszko, 2020); in which a high volume of alcohol is needed to boost the reaction rate and enrich the oil conversion (Wongjaikham et al., 2021). Various feedstocks have been evaluated for biodiesel production, but food waste is regarded as highly suitable due to the balanced ratio between linolenic and palmitic acids (Carmona-Cabello et al., 2021, 2019). According to Carmona-Cabello et al. (2021), biodiesel production can be carried out by extracting fats/oils from food waste, following the fermentation to generate hydrolytic enzymes to later transform the oil into biodiesel. Prior to the hydrolysis steps, however, the oil content in food waste should be separated (Almutairi et al., 2021). pH control within the process is important to optimize lipid production (Gao et al., 2019).

Another potential route for biodiesel production is integrating the composting process and BSF to degrade food waste and produce larvae. BSF larvae (BSFL) have emerged as a potential feedstock candidate for biodiesel production. BSFL offers many advantages, including cost-efficiency, high-quality biodiesel (depending on the treatment of BSFL), fast growth rate, and sustainability (dried larvae can also be further used as animal feed and larvae manure as biofertilizer) (Feng et al., 2020). Interest in this concept is increasing due to the abundant nutrient compounds found in food waste. It is reported that the lipid extraction from BSFL with non-catalytic transesterification method showed the highest yield of biodiesel (94.1 %) when compared to the conventional method (i.e. base-catalyzed transesterification) (Jung et al., 2022). The integration of AD technology with BSFL composting has been highlighted by Elsayed et al. (2020). The study revealed that the digestate from the AD of rapeseed straw and chicken manure could be used for BSFL rearing, where larvae were further valorized into biomethane and biodiesel. The study also emphasized that the type of feedstock affected Fatty Acid Methyl Esters (FAMEs) recovery and composition, hence influencing the quality and quantity of the resulting biodiesel. Leong et al. (2016) also explored other potential organic wastes (i.e. fruit waste, palm decanter, and sewage sludge) as feedstock in composting for BSFL production. This study reported that fruit waste resulted in the highest yield of FAMEs compared to other waste feedstock. Sewage sludge feedstock showed a negative growth rate of BSFL, possibly due to the presence of extracellular polymeric substances (EPS) which hindered the degradation process. Isibika et al. (2021) observed that composting of fish waste alone gave a negative growth of BSFL. However, when fish waste was co-composted with fruit wastes (i.e. banana and orange peel) with a ratio of 25:75%, this significantly enhanced the growth of BSFL and the biomass conversion efficiency. The studies above highlight that the type of feedstock clearly influences the growth and quality of life of BSFL (i.e. maturity, size, and survival rate), which may, in turn, affect the quality of the resulting biodiesel. A summary of food waste utilization for biodiesel is shown in Table 6.

Table 6. Summary of previous studies on biodiesel of food waste

| Class of food waste | Transesterification reaction | | | | FAME Conversion (%) | Density at 15 ºC (kg/m$^3$) | Kinematic Viscosity (mm$^2$/s) | CV (MJ/kg) | Refs. |
|---|---|---|---|---|---|---|---|---|---|
| | Catalyst | Ratio of Solvent | Time (h) | Temp. (ºC) | | | | | |
| Food waste from hostel | 2.5 % ww ($H_2SO_4$) | 1:11 M = Lipid:Methanol | 2-2.5 | 65 | 32.3 | 872 | 2.2 | 31.38 | (Barik et al., 2018) |
| Kitchen food waste | 0.5 % ww ($H_2SO_4$) | 1:6:30 = Lipid:co-solvent (MTBE):solvent (Methanol) | 0.067 | 170 | 96.87 | 875-882 | 4.41 | 39.2-41.5 | (Priyadarshi and Paul, 2018) |
| Bakery waste | 5 % ww (KOH) | 1:10 M = Lipid:Methanol | 2 | 60 | 100 | - | - | - | (Karmee et al., 2015) |
| | 10 % ww Lipase Novozyme-435 | 1:5 M = Lipid:Methanol | 24 | 40 | 90 | - | - | - | |
| Instant noodle | 15 %(w/v) Lipase Novozyme-435 | 1:9 M = Lipid:Methanol | 36 | 40 | 95.4 | - | - | - | (Yang et al., 2014) |

Note: CV is calorific value, FAME is fatty acid methyl ester

### *3.4 Biohydrogen*

Hydrogen ($H_2$) is conventionally produced through thermochemical processes. The combustion of $H_2$ for energy is environmentally friendly because of its lower carbon emissions e.g. GHGs, such as $CO_2$ and $CH_4$ (Wong et al., 2014). Hydrogen also has a higher heating value (141.9 MJ/kg) compared to other fuel types such as methane (55.5 MJ/kg), gasoline (47.5 MJ/kg), and diesel (44.8 MJ/kg) (Nikolaidis and Poullikkas, 2017). According to Chandrasekhar et al. (2015), hydrogen can be obtained from fossil fuels (using hydrocarbon reforming and pyrolysis methods) and renewable sources (using biomass process and water splitting methods). Hydrogen produced by biological processes and biomass sources is called biohydrogen. Balat and Kırtay (2010) reviewed that biohydrogen can be produced from biomass to replace conventional fuels, i.e. natural gas, heavy oils, naphtha, and coal.

Several methods can be applied to generate biohydrogen, including electrodialysis, which can remove the VFAs in food waste composition (Hassan et al., 2019); fermentation via granular microbial preparation suitable for liquid food waste (Hovorukha et al., 2021); non-catalytic and catalytic steam and gasification which involve complex chemical mechanisms (Valizadeh et al., 2021). Other potential methods for biohydrogen production include photo fermentation (PF) (Azwar et al., 2014; Budiman and Wu, 2018); dark fermentation (DF) (Budiman and Wu, 2018; Rodríguez-Reyes et al., 2021); photo-dark fermentation, biophotolysis of green microalgae and cyanobacteria, or electrochemical and bio-electrochemical processes (Budiman and Wu, 2018). Among these conversion technologies, Balat and Kırtay (2010) reported that biomass gasification offers the easiest and most economical route for producing renewable hydrogen. However, alternative studies have emphasized that PF and/or DF is considered the most widely adopted approach due to its relatively low-cost and energy-saving technology (Budiman and Wu, 2018; Cappai et al., 2018; Rodríguez-Reyes et al., 2021). PF is a fermentative process involves photosynthetic microorganisms and directly converts organic materials to hydrogen (Kucharska et al., 2021). While DF is a process operated in the absence of -light and under anaerobic conditions involving anaerobic microorganisms which convert organic material into hydrogen and $CO_2$. Various factors can affect the DF performance, including the type of feedstock used, pre-treatment approach, presence of inhibitory compounds, and the fermentation medium utilized (Dareioti et al., 2021). Yun et al. (2018) found that DF is considered the most practical approach for the conversion of food waste into biohydrogen because it can make the hydrolysis of carbohydrates more effective (Jung et al., 2021; Usman et al., 2020). DF can also be coupled with an AD technology to further valorize the residue from DF to produce biomethane (Sittijunda et al., 2021). Other studies by Pu et al. (2019) and Jang et al. (2015) have also highlighted that biohydrogen can be produced through the acidogenesis step during the AD process, which involves microorganisms converting organic substances into $CH_4$ (as a primary product) and hydrogen (as a by-product). The summary of food waste utilization for biohydrogen is shown in Table 7.

Table 7. Summary of previous studies on biohydrogen of food waste

| Class of food waste | Operating Condition | | | | | $H_2$ production (L/kgVS) | Refs. |
|---|---|---|---|---|---|---|---|
| | Reactor operation mode | Vol. of reactor (mL) | pH | Temp. (ºC) | Inoculum | | |
| Food waste from domestic kitchen | Batch | 800 | 5.5 | 55 | Sludge solution | 114.1 | (Deheri and Acharya, 2020) |
| Heat-treated of food waste from student canteen | UASB | 80 | 6.5 | 37 | Anaerobic sludge | 75.3 | (Pu et al., 2019) |
| Alkaline-treated food waste from cafeteria | Batch | 300 | 6.0 | 37 | None | 156 | (Jang et al., 2015) |
| Food waste | Batch with pre-treatment (heat/H, acid/A, base/B, ultrasonic/U and combination (UH, UB, UA)) | 200 | 5.5 | 37 | Anaerobic sludge | 97 (U)<br>75 (H)<br>55 (A)<br>46 (B)<br>118 (UA)<br>78 (UH)<br>67 (UB) | (Elbeshbishy et al., 2011a) |
| Synthetic food waste | • CSTR<br>• CSTR with sonicated feed<br>• SBHR | 2000 | - | 37 | Anaerobic sludge | • 157<br>• 193<br>• 258 | (Elbeshbishy et al., 2011b) |
| Food waste | Batch | 100 | 7 | 37 | 9 bacteria | 14.4 - 39.6 | (Xiao et al., 2013) |
| Complex food waste from university cafeteria | Batch (sonicated /S and unsonicated/US feed) | 125 | 5.5 | 37 | Seed sludge | 85 (US feed)<br>149 (S feed) | (Gadhe et al., 2014) |

Note: CSTR is continuous stirrer tank reactor, SBHR is sonicated biological hydrogen reactor , S is sonicated pre-treatment, US is unsonicated pre-treatment, UASB is up-flow anaerobic sludge blanket, UH is ultrasonic-heat pre-treatment, UB is ultrasonic-base pre-treatment, UA is ultrasonic-acid pre-treatment

### ***3.5 Biochars***

Fu et al. (2019) stated two thermochemical pathways of converting food waste into biochar and hydrochar, including pyrolysis and hydrothermal carbonization. Pyrolysis is the thermochemical decomposition of biomass at a high temperature (commonly ≤ 600 °C) with limited or no oxygen available, resulting in a solid carbonaceous product known as biochar (Aller, 2016). Hydrothermal carbonization is a promising thermochemical process carried out in the presence of water (as the reaction medium) at temperatures of 180–300 °C. This process, conducted under autogenous pressure, results in a solid carbonaceous product called hydrochar (Kambo and Dutta, 2015). This study reported that despite the operation requiring water as a medium, hydrothermal carbonization is effective for treating feedstock with higher water content. Akarsu et al. (2019) found that hydrochar from food waste and digestate (resulting from hydrogen fermentation) has a higher combustion reactivity than lignite, which indicates its potential for further applications. Wang et al. (2018c) also reported that hydrochar from food waste produces a clean solid biofuel.

Elkhalifa et al. (2019) reported that biochar production from food waste can use slow and fast pyrolysis. The study reported that the nature of the feedstock (i.e. the composition of food waste), reactor configuration, and process condition influence the quality of the resulting biochar. Many considerations need to be considered when converting food waste into biochar, in particular the technical challenges such as optimizing pyrolysis process design and operational conditions. The study also suggested that slow pyrolysis produces better quality biochar than fast pyrolysis. Fu et al. (2019) compared the production of food waste biochar using pyrolysis and hydrothermal carbonation pathways, resulting in the biochar and hydrochar having comparable qualities to the commercially available biochars. Ul Saqib et al. (2019) reported that the co-hydrothermal carbonation process effectively converts food waste into biochar or hydrochar. Furthermore, the chars exhibited thermally stable fuel properties compared to those from conventional hydrothermal processing.

Randolph et al. (2017) also indicated the potential uses of MSW for the production of value-added biochars. The operational condition of the conversion technology (i.e. pyrolysis) and the substrate characteristics were found to impact the properties of biochar (i.e. pH, surface area, bulk density, and electrical conductivity). Kaushik et al. (2014) demonstrated that biological pre-treatment with an enzymatic approach enhances the quality of biochar in terms of an increase in calorific value.

Hassen-Trabelsi et al. (2014) studied biochar produced from waste animal fats. This study found that these biochars had poor quality (i.e. low carbon content and high ash content) and was therefore not considered suitable as a renewable energy resource. Alternative uses of biochar from food waste have also been reported in the literature. For example, it can be utilized as a multi-element supplement for soil conditioning (i.e. water retention, aggregate stability, and micronutrient contents) and plant growth (Zhang et al., 2017c; Randolph et al., 2017); for wastewater treatment (Chu et al., 2020; Xue et al., 2019); a green ingredient for cement mortar (Gupta et al., 2018); or soil-carbon sequestration (Randolph et al., 2017). These findings confirm that transforming food waste into biochar offers multiple benefits. The summary of food waste utilization for biochars is shown in Table 8.

Table 8. Summary of previous studies on biochar of food waste

| Class of food waste | Type of reactor | Process Condition | | HHV (MJ/kg) | Surface area ($m^2/g$) | Refs. |
|---|---|---|---|---|---|---|
| | | Temp. (ºC) | Time (h) | | | |
| Multi-ethnic food courts waste | 500 mL Parr stirred pressure batch reactor | 350 | 0.33 | 26.9 | - | (Kaushik et al., 2014) |
| Woodchips | Lindberg furnace | 700 | 2 | - | 298.2 | (Randolph et al., 2017) |
| Mixed food waste | Tubular reactor under $N_2$ atmosphere | 500 | 4 | - | 17.77 | (Fu et al., 2019) |
| Cooked rice | 2L stainless steel pressure reactor | 300 | 2 | - | 53.67 | |
| Food waste : coal (1:1) | 1L batch high-temperature high pressure vessel | 300 | 1 | 28.6 | - | (Ul Saqib et al., 2019) |

### *3.6 Solid fuel - pellets and briquettes*

Wang et al. (2018a) investigated the potential of food waste as a feedstock for the production of solid fuel pellets using hydrothermal carbonation technology. This study showed that increasing wood sawdust concentration into food waste was correlated with an increased tensile strength of solid fuels pellets. The study revealed a high food waste ratio during hydrothermal carbonation generated pellets with higher combustion behaviors. Zhai et al. (2018) also reported similar trends whereby fuel pellets made from hydrochar bound with molasses exhibited improved combustion behavior compared to those bound with molasses and lime.

Sharma and Dubey (2020) compared the quality of pellets made from hydrochar derived from yard waste and food waste. The study showed that a combination of both wastes was optimal for solid fuel pellets production, without the addition of external binding material. The study also found that as the soft lignin of yard waste can act as a natural binder. Food waste pellets had lower durability compared to yard waste pellets. Therefore, a combination of hydrochar of food waste and yard waste may potentially enhance the overall quality of the pellets. Wang et al. (2018b) studied four different MSW (i.e. dog manure, horse manure, apple pomace, and tea waste) as substrates for solid fuel pellets. Synthetic binding material was added to increase the pellet's durability and tensile strength. The results indicate that tea waste pellets have better combustion behaviors confirming their potential as an energy resource and substituting fossil fuels. Apple pomace pellet exhibited poor combustion performance indicating that the waste was unsuitable as feedstock. Wang et al. (2019) examined the impact of adding molasses binder to food waste on the quality of the hydrochar pellets. The results showed a significant improvement in mass density, tensile strength, and combustion properties of the hydrochar (i.e. solid fuel pellets). A summary of the recent studies on food waste as a feedstock for solid fuel pellets can be seen in Table 9.

Table 9. Summary of previous studies on solid fuel pellets of food waste

| Class of food waste | Binding agent | Pelletization condition | | Tensile strength (MPa) | Mass density (kg/m$^3$) | Calorific Value (MJ/kg) | Refs. |
|---|---|---|---|---|---|---|---|
| | | Pressure (MPa) | Time (s) | | | | |
| Food waste from restaurant | Molasses | 10 | 30 | - | 936.8 | 32.36 | (Zhai et al., 2018) |
| Food waste from restaurant | Wood sawdust | - | - | 1.33 | 2,985 | 31.49 | (Wang et al., 2018a) |
| Apple pomace<br>Tea pomace | NovoGro | - | - | - | 1,240<br>1,010 | 16.02<br>19.52 | (Wang et al., 2018b) |
| Food waste from university | Molasses | 8 | 30 | 6.44 | 1,287.2 | 25.95 | (Wang et al., 2019) |
| Food waste from hostel mess | Yard waste | 250 | 30 | 2.64 | 1,678 | 27.64 | (Sharma and Dubey, 2020) |

Briquetting technology involves various processes of binding and densification of material, aiming to improve its handling characteristics and enhance calorific value. Srivastava et al. (2014) reported that briquetting of food waste, specifically vegetable waste is a cost-effective approach. This study found that food waste briquettes can be made without external binders. Suhartini et al. (2011) also demonstrated a good example of organic waste valorization into briquettes using a simple and low-cost technology of natural binding and compression (or densification). Briquettes from food waste can be used as a fuel in domestic cooking (Srivastava et al., 2014); boilers and gasifiers (Pareek et al., 2011). Espinoza-Tellez et al. (2020) reported that food waste as a briquetting substrate offers non-toxic and non-polluting recycled materials as well as an appealing alternative for non-renewable energy substitution. Afsal et al. (2020) studied the combination of vegetable waste and sawdust into briquettes with the ratio of 25, 50, 75, and 100% by weight using bentonite clay as a binding agent. The results showed that composite briquettes had higher calorific value and VS content compared to vegetable-waste-only briquettes. The highest heating value/HHV (15.721 MJ/kg) was obtained from briquettes made of 25:75 (vegetable waste: sawdust) ratio. The study also revealed that despite lower lignin content in vegetable waste, the composite briquettes had better quality compared to other lignocellulosic-based briquettes. The summary of food waste utilization for briquettes is shown in Table 10.

Table 10. Summary of previous studies on briquettes of food waste

| Class of food waste | Binding agent | Bulk density (kg/m$^3$) | Fixed carbon (%) | Calorific value (MJ/kg) | Refs. |
|---|---|---|---|---|---|
| Cauliflower/ cabbage leaves | None | 509 | - | 12.39 | (Srivastava et al., 2014) |
| Coriander stalk & leaves | None | 747 | - | 13.70 | |
| Field beans | None | 685 | - | 16.60 | |
| Green pea pods | None | 557 | - | 10.26 | |
| Durian peels | Starch and calcium hydroxide (Polyscientific) | - | 9.44 | 18.60 | (Mitan et al., 2018) |
| Banana peels | None | - | ~10 | 47.13 | |
| Jackfruit peels | Tapioca flour | - | 58.12 - 61.42 | 20.10 – 22.60 | (Pratiwi et al., 2019) |
| Vegetable market wastes | Bentonite clay | - | 21.66 | 14.00 | (Afsal et al., 2020) |

### *3.7 Bio-oil*

Bio-oil is a liquid fuel that can substitute gasoline and can be produced using various technologies such as pyrolysis, gasification, and hydrothermal processes (Karmee, 2016). Hassen-Trabelsi et al. (2014) found that bio-oil from the pyrolysis of food waste (specifically from waste animal fats) had advantageous properties, making it suitable for engines or use as synthetic fuels. Chen et al. (2019a) investigated hydrothermal liquefaction (HTL) of food waste for bio-oil generation. In this study, food waste was pre-treated with $K_2CO_3$ at 100 ºC for 1 hr then at 300 ºC for 1 hr. Using this method, bio-oil has a HHV of 34.79 MJ/kg, about 53% higher than the initial food waste of 22.74 MJ/kg. This study shows that bio-oil from food waste offers better potential as a substitute for traditional fuels due to its rapid ignition and burning capacity. The study suggests that bio-oil is mainly derived from the conversion of carbohydrates and proteins in food waste.

Sakuragi et al. (2016) investigated the utilization of industrial food waste (i.e. spent coffee grounds (SCG), soybean, and rapeseed cake) for bio-oil extraction for further valorization into biodiesel. The study revealed that SCG has the highest bio-oil yield (16.8%), while other food wastes exhibited lower yields with values of 0.97% (soybean) and 2.6% (rapeseed cakes). The findings of this study highlighted that SCG has potential as a substrate for biofuel production. Kostyukevich et al. (2018) studied the characteristics of bio-oil from three different sources of food waste, including meat, cheese, and fruit. The results suggested that cheese generates the highest bio-oil yield with a value of ~75%, followed by meat (~60%), and fruit (~10%), respectively. However, the molecular compositions of the bio-oil were similar to bio-oil produced from algae with regards to their functional bonds of N, $N_2$, $ON_2$, etc. This finding indicated that food waste offers good potential for bio-oil production; however, the quality is influenced by the nature/composition of food waste. Mahmood et al. (2016) compared the hydrothermal oxidation (HOT) process of food waste to bio-oil and hydrochar fuels, with and without enzymatic pre-treatment. The study revealed that an increase in temperature had positive effects on increasing bio-oil yields and hydrochar quality. However, when combined with enzymatic pre-treatment the bio-oil yields were significantly reduced. This result indicates that the HOT process without enzymatic pre-treatment offers a superior yield and quality of bio-oil from food waste. Kadlimatti et al. (2019) also reported effective bio-oil production from microwave-assisted (MA) pyrolysis of food waste. The results demonstrated that bio-oil yield from MA pyrolysis was 30.24 % wet weight (ww) under optimum conditions. The summary of food waste utilization for bio-oils and hydrochar is shown in Table 11.

The aforementioned studies have highlighted that the conversion of food waste into bio-oil and hydrochar are effective. Längauer et al. (2018) indicated that food waste-derived bio-oil is eco-friendly and offer sustainable bioenergy resources, and liquefaction routes offer better conversion efficiency. However, Karmee (2016) emphasized that, despite efforts to scale up bio-oil production using pyrolysis technologies, bio-oil is still not commercially available in fuel stations, whereas biodiesel and bioethanol are widely available.

Table 11. Summary of previous studies on bio-oils of food waste

| Class of food waste | Type of reactor | HTL condition | | Yield (%) | Refs. |
|---|---|---|---|---|---|
| | | Temp. (ºC) | Time (min) | | |
| Food waste from recycle field | 1 L semi-pilot batch reactor (316 Stainless Steel) | 320 | 30 | 32.90 | (Chen et al., 2019b) |
| Lamb, poultry and swine fatty wastes | Fixed bed stainless steel reactor with 30 cm height and 15 cm internal diameter. | 500 | 20 | 58 – 77.9 | (Hassen-Trabelsi et al., 2014) |
| Mixed food waste from hotel | Quartz flask in microwave system which is facilitated with magnetron | 400 | 30 | 30.24 | (Kadlimatti et al., 2019) |
| Cheese, meat and fruits | 0.5 L reactor which is heated from the outside | 300 | 150 | 75.8, 60.5 and 9.9 | (Kostyukevich et al., 2018) |

## 4. Pre-treatments of food waste

Pre-treatment is often employed to break down the organic material in the food waste, thus making the conversion to bioenergy more effective and efficient. Various pre-treatment routes are available, including physical/mechanical, biological, chemical, thermal, or a combination of these (Figure 4).

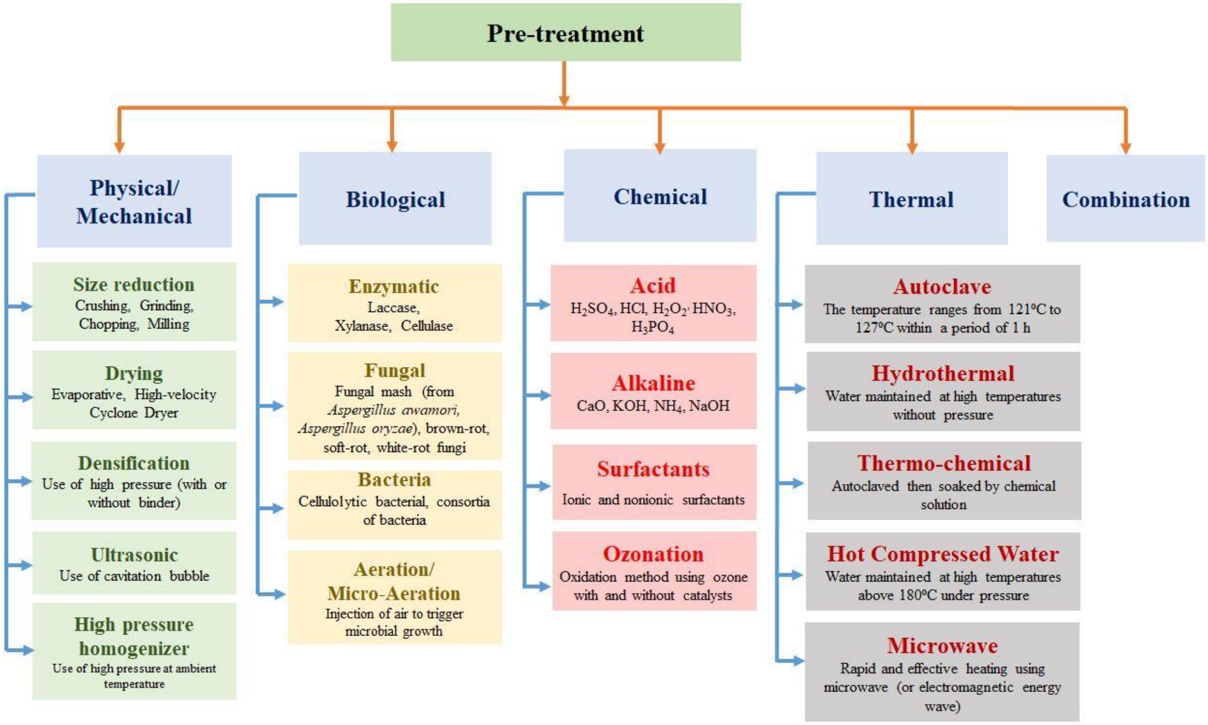

**Figure 4.** Pathways of pre-treatment for food waste to bioenergy

### *4.1. Physical/Mechanical pre-treatment*

Physical or mechanical pre-treatment techniques can be classified into size reduction processes (i.e. crushing, grinding, etc.), drying (i.e. evaporative, high-velocity cyclone dryer, etc.), and densification (Angulo-Mosquera et al., 2021; Arshadi et al., 2016). The physical pre-treatment is often associated with reducing the particle size to increase the surface area or enhance the solubilization (Kondusamy and Kalamdhad, 2014). The surface area could be increased by milling/chopping/grinding to make it more accessible for hydrolytic enzyme adsorption in subsequent steps. However, excessively small particle sizes can overstimulate hydrolysis and acid production, leading to the accumulation of ammonia and VFA, which may potentially be the next step inhibitory (Agyeman and Tao, 2014). Therefore, the particle size must be adjusted according to the target product. Karthikeyan et al. (2018) reported that food waste particles of < 2 mm favor high $CH_4$ recovery in the AD process. Furthermore, the efficacy of physical pre-treatment is reported for co-digestion of food waste and cattle manure in biogas production (Agyeman and Tao, 2014). Other studies by Izumi et al.(2010) and Okoro-Shekwaga et al. (2020) suggest that reducing the particle size of food waste prior to AD has improved organic matter solubilization and methane yield.

Drying has also been studied as a pre-treatment method for the valorization of food waste. The hygienic dehydration of food waste resulted in its significant mass reduction of about 70 % w/w. Dried food waste is easier to handle than wet food waste because its low moisture content prevents biological decomposition and limits odor emissions (Sotiropoulos et al., 2015). Drying could be applied to facilitate storage and protect the readily fermentable sugars for bioethanol production because low water content will inhibit the activity of microorganisms (Prasoulas et al., 2020). Karouach et al. (2020) showed that combined mechanical-ultrasonic pre-treatment (CMUP) of food waste prior to AD significantly improved methane production from 0.382 to 0.493 $m^3$ $CH_4$/kg VS. It was postulated that this improvement was due to homogenization of food waste and monolithic cavitation that creates millions of microbubbles. These microbubbles have a mechanical effect on the organic material leading to molecular disintegration and promoting chemical degradation through the formation of free radicals. Gadhe et al.(2014) and Elbeshbishy et al. (2011b) reported that ultrasonic pre-treatment of food waste prior to DF enhances biohydrogen production. Ma et al. (2011) found that high-pressure homogenization pre-treatment of food waste resulted in a significant increase in methane production. Densification pre-treatment of food waste using high pressure (with or without a binder) is necessary for the production of solid fuel pellets, briquettes, or prior to thermal conversion routes (i.e. pyrolysis, gasification, etc.) (Arshadi et al., 2016).

Many positive benefits are offered from physical/mechanical pre-treatments to improve biomass characteristics. However, several studies have shown that these processes require high energy input and may generate recalcitrant compounds, which may hinder subsequent conversion processes (Akbay et al., 2021; Elbeshbishy et al., 2011a; Kannah et al., 2020).

### *4.2. Biological pre-treatment*

Biological pre-treatment of food waste utilizes biological agents (i.e. fungal, bacteria) or enzymes to break down food waste prior to conversion. Kiran and Liu (2015) and Kiran et al. (2015) studied the impact of fungal pre-treatment (i.e. using fungal mash produced by *Aspergillus awamori*) on the efficacy of food waste conversion to bioethanol. The study revealed that fungal pre-treatment improved glucose production from food waste, kinetically accelerated glucose production (especially at the initial stage of hydrolysis), resulting in higher bioethanol production overall. Yin et al. (2016) reported that fungal pre-treatment of food waste prior to AD leads to increased methane yields. Han et al. (2015) found that fungal pre-treatment of food waste using *Aspergillus awamori* and *Aspergillus oryzae* effectively improved DF performance, indicated by higher hydrolysis rates, better food waste degradation, and higher biohydrogen yields. Kiran et al. (2014) highlighted that fungal pre-treatment of food waste combined with microalgae cultivation, may provide renewable feedstock and an effective conversion route for biodiesel production. Promon et al. (2018) highlighted that the use of cellulolytic bacterial (i.e. *Bacillus substilis*), as a biological pre-treatment of vegetable peels, enhanced the efficacy of bioethanol fermentation. Fermentation of pre-treated vegetable wastes with *Bacillus substilis* has a higher bioethanol production rate (141.7 gm/L (w/v) and bioethanol concentration of 52%, compared to that of untreated with values of 62.1 gm/L and 12%, respectively. Enzymatic pre-treatments are considered to be a ‘greener approach’ to enhancing the efficacy of food waste conversion to bioenergy, such as biogas or biomethane production (Meng et al., 2017; 2015); biohydrogen (Wang et al., 2010); biodiesel, bioethanol, hydrochar, and bio-oil (Karmee, 2016). Kaushik et al. (2014) reported that enzymatic-assisted pre-treatment of food waste prior to hydrothermal carbonation process improves bio-oil quality.

An alternative biological pre-treatment approach involves injecting oxygen into the bioreactor to control anaerobic and aerobic biological activity. This is called aeration/micro-aeration pre-treatment. The basic principle of the aeration pre-treatment is to hydrolyze complex substrates by mobilizing enzymes released by the microbial community, thus delaying the formation of VFAs (Banu et al., 2020; Fisgativa et al., 2018). This pre-treatment method is widely applied to increase the hydrolysis of complex organic components with higher biodegradability, such as food waste (Lim and Wang, 2013). Fisgativa et al. (2016) studied food waste pre-treatment involving four different oxygen rates in the air (0%, 5%, 10%, and 21%) for 4 days. The results explained that aerobic pre-treatment led to a diversification of the bacterial community and *Proteobacteria* dominance (present in 21% $O_2$), indicating a high production of exo-enzymes. Lim and Wang (2013) also used aerobic/micro-aeration pre-treatment by adding 37.5 mL $O_2/L_R$-day to the liquid food waste once daily over 4 days. The study indicated that oxidation-reduction potential (ORP) of the pre-treated food waste reactor was similar to the untreated reactor (un-aerated or anaerobic condition). This indicates that the oxygen added to the pre-treated reactor was consumed by the facultative microorganism, and both reactors had anaerobic zones where fermentation could occur. The VS degradation in pre-treated food waste was l0% higher than untreated food waste, suggesting that aeration, as a pre-treatment, stimulates the production of exo-enzymes by aerobic microorganisms. This could potentially lead to a better conversion efficacy for pre-treated food waste.

Biological pre-treatments require carefully controlled conditions to optimize microorganisms or enzymes activity which often require longer pre-treatment times (Mozhiarasi, 2021). Banu et al. (2020) highlighted that using pure cultures of microorganisms to pre-treat food waste may disadvantage competition with the indigenous microorganisms. Biological pre-treatment does not necessarily require complex and energy-intensive technology; therefore, it offers various advantages in terms of environmental sustainability and cost-effectiveness (Kannah et al., 2020).

### *4.3. Chemical pre-treatment*

Chemical pre-treatments of food waste can be utilized such as acid, alkaline, surfactants, $H_2O_2$, or ozone to degrade the organic material, leading to improved degradation or conversion rates (Banu et al., 2020; Kannah et al., 2020). Various chemicals are used in acid pre-treatments, including sulphuric acid ($H_2SO_4$), hydrogen peroxide ($H_2O_2$), hydrochloric acid (HCl), nitric acid ($HNO_3$), and phosphoric acid ($H_3PO_4$) (Begum et al., 2021). Several studies have demonstrated that acid pre-treatment (using $H_2SO_4$ solution) at pH 2 and 4 have improved biogas production from food waste derived from the fruit-juice industry (Akbay et al., 2021). Ma et al. (2011) also demonstrated that using acid pre-treatment (i.e. 2N HCl solution at pH 2) led to an increase in soluble COD released from food waste, subsequently leading to a higher biomethane yield. Elbeshbishy et al. (2011a) reported that acid pre-treatment of food waste using 1N HCl at pH 3 prior to DF increased COD solubilization and VFA production, thus increasing biohydrogen production. Kim et al. (2014) reported a significant improvement in biohydrogen production from food waste following acid pre-treatment (6 M HCl at pH 2), possibly due to higher carbohydrate degradation. Salem et al. (2018) emphasized that $H_2O_2$ pre-treatment enhanced the efficacy of two-stage AD of potato waste, giving the highest biohydrogen production of 1.88 L/L/day and biomethane production of 1.89 L/L/day, respectively. The study demonstrated that $H_2O_2$ pre-treatment was more effective than acid or alkaline pre-treatment for biohydrogen and biomethane conversion routes. Other studies have also emphasized that $H_2O_2$ pre-treatment was highly effective for the pre-treatment of organic wastes (Ambrose et al., 2020; Begum et al., 2021). Several factors influence the performance of acid pre-treatment processes, including the concentration of acid and substrates, the contact or mixing duration, and the process temperature (Zhao et al., 2022).

Alkaline pre-treatment commonly utilizes CaO, KOH, $NH_4$, and NaOH solutions to break down the organic chains and solubilize the lignin in organic materials (Chandrasekhar et al., 2015; Linyi et al., 2020). These alkaline solutions were found to positively impact biogas/methane production with no inhibitory effect on the AD process (Linyi et al., 2020). Various studies have highlighted the benefits of applying alkaline pre-treatment on food waste for improving biogas and methane yields. Menon et al. (2016) used NaOH solution at pH 8, 9, 10, 11, and 12 to pre-treat food waste prior to the AD process. The study confirmed the improvement in biogas production after NaOH pre-treatment, with pH 8 and 9 resulted in the best AD performance. Akbay et al. (2021) reported that alkaline pre-treatment of food waste with NaOH solution at pH 9 increased biogas production by 8.1%, while pre-treatment at pH 11 resulted in a reduction by 6.9%. This study highlighted that a high dose of NaOH negatively impacted metabolic routes of anaerobic consortia, thus decreasing overall biogas production. While Jang et al. (2015) found that alkaline pre-treatment of food waste with 6N KOH (pH 12) led to increase biohydrogen production (162 mL $H_2$/g VS) compared to that at pH 9 (63 mL $H_2$/g VS). Elbeshbishy et al. (2011a) reported that alkaline pre-treatment of food waste with 1N NaOH at pH 11 produced 46 mL $H_2$/g VS biohydrogen. These findings confirm that process control is critical in both acid and alkaline pre-treatments, with dosage and type of chemical used impacting the efficacy and efficiency of lignocellulosic and cellulosic degradation, which in turn impacts the conversion efficiency (Zou et al., 2020).

Surfactants can also be used as a chemical pre-treatment process. Elsamadony et al. (2015) suggested that organic fraction of MSW (OFMSW) treated with non-ionic surfactants (i.e. Polysorbate 80/Tween 80 and Polyethylene glycol/ PEG 6000) increased the substrate biodegradation efficacy, resulting in higher biohydrogen production. However, a decline in biohydrogen production was observed when increasing Tween 80 concentration from 2.8% to 5.6%. This dose was deemed to be potentially toxic to the microorganisms. Shanthi et al. (2018) reported that the use of surfactant (i.e. sodium dodecyl sulphate or SDS) combined with ultrasonic pre-treatment could increase the delignification of FVW to 72%, thus improving methane yield by 48.8%. Surfactant compounds adsorb the hydrophobic component of feedstock substrates, thus reducing the surface tension of water and increasing the accessibility of digestive enzymes to the substrate (Elsamadony et al., 2015; Kavitha et al., 2016; Shanthi et al., 2018). Ariunbaatar et al. (2014) found that ozonation, as a chemical pre-treatment of food waste, increases cumulative biomethane production; however, no positive effect was observed on the production rate. Kondusamy and Kalamdhad (2014) added that the ozonation pre-treatment is not suitable for food waste due to its high content of readily biodegradable organic matter.

Despite many advantages from chemical pre-treatment processes in terms of organic degradation, their usage is widely recognized can pose a risk to the natural environment if not managed correctly (Koyama et al., 2017).

Therefore, monitoring and controlling excessive pH or potential toxicity risks (with neutralization or stabilization) is often necessary (Salihu and Alam, 2016). Chemical pre-treatment can require large quantities of raw materials which can increase the operational costs of the process (Kannah et al., 2020; Koyama et al., 2017).

### *4.4. Thermal pre-treatment*

Thermal pre-treatment of food waste aims to break down the recalcitrant organic matter using high temperatures, thereby increasing the solubilization of food waste (Gnaoui et al., 2020; Menon et al., 2016). Various factors such as optimal temperature, contact time, and substrate composition are still challenging for thermal pre-treatments (Akbay et al., 2021; Gnaoui et al., 2020; Kannah et al., 2020). Despite these operational challenges, several studies have reported the positive benefits of thermal pre-treatment on food waste. Menon et al. (2016) evaluated the thermal pre-treatment of food waste using an autoclave at 80, 105, and 130 ºC (each for duration time of 20, 40, and 60 min). Their study demonstrated that pre-heating food waste (at 130 ºC for 60 min) resulted in higher COD solubilization (~47 %), contributing to higher biogas production. This study concluded that thermal pre-treatment could inhibit the onset of hydrogen production, making all solubilized COD available for methanogenic bacteria. Liyanage and Babel (2020) reported a higher methane yield from food waste following thermal pre-treatment at 80 ºC.

Other potential thermal pre-treatments include hydrothermal processing, steam explosion, and microwave pre-treatment. Sharma et al. (2007) found that thermal pre-treatment on kinnow waste and banana peels using steam explosion (at 15 psi for 1.5 h) enhanced the production of total reducing sugars, leading to improved fermentation efficacy (83.52%) and bioethanol yield (0.426 g/g). Elbeshbishy et al. (2011a) reported that hydrothermal pre-treatment (at 70 ºC for 30 min) without acid addition resulted in higher COD solubilization and biohydrogen production than pre-treatment with acid addition. Microwave pre-treatment has been highlighted as a potential future pre-treatment to enhance the valorization of food waste (Angulo-Mosquera et al., 2021; Zhang et al., 2016). Zhang et al. (2016) studied the effect of microwave pre-treatment on co-digestion of food waste with sewage sludge (SS). Their study revealed that microwave pre-treatment (100 ºC) on food waste, following co-digestion with untreated SS at various ratios (1:1, 2:1, 2:3, and 3:2) was found to enhance methane production in the range of 3.96 % - 16.99 % respectively. This improvement may be due to increased organic matter solubilization, cell destruction, or release of EPS from pre-treated food waste.

Kannah et al. (2020) and Menon et al. (2016) have emphasized that thermal pre-treatments of food waste result in higher solubilization (i.e. ~47%) compared to other pre-treatments. However, thermal pre-treatments are energy-intensive due to high electrical input requirements (Ma et al., 2011). It may also lead to the production of inhibitory compounds (such as furfurals, hydroxymethylfurfural/HMF, melanoidins, caramelans, etc.) to the AD process (Akbay et al., 2021; Menon et al., 2016).

## 5. Critical overview of food waste conversion to bioenergy

Transforming food waste into bioenergy presents many development opportunities in Indonesia. These include economic benefits (i.e. inward investment, income generation, job creation), social benefits (i.e. energy security, poverty reduction, and improved health), and environmental benefits (protection of non-renewable resources, reduced GHG emissions) (Gold, 2011). Sharma et al. (2013) stated that challenges and uncertainties in the biomass supply chain include the following factors: biomass supply, weather, biomass properties such as moisture content, biomass cost, technology, expansion plans, demand fluctuations, biofuel price, change of the government incentives, change of regulations and policies, and natural or human disasters. Currently, food waste in Indonesia is managed via landfill disposal and waste combustion, which are considered first-generation valorization protocols. Therefore, developing more sustainable and cost-effective food waste conversion systems is critical, in particular for bioenergy provision (Ong et al., 2018). The government support in the form of policy and financial instruments (incentives and financing options) are required to promote the wider adoption and implementation of food waste conversion pathways in Indonesia. Furthermore, integration of supply chain and logistics, greater synergy between waste and energy agencies, consumer perceptions, and behavior change will also be important in driving a transition to more sustainable waste practices in Indonesia.

### *5.1 Supply chain and logistics*

Yue et al. (2014) have identified that biomass to bioenergy supply chain system consists of biomass production, biomass logistics, biofuel production, biofuel distribution, and biofuel end-use. Supply chain and logistics management are essential for successfully implementing waste biomass to bioenergy. Operational and sustainability challenges across the supply chain include harvesting, collection, storage, transport, pre-treatment techniques, and the overall supply system design (Iakovou et al., 2010; Gold and Seuring, 2011; Sharma et al., 2013). Iakovou et al. (2010) added that there are two main issues of supply chain and logistics of waste conversion to bioenergy, including cost and its logistics operational complexity. In the biomass to bioenergy supply chain, efficient biomass logistics are vital as delays can lead to biomass degradation and emissions to the environment. Therefore, logistics companies must consider the time-sensitive feedstock collection, storage, and delivery operations. While the challenges in the supply chain and logistics include legal and political framework, environmental and social, utilization rivalries, citizen resistance, and technological drawbacks (Gold, 2011); as well as conflict over land for food and energy (Yue et al., 2014).

In the case of food waste, Pfaltzgraff et al. (2013) stated that residues arising within the food supply chain residues (i.e. unavoidable food waste, food loss) are a promising resource for further valorization to high value-added products. Nunes et al. (2020) highlighted that various logistical considerations are necessary, including the density of waste, sale price, transport cost, seasonality, high moisture content, geographic dispersion, and low heating values. However, infrastructure and transportation remain as enormous challenges in converting food waste into bioenergy. Therefore, deepening our understanding of critical challenges and carefully considering efficient supply chain design and operation is critical for successful implementation. Involving stakeholders and producers in planning, projection, implementation, and decision-making processes at all levels is also crucial to project success (Iakovou et al., 2010). Elevated raw material costs and restrictive waste disposal legislation drives perceptions of food waste as a resource rather than a problem. Various factors need to be considered when developing sustainable supply chains and logistics for food waste to bioenergy systems, as shown in Figure 2. These complex systems are composed of various actors and providers at different market levels to ensure better performance and ease access to value chains, as well as to reduce potential environmental risks (FAO, 2014, 2011).

As stated by Kristanto and Koven (2019) and Soma (2017a), the challenges over the supply chain and logistics of food waste in Indonesia include: (1) no implementation of waste separation/segregation (i.e. recycling), where food waste mixed with other organic/inorganic waste is directly transported to landfills or temporary dumpsites, and (2) a lack of food waste management's infrastructure. Kristanto and Koven (2019) added that 60-70% of food waste is directly disposed of to landfills, while the remaining 30-40% is disposed to river bodies, burned or managed by local community via composting. This condition indicates that food waste management poses a challenge for future valorization pathways. Robust waste management practices are required to effectively mobilize these organic waste materials and divert them to more sustainable treatment pathways.

In the Indonesian context, the current supply chain of food waste for bioenergy generation includes sources, collection, transportation, treatments (i.e. composting, AD, or landfills), and utilization (i.e. end-users), as shown in Figure 5. The primary sources of food waste are from households (i.e. kitchen, which accounted for 58% of the total food waste) and commercial enterprises (i.e. restaurants, traditional markets). Furthermore, within this framework, various actors involved include households or commercials (as food waste generator), local government (as rules-making and food waste management), local community or producers (as food waste treatment), and end-users (as customers, i.e. households, farmers, or commercials) (Amir et al., 2016). The composting and AD of food waste options are currently managed by an individual (i.e. household/home composting or AD system) and the local community (i.e. centralized composting or AD system), for achieving better environmental and social benefits (Loan et al., 2019). Both technologies can be operated by individual or private composting business units aiming for commercial and economic benefits.

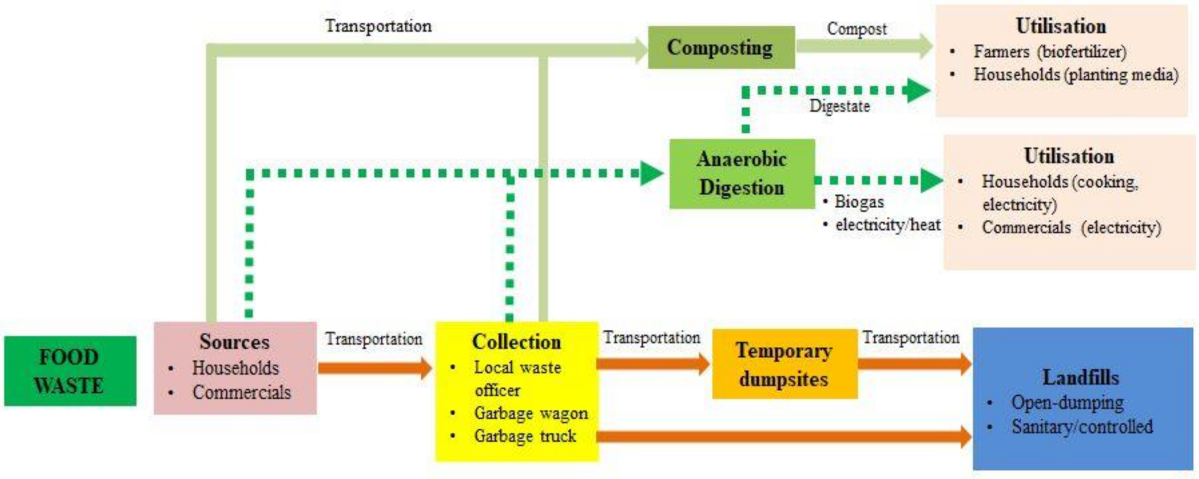

**Figure 5.** The food waste supply chain and management in Indonesia (Adapted from (Kristanto and Koven, 2019; Amir et al., 2016; Loan et al., 2019; Soma, 2017a)

### *5.2 Environmental and economic perspectives: bioeconomy concepts*

This study has explored opportunities to mitigate the environmental impacts of food waste and generate sustainable energy. It is also essential to consider any direct or indirect impacts of these proposed new process pathways on the environment. In 2020, China treated 125 Mt of food waste which required 30.1 tons oil-Eq of fossil fuels and 16.7 Mt of freshwater, which released 37.5 Mt of $CO_2$-Eq (Liu et al., 2021). Therefore, it is critical to highlight the potential environmental impacts of each conversion technology to inform and influence future decisions regarding treatment pathways (Edwards et al., 2018; Jones et al., 2022; Sridhar et al., 2021). Several studies have emphasized that life cycle assessment (LCA) is a comprehensive tool or method for comparing or investigating the environmental impacts within each life stage of a process, product, or activity (Jain et al., 2022; Strazza et al., 2015). Thus, the impacts at each stage can be managed and mitigated where necessary (Dolci et al., 2021; Kothari et al., 2020; Sillero et al., 2021; Yoshikawa et al., 2021). LCA has four key elements include defining the goal and scope of the assessment, developing an inventory, the impact assessment, and the interpretation of the assessment. The results can inform the most sustainable and viable future scenarios from a technical and environmental perspective (Hobbs et al., 2021; Rahman et al., 2019).

Converting food waste to bioenergy, with the support of sustainable supply chains and logistics, may provide an attractive solution for mitigating the problems of non-renewable energy depletion and climate change, as well as reducing carbon footprints (Kumar and Singh, 2019). Many LCA studies have underlined the potential environmental benefits and risks from valorizing of food waste to bioenergy. Xu et al. (2015) compared two scenarios of food waste treatment technologies, including landfilling systems and AD for biogas production. Their study found that the scenario of applying AD technology provides greater benefits due to its lower environmental impact and higher energy recovery opportunities. Opatokun et al. (2017) compared three scenarios for food waste treatment, including AD, pyrolysis, and integrated AD with pyrolysis technology. The results showed that both AD alone and integrated AD with pyrolysis scenarios provide the lowest environmental impacts on climate change and water depletion, while pyrolysis generated the highest environmental impacts (i.e. water and mineral depletion, climate change). They further stated that the integrated treatment system offers more economic benefits from producing bioenergy and high value-added products (i.e. biochar and bio-oil). Other studies have also highlighted that implementing AD of food waste for biogas production (either as a single or integrated system) provide the best environmental performance (i.e. lower environmental impacts) compared to other treatments such as landfills, incineration, and pyrolysis (Ahamed et al., 2016; Edwards et al., 2018; Liu et al., 2021; Tian et al., 2021). However, pre-treatment, the addition of additives, and careful monitoring are required, especially with food waste containing high oils, salts, and protein (Sridhar et al., 2021). An LCA study on biodiesel production from food waste by integrating BSFL composting was reported by Salomone et al. (2017), which demonstrated lower environmental impacts (i.e. minimize land-use for production of lipid-based plants) compared to the conventional technology. The summary of environmental and economic considerations from transforming food waste to bioenergy using various conversion technologies is shown in Table 12.

Table 12. Summary of LCA studies on food waste conversion to bioenergy

| Conversion technology | Products | Description | Environmental performance | Economic consideration | Ref. |
|---|---|---|---|---|---|
| Anaerobic digestion (AD) | - Biogas<br>- Biomethane<br>- Biofertilizer | AD of food waste technology is applied in a single- or two-stage system | - Lower impact on climate change (lower global warming potential/GWP)<br>- Lower carbon emission and GHG<br>- Lower impact on water depletion, fossil fuel depletion, and ozone depletion | Additional economic benefits from the production of bioenergy and value-added products (i.e. compost/biofertilizers) | (Ahamed et al., 2016; Edwards et al., 2018; Liu et al., 2021; Opatokun et al., 2017; Sridhar et al., 2021; Tian et al., 2021; Xu et al., 2015) |
| Integrated AD with pyrolysis | - Biogas<br>- Biomethane<br>- Biochars<br>- Bio-oil | Digestate from the AD of food waste was dried and used as feedstock for pyrolysis | - Much lower impact on climate change (lower GWP)<br>- Lower impact on water depletion, fossil fuel depletion, and ozone depletion | Better economic benefits from increased production of bioenergy and value-added products | (Opatokun et al., 2017; Wang et al., 2021; Zhou et al., 2021) |
| Simultaneous Saccharification and Fermentation (SSF) or Separated Hydrolysis Fermentation (SHF) | Bioethanol | Food waste, combined with pre-treatment, was fermented into bioethanol | - Lower impact on climate change (lower GWP)<br>- Lower carbon emission and GHG<br>- Lower impact on impact category of acidification potential/AP, eutrophication potential/EP, terrestrial eutrophication potential/TEP, and marine eutrophication potential/MEP<br>- Higher wastewater generation with high COD concentration | Expensive to produce if bioethanol concentration is low (5-10%) | (Demichelis et al., 2020; Ebner et al., 2014; Konti et al., 2020; Sridhar et al., 2021) |
| Transesterification | Biodiesel | Bio-oil was extracted from food waste, then converted into biodiesel | - Lower impact on eutrophication and air emission compared to incineration<br>- Higher cumulative energy demand (fossil fuel consumption) | - Preferred option for food waste with oil content > 5% due to higher energy yield<br>- Lower economic benefits than AD technology<br>- Higher economic benefits compared to incineration | (Ahamed et al., 2016; Mahmood et al., 2016; Sridhar et al., 2021) |
| Integrated BSFL composting | - Biodiesel<br>- Feed<br>- Compost | Food waste was used as feedstock for composting to produce BSFL. The dried larvae were used for fish food (feed) and | - Lower impact on climate change (lower GWP), which was much lower than incineration<br>- Lower impact on land-use | Better economic benefits from the production of biodiesel and various high value-added products (i.e. feed and compost) | (Guo et al., 2021; Mertenat et al., 2019; Salomone et al., 2017; Song et al., 2021) |

|  |  |  |  |  |  |
|---|---|---|---|---|---|
|  |  | biodiesel production | - Lower energy use |  |  |
| Dark Fermentation (DF) | Biohydrogen | Single-stage process using microorganisms to convert organic matter into biohydrogen under the absence of light and $O_2$ | - Lower GHG emissions<br>- Higher impact on fossil fuels use, respiratory inorganics potential, and carcinogenic potential carcinogens | Additional economic benefits from the production of bioenergy | (Ochs et al., 2010; Thi et al., 2016; Tian et al., 2019) |
| DF combined with AD | - Biohydrogen<br>- Biomethane | Two-stage process. First, food waste was fed into the DF reactor to produce biohydrogen. Second, the effluent from the DF reactor was used as feedstock in the AD reactor for producing biomethane | Higher environmental burdens compared to single AD process, including indicators of fossil fuels depletion, reduction of climate change impact, carcinogens, ecotoxicity, and respiratory of inorganics. | - Better economic benefits from the production of two valuable bioenergy and value-added products (i.e. biofertilizer/digestate)<br>- Higher revenues compared to single AD or DF process | (Bastidas-Oyanedel and Schmidt, 2018; Patterson et al., 2013; Thi et al., 2016) |
| Photo Fermentation (PF) | Biohydrogen | Single-stage process using photosynthetic bacteria to convert organic matter into biohydrogen in the presence of light, and the absence of $O_2$ and $N_2$ | - Lower GHG emissions<br>- Higher impact on fossil fuels use, respiratory inorganics potential, and carcinogenic potential carcinogens | Additional economic benefits from the production of bioenergy | (Ochs et al., 2010; Thi et al., 2016; Tian et al., 2019) |
| Consequential/combined dark and photo fermentation | Biohydrogen | Two-stage process which consisted of DF reactor first, then the VFA-rich effluent from DF reactor is becoming feedstock for PF reactor | - Lower GHG emissions<br>- Lower human health, ecosystem quality, and resource depletion | - Better economic benefits due to higher $H_2$ yield, leading to a cost-effective process<br>- Economically feasible for industrial application | (Dahiya et al., 2018; Han et al., 2016a; Ochs et al., 2010; Tian et al., 2019) |
| Gasification | Biohydrogen | Use of gasification technology to directly convert organic waste into biohydrogen | - Lower GHG emissions<br>- Lower impact on climate change (lower GWP) eutrophication potential, and photochemical ozone creation potential, compared to the conventional technology | Additional economic benefits from the production of bioenergy | (Siddiqui and Dincer, 2019; Tian et al., 2019; Wulf and Kaltschmitt, 2012) |
| Pyrolysis | - Biochar<br>- Bio-oil<br>- Syngas | Modes of pyrolysis techniques:<br>- slow pyrolysis | - Higher impact on water depletion, fossil fuel depletion, and mineral depletion | - High cost for operation and maintenance<br>- Additional economic benefits | (Elkhalifa et al., 2019; Opatokun et al., 2017; Sridhar et al., 2021) |

|  |  |  |  |  |  |
|---|---|---|---|---|---|
|  |  | - fast pyrolysis<br>- catalysis pyrolysis<br>- microwave assisted pyrolysis<br>- hydropyrolysis<br>- co-pyrolysis | - Higher impact on climate change<br>- Potential impact of terrestrial acidification and freshwater eutrophication<br>- | from the production of bioenergy and value-added products (i.e. biochars) |  |
| Torrefaction | - Solid fuel pellets (or bio-coal)<br>- biochar | Endothermic treatment at 200-300 °C to produce solid fuels. This includes wet and dry torrefaction | - Higher energy consumption<br>- Lower GHG emissions | - High operational cost due to transportation for waste collection, waste to conversion plant, and ash transportation from conversion plant | (Akbari et al., 2021; Goyal et al., 2018; Li and Wright, 2020) |
| Briquetting | Briquettes | Densification of food waste with and without binder addition | - Higher impact on human toxicity (HT) and GWP<br>- Minimal impact on ozone layer depletion (ODP)<br>- Lower energy use | - Lower production cost<br>- Potential economic benefit from use for cooking and electrical in developing countries<br>- More cost-effective compared to biochar production | (Angulo-Mosquera et al., 2021; Duman et al., 2020; Muazu et al., 2021; Sparrevik et al., 2014) |
| Liquefaction | Bio-oil | Thermochemical treatment of food waste with no presence of $O_2$ | - Higher impact on climate change (high GWP)<br>- Higher energy consumption<br>- Lower impact on acidification potential, eutrophication potential, toxicity, and photo-oxidant formation | - Higher cost for wastewater treatment<br>- Better economic feasibility if food waste as feedstock | (Aierzhati et al., 2021; Hosseinzadeh-Bandbafha et al., 2020; Lee et al., 2020) |

There is a need to valorize food waste into more valuable products without creating waste (i.e. zero waste and waste to resource). Randolph et al. (2017) pointed out that converting food waste into high value-added products can alleviate environmental impacts associated with its disposal and have a positive impact on local economies. For example, pyrolysis of food waste may generate additional income from producing alternative fuels products (i.e. syngas, bio-oil, biochars, etc.) or from biochar application as a soil conditioner (Elkhalifa et al., 2019). Other studies have also highlighted the economic benefits from the application of various conversion technologies for food waste, including AD, transesterification with or without BSFL composting system, fermentation, etc. (Ahamed et al., 2016; Edwards et al., 2018; Liu et al., 2021; Opatokun et al., 2017; Salomone et al., 2017; Sridhar et al., 2021; Tian et al., 2021; Xu et al., 2015); this is illustrated in detail in Table 12.

Figure 6 illustrates the concept of a sustainable biorefinery for food waste through bioenergy generation and the creation of local circular economies (or bioeconomies). According to Read et al. (2020), developing a circular economy for food waste should focus on valorizing the waste and reducing natural resources utilization across the food supply chain system. Ohja et al. (2020), for instance, demonstrated that adopting circular economy consideration on food waste for insect-based bioconversion might give promising economic benefits and commercialization as a source of bioenergy (i.e. biodiesel) and high value-added products (i.e. animal feed, nutrients, and fertilizer). The development and adoption of a circular economy for food waste valorization as bioenergy sources require support from the government. A previous study highlighted five key roles of government for adopting circular economy models in tackling food waste, including the creation of vision at all levels, engagement with relevant stakeholders, provision of economic incentives, involvement of urban management levers, as well as legislations and regulations (i.e. consumers empowerment, products information, and consumer protection) (KPMG, 2020).

### *5.3 Technical feasibility and challenges*

Based on the comparative review of technological approaches presented in Table 3, several options for converting food waste to bioenergy are feasible for implementation in Indonesia. Firstly, with a TRL of 8-9, AD technology is commercially available at various scales from households to industrial applications (Indrawan et al., 2018). AD technology for biogas production has been successfully implemented in Indonesia through the BIRU and RUMAH ENERGI programs (Bößner and Al, 2019; Silaen et al., 2020; Taylor and Al, 2019). Secondly, the integration of AD with composting offers good potential. Various studies have highlighted the widespread and successful application of composting projects in Indonesia, including vermicomposting (Cholilie et al., 2019); BSFL composting (Ibadurrohman et al., 2020); and conventional composting systems (Sekito et al., 2019). These findings may indicate that integrated AD plus vermicomposting or BSFL composting systems are plausible option, generating biogas, compost (biofertilizer), and dried biomass (i.e. protein from the earthworm, protein/lipids from dried BSFL). Kristanto and Koven (2019) proposed the integration of composting AD technology, waste recovery unit, and controlled landfilling as a disposal approach for mixed food waste management in Depok City, Indonesia. The results indicated that, based on the treatment of 1,120 tons food waste/day, the waste could be distributed to the composting system (150 tons food waste/day), the AD system (500 tons food waste/day), the waste recovery unit

(80 tons food waste/day), and the controlled landfills (390 tons food waste/day), in which this integrated configuration emits the lowest carbon emissions.

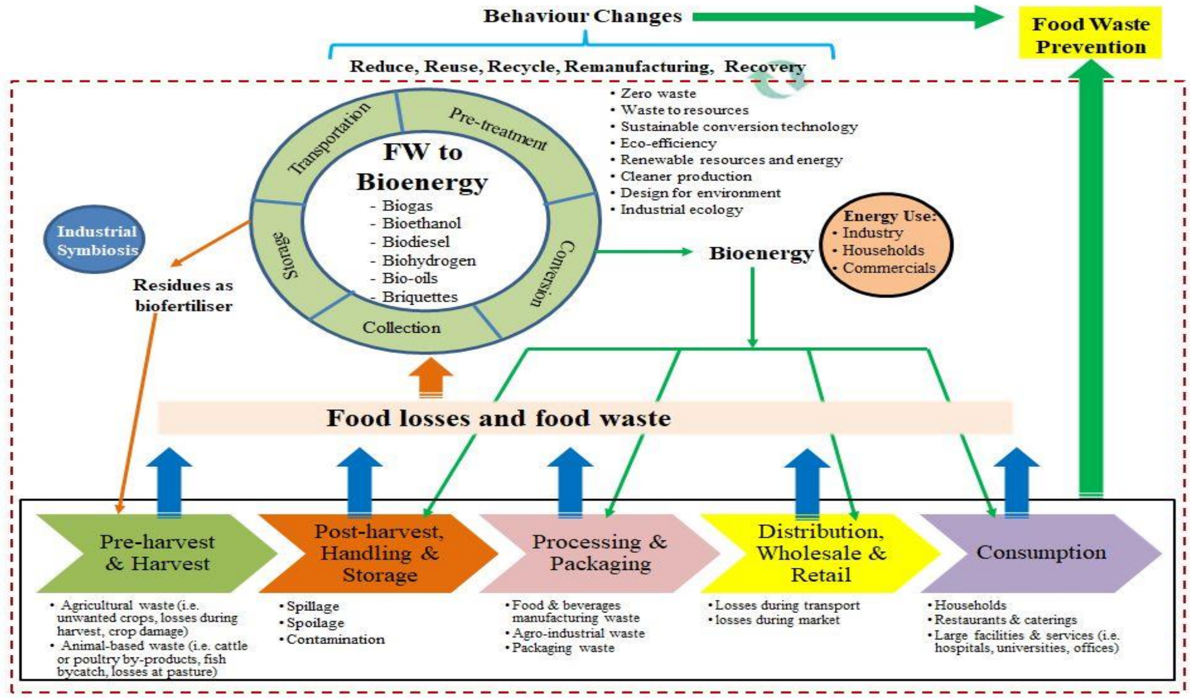

**Figure 6.** Concept of circular economy for food waste to bioenergy (Adapted from Ohja et al. (2020) and KPMG (2020))

With transesterification (as a process for biodiesel production) and fermentation (for bioethanol production), the existing regulation and substantial government supports facilitate the commercialization of these high TRL technologies. As a result, there have been many successful bioethanol and biodiesel production applications from various wastes (i.e. residues from oil palm industry or sugarcane industry) in Indonesia (Indrawan et al., 2017; Ong et al., 2018). Integration of BSFL composting with biodiesel conversion technology (i.e. transesterification) has previously been reported in several studies (Guo et al., 2021; Mertenat et al., 2019; Salomone et al., 2017; Song et al., 2021). Within this concept, the protein content of dried BSFL is further extracted into feed (i.e. fish feed) and the lipids content is for biodiesel. Yet, by considering the sustainability and bioeconomy perspectives, the option of a single AD system and the integration of BSFL composting system with AD or transesterification may provide better benefits.

Despite proven technological feasibility, various challenges remain regarding the biorefining of food waste for bioenergy production. For example, the presence of intermediate harmful chemical compounds (which can impact process efficiency), lack of adequate process control and monitoring, and performance stability issues surrounding

AD of food waste (i.e. foaming problems due to high protein/lipids in food waste) (Sen et al., 2016; Sridhar et al., 2021). Other technical challenges include source separation and variability in food waste composition (Ong et al., 2018; Santagata et al., 2021); potential contamination and high water requirements (i.e. for certain AD systems) (Ahamed et al., 2016); as well as scalability and energy-intensive process requirements (i.e. for pyrolysis, pre-treatments, etc.) (Angulo-Mosquera et al., 2021).

### *5.4 Policies and financial supports and challenges*

The state's power and control over natural resources are inherent in energy management. This is consistent with the Constitution of the Republic of Indonesia (Article 33) that "The land, the waters and the natural resources within shall be under the powers of the State and shall be used to the greatest benefit of the people". The derivative regulations as described in the attachment to Law Number 23 of 2014 concerning Regional Government also mandate that energy development policies (including bioenergy) are the authority of the central and provincial governments. This means that all bioenergy development projects at the district and city levels, especially large-scale projects and for the public interest, must obtain approval from the central and/or provincial authorities.

The semi-centralistic paradigm in controlling energy management indicates that the Indonesian Government is serious in making energy management into the country's priority agenda. As stipulated in the National Energy Policy/NEP, the Government stated a renewable energy mix target of ~23% by 2025. Furthermore, in the first Nationally Determined Contribution (NDC) document of the international Paris Agreement, Indonesia expressed a commitment to reduce emissions by 26% (unconditional) and up to 41% (with international assistance) in 2030. Therefore, the Government issued several policies and infrastructure support in developing renewable energy, one of which is transforming food waste into bioenergy. Some of the policies and infrastructure support provided include: (1) small-scale biogas development program, (2) MSW based power plant development program, (3) incentive to purchase electricity from MSW power plant (PLTSa), biomass power plant (PLTBm), and biogas power plant (PLTBg), and (4) tax incentives.

The small-scale biogas development program known as BIRU program is a collaborative program between MEMR and an NGO called the *Yayasan Rumah Energi* (BIRU, 2021; Haryanto et al., 2020). The BIRU program was initially launched as an initiative between two NGOs, include Hivos and SNV (Bößner et al., 2019; Bößner and Al, 2019; Taylor and Al, 2019). The BIRU program has two applications: concrete dome (or fixed-dome) and BIOMIRU technology. Fixed-dome technology targets rural areas that can treat cattle manure in a large land area. BIOMIRU technology targets for urban groups to produce biogas from food waste in a limited land area. This program aims to solve environmental problems relating to waste management, establish a circular economy, and create jobs. From 2009 to 2019, the BIRU program built 24,769 biogas reactors in 12 provinces in Indonesia, (such as Lampung, West Java, Jakarta, Banten, Central Java, Yogyakarta, East Java, South Sulawesi, Central Sulawesi, Bali, West Nusa Tenggara, and East Nusa Tenggara) (BIRU, 2021). However, this program only focuses on small-scale biogas production managed by individual households and has not yet expanded the development of centralized medium- or large-scale biogas reactors. There has been some criticism surrounding the sustainability of this program. Several digesters are allegedly no longer operating due to a lack of public understanding of the maintenance of biogas technology (Listiningrum et al., 2021). Furthermore, underground concrete digesters have experienced ongoing technical problems influenced by the local climate, with many prone to cracking and leaking due to seasonal temperature changes (Silaen et al., 2020).

In February 2016, the Indonesian Government issued a Presidential Regulation on the ‘Acceleration of Waste to Energy Development’ in seven cities (i.e. Jakarta, Tangerang, Bandung, Semarang, Surakarta, and Makassar). According to this regulation, waste to energy (WtE) is defined as a power plant that utilizes MSW (such as food waste, yard waste, and plastic waste) as renewable energy via thermal process technology (i.e. gasification, incinerator, and pyrolysis). The regulation states that the minimum capacity for the treatment is 1,000 tons of waste per day. On 19 July 2016, a judicial review was conducted to the Supreme Court on this Presidential Regulation by fifteen individuals and six NGOs, questioning aspects of human health and the environment. Therefore, it is necessary to prioritize the principle of early caution in determining the technology used. The issues of health and safety regulations are essential in any energy development. For instance, Sitorus et al. (2013) stated that various considerations have to be considered when building AD of food waste, such as the health and safety regulations of standing gas, fire, and building. This public concern was confirmed by the Court, thus on 2 November 2016, the Presidential Decree Number 18 Year 2016 was canceled. Therefore, a new Presidential Regulation was issued in April 2018 (i.e. Presidential Regulation Number 35 of 2018), emphasizing the use of environmentally friendly technology for Municipal Waste Power Plants. This regulation supports various facilities such as providing funding, facilitating the land acquisition, offering supervision guidance, setting Feed-In Tariff policies, and securing market availability by requiring the state electricity company (PT. PLN) to purchase the produced electricity.

The government support for WtE is also demonstrated via the Feed-In Tariff policies, which oblige PT. PLN to purchase electricity generated by WtE as regulated in the Regulation of MEMR No. 44 Year 2015. The electricity tariff from methane gas produced by sanitary landfills or AD is 16.55 cents USD/kWh. This tariff is applied for medium- and high-voltage grids, with a maximum capacity of 20 MW. While for thermal utilization using thermochemical technology such as an incinerator, the tariff is 18.77 cents USD/kWh for medium- and high-voltage grids with a maximum capacity of 20 MW. This policy is expected to accelerate investment in renewable energy while improving the municipal waste management quality (MEMR, 2017).

Further examples of supportive Feed-In Tariff policies include those for bioenergy-based power plants, such as Biomass Power Plant (PLTBm) and Biogas Power Plant (PLTBg). Two purchase schemes are stated in the Regulation of MEMR Number 21 Year 2016. The first scheme is the purchase of electricity from PLTBm and PLTBg holders of Electricity Supply Business License (IUPTL), which is a license to provide electricity for public purposes. The second scheme is to purchase excess power from PLTBm and PLTBg owned by the holder of an Operation Permit, namely a license to supply electricity for its interests. The rates for the two schemes can be seen in Table 13.

Table 13. Feed-in Tariff policies for bioenergy based power plant in Indonesia

| No. | Energy | Capacity | Electricity Tariff | Note |
|---|---|---|---|---|
| | | *Medium to High Voltage* | | |
| 1. | Biomass | Until 20 MW | 13.50 USD/kWh x F | • Non MSW<br>• Power from IUTPL Holder |
| 2. | Biomass | 20 to 50 MW | 11.48 USD /kWh x F | |
| 3. | Biomass | More than 50 MW | 10.80 USD/kWh x F | • Non MSW<br>• Power from IUTPL Holder |
| 4. | Biomass (Excess Power) | Until 20 MW | 13.50 USD/kWh | • Non MSW<br>• Excess Power from Operation License Holder |
| 5. | Biomass (Excess Power) | 20 to 50 MW | 11.48 USD/kWh | • Non MSW<br>• Excess Power from Operation License Holder |
| 6. | Biomass (Excess Power) | More than 50 MW | 10.80 USD/kWh | • Non MSW<br>• Excess Power from Operation License Holder |
| 7. | Biogas | Until 20 MW | 10.64 USD/kWh x F | • Non MSW<br>• Power from IUTPL Holder |
| 8. | Biogas | 20 to 50 MW | 9.05 USD/kWh x F | • Non MSW<br>• Power from IUTPL Holder |
| 9. | Biogas | More than 50 MW | 8.51 USD/ kWh x F | • Non MSW<br>• Power from IUTPL Holder |
| 10. | Biogas (Excess Power) | Until 20 MW | 10.64 USD/kWh | • Non MSW<br>• Excess Power from Operation License Holder |
| 11. | Biogas (Excess Power) | 20 to 50 MW | 9.05 USD/ kWh | • Non MSW<br>• Excess Power from Operation License Holder |
| 12. | Biogas (Excess Power) | More than 50 MW | 8.51 USD/kWh | • Non MSW<br>• Excess Power from Operation License Holder |
| 13. | MSW | Until 20 MW | 16.55 USD/kWh | Landfill, Anaerobic Digestion, or something similar |
| 14. | MSW | Until 20 MW | 18.77 USD/kWh | Thermochemical |
| 15. | MSW | 20 to 50 MW | 15.95 USD/kWh | Thermochemical |
| 16. | MSW | Until 50 MW | 13.14 USD/kWh | Thermochemical |
| | | *Low Voltage* | | |
| 1. | Biomass | Until 20 MW | 16.00 USD/kWh x F | • Non MSW<br>• Power from IUTPL Holder |
| 2. | Biomass | Until 20 MW | 16.00 USD/kWh | • Non MSW<br>• Excess Power from Operation License Holder |
| 3. | Biogas | Until 20 MW | 13.14 USD/kWh x F | • Non MSW<br>• Power from IUTPL Holder |
| 4. | Biogas | Until 20 MW | 13.14 USD/ kWh | • Non MSW<br>• Excess Power from Operation License Holder |
| 5. | MSW | Until 20 MW | 20.16 USD/kWh | Landfill, Anaerobic Digestion, or something similar |
| 6. | MSW | Until 20 MW | 18.77 USD/kWh | Thermochemical |

Note: F as an incentive factor based on the region where the power plant installed: Java Island (1.00); Sumatera Island (1.15); Sulawesi Island (1.25); Kalimantan Island (1.30); Bali, Bangka, Belitung, and Lombok Islands (1.50); Riau Islands, Nusa Tenggara, and Other Islands (1.60); Maluku and Papua Islands (1.70)

Source: MEMR (2017)

In addition to electricity, NEP encourages renewable energy (from biomass or waste valorization) for transportation. To date, there have been no specific programs focusing on bioenergy for transportation from food waste. In developing bioenergy, especially food waste to electricity, the Government of Indonesia provides tax incentives in the form of: (1) tax allowance, (2) exemption from import duty, and (3) tax holiday. The tax allowance facility is a tax relief policy with a certain amount of deduction against the income tax of a business entity as regulated in Government Regulation Number 78 of 2019 jo. The Decree of the Investment Coordinating Board Number 6 of 2018 and the Regulation of MEMR Number 16 Year 2015. NRE entrepreneurs are given a net income reduction facility by 30% of the total investment value in the form of tangible fixed assets. This includes land occupied for main business activities, which is charged for 6 (six) years (at 5% per year) as long as it meets the criteria (i.e., high investment value for export, high labor absorption, and high local content).

The import duty exemption facility is applied to machinery and equipment, goods, and raw materials for production for 2 years. Within this scheme, the companies will get an additional 2-year exemption for raw materials if using local production machines and equipment (at least 30% of the total investment value). This exemption is stipulated in the Minister of Finance Decree Number 176/PMK.011/2009 jo. Regulation of the Minister of Finance Number 188/PMK.010/2015, Decree of the Minister of Finance Number 66/PMK.010/2015, and Regulation of the Investment Coordinating Board Number 13 of 2017. Furthermore, a capital good import duty exemption facility is provided to develop and expand the power generation industry that transforming bioenergy to electricity for public use.

Then, the tax holiday facility, which is a tax facility applied to newly established companies qualified as a pioneer industry. The companies will be given the freedom to pay corporate income tax for a certain period as regulated in Regulation of the Minister of Finance Number 35/PMK.010/ 018 and Regulation of the Investment Coordinating Board Number 1 Year 2019. A corporate income tax deduction is given for 5-20 years with a minimum investment of 35 Million USD and a maximum investment of 2.1 Billion USD. Pioneer industries that are entitled to this facility must meet the following conditions: (1) constitute new investment, (2) meet the minimum investment plan value of 35 Million USD ), (3) comply with provisions on the ratio between debt and capital as referred to in the Regulation of the Minister of Finance concerning the determination of the ratio between debt and company capital to calculate Income Tax, (4) have never received a notification of rejection of corporate Income Tax withholding by the Minister of Finance, and (5) have the status of an Indonesian legal entity. Finally, for mini tax holidays (or tax breaks) for investments in pioneer industries that do not qualify for a tax holiday. Within this scheme, corporate income tax deductions will be given by 50% of the total corporate income tax payable for new investment with the least value of 7 Million USD and not more than 35 Million USD.

In Indonesia, regulations specific to the conversion of food waste to bioenergy are lacking and only focusing on waste management and waste disposal generally (Ong et al., 2018). Current regulations are limited to the construction of WtE power plants for electricity production. There are currently no regulations relating specifically to the development of waste to bioenergy other than electricity, such as biofuels (i.e. biodiesel, bioethanol, bio-oil, biohydrogen) and biomass (i.e. briquettes, solid fuel pellets). To date, the policies are focused on the first-generation biofuels. There is no policy relating to second-generation biofuels, such as from food waste. The communities can develop biogas from food waste; however there is currently no government supports (i.e. funding, market provision, standardization, etc.). Therefore, to increase the development food waste to bioenergy, the local governments can take a leading role by making policies, allocating funds, and making related programs, as mandated in Law Number 18 Year 2008 (Article 6e) about Waste Management.

### *5.5 Behavior change - shifting to food waste prevention and reduction*

In Indonesia, consumer behavior has historically centred around the principle of “buy today, eat today” with traditional food infrastructures (such as mobile vegetable sellers and wet markets) being prevalent across the country. However, in recent years, these traditional outlets have been replaced by modern alternatives (such as supermarkets) who promote offers such as “buy one get one free”. This shift in consumer behavior has resulted in an increased volume of food waste. Soma (2018) suggests that developing a holistic understanding of the spatial transformation and consumption patterns in urban cities is critical in developing relevant food waste prevention strategies in Indonesia. Soma (2017b) pointed out that the interclass dynamics of the household (i.e. power dynamics between employers and domestic helpers) needed to be better understood the broader phenomenon of food waste in Indonesia. Thus, the solutions to food waste prevention and food insecurity that are socially and environmentally just can be developed.

Indonesia has unique socio-cultural elements which contribute to people’s perspectives on food waste (Fox et al., 2018). For example, Soma (2017a) highlighted that many people still practice burying or dumping food waste either at temporary dumpsites or on street corners. This is because of their lack of knowledge and understanding of reducing, reusing, and recycling (3R) of food waste. Soma (2017b) also reported that household food provisioning practices influence food waste generation in Indonesia. Therefore, shifting the people’s or community’s behavior on food waste and how to manage the food waste is critically needed. Trihadiningrum et al. (2017) stated that improving public awareness is a crucial step to achieving sustainable food waste management practices. Many studies reported that behavior change (particularly implementing sustainable behaviors) is driven by improving their environmental knowledge (Lukman et al., 2013; Vicente-Molina et al., 2013; Zsóka et al., 2013; Soma et al., 2021). These studies reported that education about the environment significantly shaped people’s actions, awareness, concern, and recognition of the impact of their activities on the environment.

Various strategies can be implemented to change behavior and perspectives on food waste. These strategies can go some way towards helping countries like Indonesia achieve the target of halving food waste, as stated in Sustainable Development Goal 12.3 (KPMG, 2020; Lipinski et al., 2017). Soma et al. (2020) studied three approaches of an information-based campaign to shift people’s behavior for food waste reduction practices include passive (i.e. handouts), community engagement (i.e. workshop, group discussion, group activities, videos, and quizzes), and gamification (i.e. online games). The study found that using these three approaches increased respondent’s awareness of food waste reduction. However, the study suggested that an augmented information-based campaign in an online game can be further used as a tool for behavior change of reducing food waste and its impact on the environment. Soma et al. (2021) reported that using information-based campaign approaches (i.e. newsletter, fridge magnet, workshop invitation, and game reminders) were found to improve people's awareness (via environmental, economic, or moral reasons) and knowledge on better food waste management. Dhokhikah et al. (2015) explored four strategies for improving people's participation in household solid waste (HSW) management practices in Surabaya, Indonesia. The strategies included intensifying training, campaigning and mass media publications (to enhance public awareness), increasing the number of 'environmentalist squads', as well as facilitating and optimizing the function of the waste bank. Inter-agency collaboration is also vital to the success of community projects. While the government is responsible for promoting sustainable practices and driving behavior change through policy, infrastructure, and education (Khair et al., 2019); a collaboration between government, and NGOs may also lead to greater and more efficient community participation (Trihadiningrum et al., 2017).

Sekito et al. (2019) proposed that people are involved in organic solid waste management activities. These findings demonstrate that environmental education through awareness-raising campaigns (i.e. passive/active, offline/online, and game/non-game approaches) can motivate people to adopt more positive and sustainable behaviors regarding food waste management. Furthermore, it is also critical to change people's behavior toward preventing the creation of food waste (i.e. waste prevention or reduction at source) via various approaches (i.e. economic incentives, awareness/education campaigns, public engagement, voluntary agreement, and better publication). With this, the volume of food waste can be reduced, leading to a reduction in treatment options, operational costs, and potential environmental impacts (Jones et al., 2022).

This review has illustrated that food waste is a promising feedstock and can be easily converted to bioenergy via various conversion pathways (i.e. physical, chemical, biological, and thermochemical). Sustainable management and valorization of food waste can incorporate the generation of bioenergy and high value-added products as part of a circular bioeconomy/biorefinery model (Mak et al., 2020). Bilal and Iqbal (2019) recommended that for securing sustainable food waste conversion with regards to bioeconomy interests, various major features must to be taken into measures. These include overall cost-effective ratio, cradle-to-grave concern, overall process efficiency, carbon footprint issues, sustainability aspects, lower processing cost, availability and renewability, and resource competitiveness. The involvement of various stakeholders (i.e. corporate, government, non-governmental, private, community, industries, and individual) needs to be considered for accomplishing the triple bottom line goals (i.e. economic, social, and environment) of the institutional performance. More importantly, the preferred method of food waste prevention should come as the priority in food waste management.

## 6. Biorefining of food waste – the proposed scenarios

Considering the previous points of the technical feasibility, commercial viability, and environmental sustainability, a biorefinery approach is proposed in Figure 6, which includes three potential scenarios. Scenario 1 is the implementation of AD for biogas production and biofertilizer. Within this scenario, there are three potential applications: (1) AD of household's food waste at a domestic/household-scale as previously implemented in BIRU or RUMAH ENERGI programs; (2) AD of traditional market food waste (large-scale generation and widely distributed across Indonesia), in which a pilot- or communal-scale AD technology can be applied; and (3) The implementation of AD of households' food waste at centralized- or communal-scale. In this case, collaboration with municipalities and local governments is needed for infrastructure and financial supports. Those potential applications of AD in Scenario 1 can be adapted either in a single- or co-digestion system of food waste with other locally available waste feedstocks (i.e. human waste, cattle manure, agricultural crops residues, agro-industrial waste). Amir et al. (2016) evaluated the potential implementation of AD of food waste in Bandung City (Indonesia). The study concluded that projects which only target biogas production (as a means of replacing LPG as cooking fuel) were not economically sustainable. However, when additional income could be generated via the sale of biofertilizer, AD of food waste was more economically sustainable.

Scenario 2 includes the application of a BSFL composting system with transesterification technology to produce biodiesel, animal feed, and compost. Within this scenario, food waste is used as a composting feedstock mixed with other potential biomass substrates, suitable for the growth of BSFL. Various studies have highlighted the potential application of this biorefinery scenario (Feng et al., 2020; Ibadurrohman et al., 2020; Jung et al., 2022). Scenario 3 consists of more complex systems which integrate AD, composting, and transesterification technologies. Within this proposed scenario, the first stage includes the application of AD to produce biogas. Then, the digestate is composted using the BSFL composting system. From this, compost and BSFL are produced. The compost can be directly sold in local markets or to relevant stakeholders (i.e. farmers as biofertilizer or households as planting media). The dried BSFL is further converted into biodiesel using transesterification technology or into animal feeds using drying or pelletizing technology. Multiple products can be produced from this scenario, including biogas, biodiesel, compost, and animal feed. Thus, this may reflect an integrated biorefinery of food waste which provides better additional resource recovery and income generation, as well as closes the loop of waste generation. Dahiya et al. (2018) emphasized the potential of biorefining food waste into bioenergy and valuable products or biochemicals, with integrated approach and application. However, further in-depth investigation is required to better evaluate the techno-economic feasibility and the sustainability of implementing these proposed scenarios.

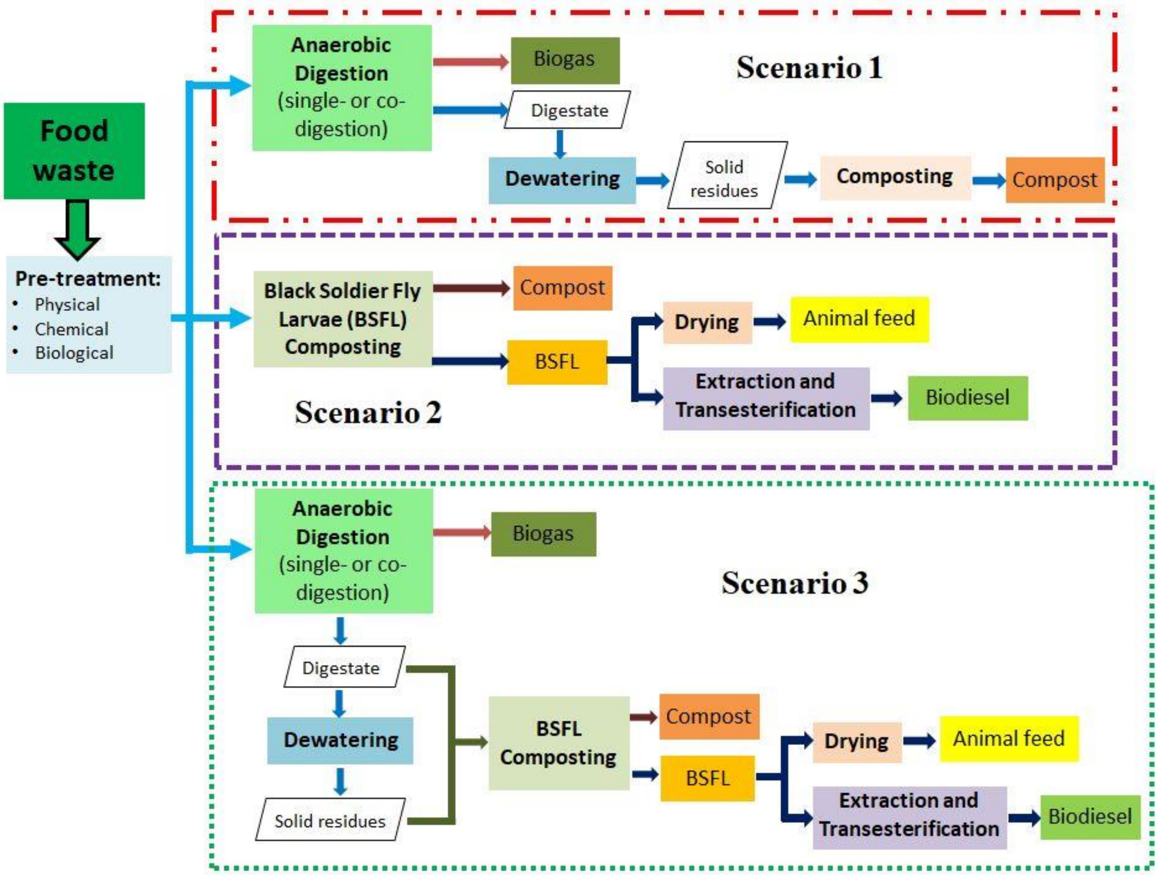

**Figure 7.** The proposed scenarios for biorefining of food waste to bioenergy in Indonesia

## 7 Conclusions and Recommendation for Future Direction

Indonesia currently has large quantities of food waste that remain underutilized and negatively impact the environment. The transformation of food waste into bioenergy and high value-added products offers multiple benefits for the environment, human health and well-being, and sustainable bioeconomies. The selection of conversion technology or valorization pathways highly depends on food waste characteristics and operational conditions. Compared to the other valorization pathways reviewed here, AD technology may offer the greatest benefits. This is because AD of food waste produces biogas and methane (which can be converted into electricity) and digestate (which can be transformed into solid and liquid biofertilizer). Based on this review, the integration of BSFL composting may present additional environmental and economic benefits. With this implementation, integrating biorefinery and bioeconomy concepts can be achieved, thus leading to a zero-waste and closed-loop system of manufacturing food waste-based high value-added products. Further research is required to optimize process performance and explore scalability and commercialization routes, ensuring future projects are economically profitable, socially acceptable, and environmentally sustainable. It may also be valuable to examine how food waste to bioenergy is correlated to sustainable food waste management, as well as the integrated biorefinery and bioeconomy. This concept offers sustainable food waste valorization with the minimum environmental consequences in a longer duration. Furthermore, improving public awareness through training, socialization, and education is critically needed to shift the socio-cultural perspectives toward food waste and its valorization.

## Conflicts of interest

The authors declare no conflict of interest.

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