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Review

Emerging technologies and sustainable strategies for municipal solid waste valorization: Challenges of circular economy implementation

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ABSTRACT

Due to an upsurge in urbanization and industrialization, huge amounts of municipal solid waste (MSW) are accumulating on our planet. Waste generation has several negative environmental repercussions, making it a topic of debate in the environmental community. In the context of the circular economy, efforts have been made worldwide to establish a systematic management approach coupled with a sustainable treatment technology to maximize the resource usage of MSW. This review systematically discusses the recent technological developments for the valorization of MSW into valuable chemicals and energy. It focuses on the circular economy concept based on the material-centric approach and highlights the sustainable processing mechanisms of MSW through chemical, biological, and thermal processes, including hybrid and integrated thermo-bio-chemical biomass waste conversion technologies. The potential economic, environmental, and health impacts of valorizing MSW material into high-value fuels and chemicals were discussed. Future perspectives and challenges in managing MSW and valorization for practical large-scale applications are also addressed. This review would be interesting for scientific and industrial communities to boost MSW management and valorization through sustainable, effective, low-cost approaches.

1. Introduction

The rising human population, urbanization, industrialization, and growing demand for consumable products to maintain society's living standards and unsustainable consumption patterns lead to the generation of a massive amount of municipal solid waste (MSW). Worldwide about 1.3–1.9 billion tons of solid waste are generated annually (Mutz et al., 2017). This amount is estimated to increase to around 3.5 billion tons by 2050. In the current total waste collection scenario, only about 11% is converted into energy, 19% is recycled, and about 70% dumped into landfills, causing many health and environmental problems (Mutz et al., 2017). Furthermore, traditional MSW management practices such as incineration and landfilling pose numerous biohazardous risks while increasing greenhouse gas (GHG) emissions contributing to climate change (Wang et al., 2017). According to Mutz et al. (2017), MSW causes a substantial socio-economic burden, and its management cost is estimated to increase by 675.5 billion dollars by 2025.

MSW valorization is an eco-friendly approach that has enabled us to realize profitable alternatives and more sustainable processes to generate high-value products, i.e., chemicals, fuels, and many other raw materials for domestic and industrial use (Kaza et al., 2018). Nevertheless, the conversion of MSW faces some limitations, such as high variation in its composition at seasonal and regional levels (Abdel-Shafy and Mansour, 2018; Velenturf et al., 2019). In addition, the high capital and operating costs remain the principal challenge facing the waste valorization process (Wong et al., 2015; Periyasamy et al., 2023; Velvizhi et al., 2022a; Velvizhi et al., 2022, making them economically

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List of abbreviations

AD	Anaerobic digestion
AOP	Advanced oxidation process
CE	Circular economy
DFF	2,5-diformyfuran
EU	European Union
FTS	Fischer-Tropsch synthesis
GHG	greenhouse gas
HMF	Hydroxymethylfurfural
HTC	Hydrothermal carbonization
HTL	Hydrothermal liquefaction
LCA	Life cycle assessment
MEC	Microbial electrolysis cells
MSW	Municipal solid waste
OFMSW	Organic Fraction of Municipal Solid Waste
PFS	Process flow sheet simulation
RDF	Refuse-derived fuel
SWM	Solid waste management
TM	Territorial Metabolism
UNCTAD	United Nations Conference on Trade and Development
US-UWet	Ultrasonic-assisted wet
VB	Valence band
VS	Volatile solid

unattractive. To counterbalance the technological and economic issues, the scientific and industrial communities have made many efforts to make the whole process more sustainable by developing novel, innovative, cost-efficient waste valorization processes (Saravanan et al., 2023; Reis et al., 2023; Kumar et al., 2023).

Worldwide, extensive research is being conducted to convert MSW into fuel and valuable chemicals by thermal and biochemical processes (Awasthi et al., 2022). Overall, MSW valorization integrates a cascading approach to increase productivity and innovation toward a circular economy (CE). This allows the progress towards sustainable goods and services to be produced to meet the ever-increasing demand, troubling and altering the environment (Patwa et al., 2021). CE principles minimize waste and pollution, maximize material use, and regenerate natural systems (Michelini et al., 2017). Although CE is broadly acknowledged to encourage reducing, reuse, and recycling (3 R) MSW and generating various chemicals and fuels that have high applications for synthesizing organic acids and enzymes, they have generally higher economic value than conventional production methods (Malinauskaite et al., 2017; Rada et al., 2017). However, the recycling and conversion of MSW into high-value chemicals and fuels face various challenges. Higher moisture content and Lower energy density lead to increasing elements such as chlorine, sulfur, and nitrogen, and higher energy input are one of the potential obstacles when building a viable and sustainable MSW disposal and treatment system. These characteristics result in higher operating expenses and a lack of economic feasibility and hence must be carefully evaluated (Beyene et al., 2018; Cimpan et al., 2015).

The review provides insight into the technological developments for the valorization of MSW into valuable chemicals and energy, particularly the chemical, biological, and thermal processes and hybrid and integrated thermo-bio-chemical biomass waste conversion technologies. It also discusses the economic, environmental, and health impacts of valorizing MSW material. Finally, it presents future perspectives and challenges in managing MSW and valorization for practical large-scale applications.

2. Trends in global MSW generation, associated problems, and opportunities

Over the last decades, the MSW generation has increased massively due to the huge industrial and agricultural activities. The projected Global waste generation per person per day varies from 0.11 to 4.54 kg, with high-income countries generating 34%, or 683 million metric tons (Di Bella and Vaccari, 2014). By 2050, global waste is expected to reach 3.40 billion metric tons, doubling population growth, as shown in Fig. 1 (Kaza et al., 2018). High-income countries are projected to increase daily per capita waste generation by 19% by 2050, while low- and middle-income countries are expected to increase by 40% or more. Low-income countries are expected to generate more than three times more waste by 2050. The East Asia and Pacific regions generate the most waste, while the Middle East and North Africa regions produce the least

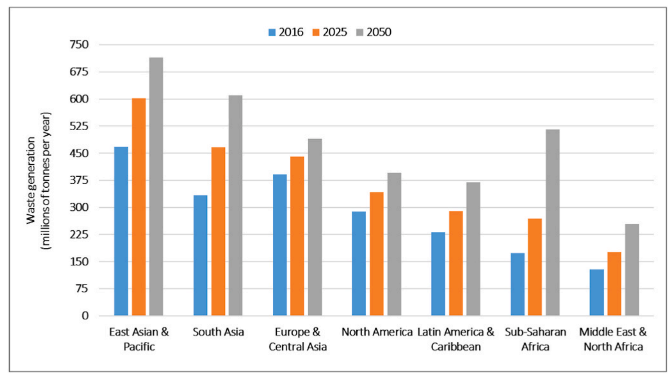

Fig. 1. Projected waste generation (millions of tonnes/years) by various regions from 2016 to 2050 adapted from (Kaza et al., 2018).

(Kaza et al., 2018).

The global waste challenge report highlights that the world generates 2.01 billion metric tons of municipal solid waste annually, with 33% not managed environmentally safely. MSW consists of 40% bio-waste, 40% recyclable content, 10% bulky goods, and 10% other types (Zabaleta et al., 2017). Rapid waste growth in Sub-Saharan Africa, South Asia, the Middle East, and North Africa is crucial for environmental health and prosperity (Kaza et al., 2018). Over half of the waste is currently openly dumped, and the accumulation of MSW contributes to air, water, and soil pollution, leading to various diseases like cholera, tuberculosis, pneumonia, tetanus, diarrhea, and whooping cough (Kaza et al., 2018; Zurbrügg et al., 2014; Villa et al., 2018).

Open dumping and burning of MSW have become a serious concern due to the elevated emissions of GHGs and are contributing to global warming (Maria et al., 2020). According to Manfredi et al. (2009), GHG emissions from landfill disposal sites were estimated at around 1000 kg CO_2-eq. t^{-1} from open waste dumping, 300 kg CO_2-eq. t^{-1} from a conventional landfill, and 70 kg CO_2-eq. t^{-1} from engineered landfill sites. It indicates that an open dump causes 50 times higher GWP than carbon-engineered landfills. Another problem associated with MSW is the limitation of the available area for disposal.

Over the decades, MSW management, recycling, and valorization have been neglected, and waste incineration has been used widely to reduce the amount of MSW in the environment. However, recently, due to the high cost of products and large consumption, the approach of valorization of MSW into valuable low-cost products, chemicals, energy, and fertilizers has been raised, and many scientific and industrial efforts have been reported (Malinauskaite et al., 2017). Nowadays, MSW valorization has become a vital part of the economy in many countries. An example of MSW conversion to produce high-value chemicals, energy, and fertilizers is shown in Fig. 2.

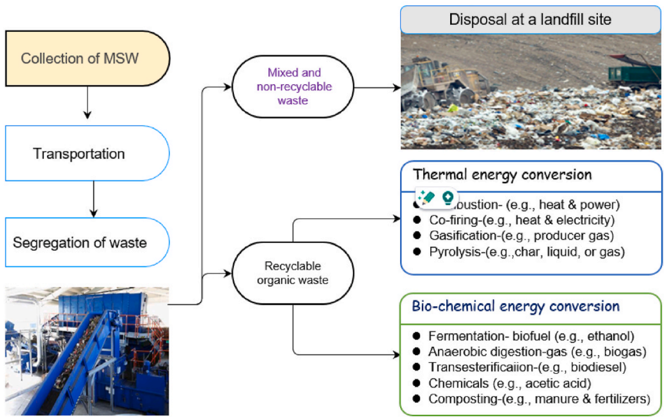

Fig. 2. MSW conversion to produce high-value chemicals, energy, and fertilizers.

3. The role of MSW utilization for circular economy

MSW is used as a raw material source for the circular economy context, getting more attention promoted by policymakers, scientists, and business communities worldwide (Malinauskaite et al., 2017). The circular economy context emphasizes a closed cycle for waste utilization and reduces resource use compared with the recycling practice, as shown in Fig. 3 (Nizami et al., 2017). According to the European Union legislation proposal on waste management and recycling published in 2018, only 43% of the MSW can be recycled, 31% goes to the landfill, and 26% goes to incineration (Eurpean commsion Plan, 2018). Therefore, the transformation of MSW into high fuels and chemicals can be an alternative solution to incineration and landfilling and can be used as a primary raw material in the CE strategy (Eurpean commsion Plan, 2018).

In this sense, it is recommended to produce diverse products with respect to the circular economy context without wasting the initial stage and convert MSW into valuable chemicals and fuels.

Because a significant amount of the organic MSW fractions is linked to environmental impacts, developing countries must integrate environmental protection with the results of the life cycle assessment (LCA) study into composting and recycling. These waste management methods are less technologically sophisticated, easier to implement, and require fewer investments (Ikhlayel, 2018). LCA principles align with the current emerging research area's circular economy concept. It must include three parts in the definition of the circular economy. These are considered ways to recover value from waste: (i) re-circulation of resources and energy, (ii) assessing the innovation introduced within society, and (iii) implementing the multi-level approach. These principles are embedded in China and European Union (EU) countries. These principles are still in the initial stages in developing countries because they need large incentives to establish SWM in urban areas (Geissdoerfer et al., 2017; Ilić and Nikolić, 2016). The circular economy context pattern should be introduced in developing countries focusing on multi-level approaches such as financial sustainability, energy recovery, fuels, and chemical options. More research must be done to develop a long-term solution and find the right technology to help the circular economy grow.

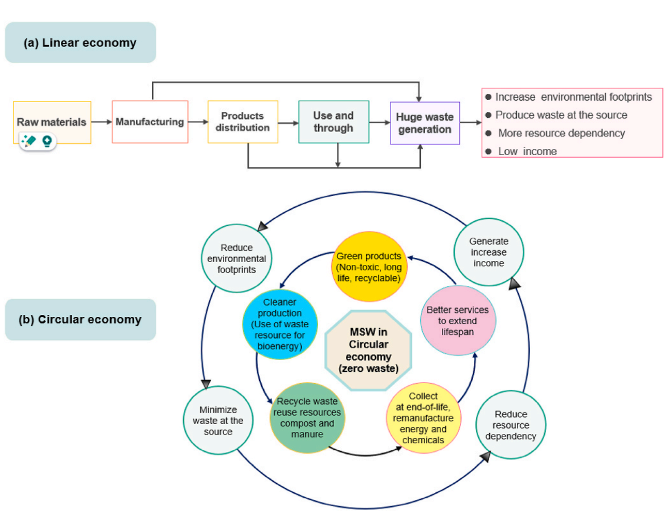

Fig. 3. Graphic representation difference between circular and linear economies.

4. Processing of MSW

The valorization processing of MSW into chemicals and fuels can be achieved by different means (Bosmans et al., 2013; Corton et al., 2016; Peng and Pivato, 2019; Prasad et al., 2020; Vaneeckhaute et al., 2017), and their cons and pros are summarized in Table 1.

4.1. Biochemical processing of MSW

Biological processes to convert MSW materials into high-value chemicals and fuels such as ethanol, methane, and hydrogen using specialized bacteria and yeast is considered promising and eco-friendly option (Ambaye et al., 2021b; Zhang et al., 2013). An example of MSW conversion to produce high-value chemicals, energy, and fertilizers is shown in Fig. 4.

4.1.1. Anaerobic digestion (AD) in the circular economy context

Anaerobic digestion (AD) is a biological method that converts organic materials into valuable gaseous fuels and chemicals. AD process involves many activities of a consortium of different anaerobic bacterial species, such as hydrolytic, acid-forming, acetogenic (e.g., *Acetivibrio*, *Clostridium*, *Bacteroides*, *Ruminococcus)* species and methanogenic (e.g., *Methanobacterium, Methanococcus,* and *Methanospirillum*) species, which produce biogas, a mixture of CH_4 and CO_2. In the past few decades, broad worldwide research on AD of MSW has been carried out to produce biogas (Ambaye et al., 2021a; Nitsos et al., 2015; Papurello et al., 2012).

MSW materials are characterized by having a high composition of proteins, carbohydrates, and minerals. Moreover, the particle size, the carbon to nitrogen (C: N) ratio, the water content (wet vs. dry digestion), and other factors can affect its digestibility and the production of methane and other gases (Ambaye et al., 2020; Jain et al., 2015). Takata et al. (2012) showed that about 223 m^3 of biogas could be produced from 1 ton of MSW material, and they concluded that to improve AD efficiency, several Strategies such as substrate pretreatment, co-digestion, additive supplementation, and parametric optimization (temperature, pH, etc.) have shown excellent aptitude for improving the AD conversion process.

Microorganisms that produce acid and methane are used in the AD process to break down complex organic compounds. The physiological growth rates and susceptibility to different process conditions differ between these two categories of bacteria. The problems in maintaining a population balance among microbes may eventually cause the AD system to fail. The refractory nature of lignocellulosic biomass and difficult-to-digest feedstock are to blame for low product (methane) output during AD. Various pretreatment procedures have been examined to boost biodegradability and methane output (Ambaye et al., 2020).

A recent report by the European Commission in 2018 showed that combinations of factors such as pretreatment and thermophilic processes with AD could increase biogas production by 10–20% (European Commission, 2018). It can also help lower the emissions of GHG by 30% and the valorization of MSW by up to 75% (Zhou et al., 2016;

Table 1
Major technologies for the conversion of waste into high-value chemicals and energy.

Technology	Products	Advantages	Disadvantages	Reference
Combustion	Oxidized products, Often gaseous products, Smoked	Sorting of waste is not required, Required less maintenance, The Refuse-derived fuel (RDF) version is more effective	High fuel consumption, The need for feed water, The need for steam infrastructure, The need to manage air pollution, and the requirement to pre-process or shred MSW	Marsh (2016)
Gasification	Gaseous energy product syngas, Consisting of H_2 and (CO) with lesser quantities of hydrocarbons, CO_2, H_2O, CH_4, N_2	Generating fuel, gas, or oil for use in a variety of applications Prefers sorted and homogenous feedstock. Little to no air pollution	Technologies that are still developing, rigid, and less competitive pose a high risk of failure, Need pre-processing and sorting. Demands a lot of maintenance. The majority of large-scale operations do not occur everywhere	Chan et al. (2019)
Plasma Gasification	Produce high-quality syngas with a high content of CO and $H_2$and minimum presence of CO_2, H_2O, CH_4, N_2, and hydrocarbons	High-temperature gasification technology decomposes waste without releasing toxic substances like Dioxin and Furan, with smaller NOx, SOx, and CO_2 content due to plasma reactors' unique structure, High temperatures cause the lowest ash and dust content due to the decomposition and gasification of C and H	Waste must be shredded (size 100 mm) for better gasification; Plasma torches consume a lot of electrical energy, A higher rate of investment results in a longer payback time than other technologies	He et al. (2009)
Pyrolysis	Biochar, bio-oil, and gases, including CH_4, H_2, CO, and CO_2.	Limiting the supply of external fuel is possible by utilizing the generated gases as fuel. Reduce MSW volume by 50–90%	The high viscosity of pyrolysis, High cost of operation, maintenance, and capital, Its application for MSW is undergoing, Sorting and pre-processing of waste are required. Waste post-processing is required	Grycová et al. (2016)
Anaerobic digestion (<ADB></B>)	CH_4 called biogas and digested slurry as manure	Recycles waste to renewable energy; lower operating costs; reduces odour from waste products	Need expert people to design at a massive scale, sometimes public objects to AD plants	Yasin et al. (2019)
Fermentation	Bioethanol and other valuable chemicals.	Very useful for waste containing fermentable sugars into energy	high inhibitory chemical furfural: need expensive enzymes that make it costliest	Kumar et al. (2023)

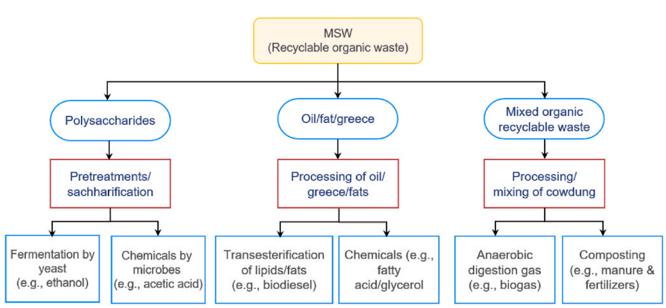

Fig. 4. Bio-chemical conversion of MSW to produce high-value chemicals, energy, and fertilizers.

Zhongming et al., 2021). This approach has opened a new chapter for establishing and developing advanced biotechnological and biochemical biogas-based products such as biomaterials and biofuels, further increasing the valorization of MSW residues (Bolzonella et al., 2018). More research must be carried out in the future to develop innovative and sustainable technological options that can integrate AD with new emerging technologies such as microbial electrolysis cells (MEC) and two-phase AD processes by including geographical and seasonal waste distribution (Gontard et al., 2018; Rasapoor et al., 2020).

4.1.2. Bioethanol and valuable chemicals production via fermentation of MSW

Bioethanol and other valuable chemicals production from biodegradable fractions of MSW rely on consecutive stages such as pretreatment/hydrolysis and fermentation (Matsakas et al., 2014; Prasad et al., 2018; Ambaye et al., 2021a). Conversion of biodegradable (polysaccharides) fractions into soluble sugars through pretreatment/hydrolysis is crucial. Hydrolysis of polysaccharides in MSW can be performed using acid or alkali pretreatment or enzymatic hydrolysis. Pretreatment using acidic or alkali is fast and cheap, but it can convert the sugars into another unwanted form, i.e., furfural and Hydroxymethylfurfural (HMF) (Prasad et al., 2018; Ravindran and Jaiswal, 2016). At the same time, the enzymatic hydrolysis process is expensive and slow. Nevertheless, it does not produce unwanted products because the disruption of cells can occur before hydrolysis and enhance efficiency. It can yield 10–15% of crude alcohol when further distilled. It can produce other products such as butanol, methanol, etc. (Wang et al., 2016). Reaming solid residues can be transformed into high-value products using gasification and liquefaction (Carrere et al., 2016).

Ethanol yield depends on the type of organic waste in MSW, pretreatment methods, fermentation techniques, and many other factors. Man et al. (2009) achieved 0.32 g ethanol/g reducing sugar, demonstrating the potential of Korean food waste leachate as a biomass resource for ethanol production. Matsakas et al. (2014) utilized household food waste (MSW) and achieved 107.58 g ethanol yield/kg dry MSW by subjecting the remaining solids after fermentation to a hydrothermal pretreatment. Zahara et al. (2021) also achieved 25 g/L of ethanol per 100 g/L of food using *Saccharomyces cerevisiae* fermentation. They further enhanced ethanol yield by 13.16% through hydrothermal pretreatment. Huang et al. (2015) used vacuum fermentation and conventional fermentation and achieved ethanol yields of 358 g/kg and 327 g/kg, respectively, from food waste on a dry basis. Favela-Torres et al. (2023) conducted a study using enzymatically pre-treated food waste and obtained 188 L of ethanol from one ton of waste (148.33 g ethanol/kg DM) on a pilot scale fermentation. Chen et al. (2021) used leftover cooked rice and achieved 0.31 and 0.43 g ethanol/g of leftover waste from simultaneous saccharification & fermentation (SSF) and separate hydrolysis and fermentation (SHF), respectively.

High-building chemicals blocks include 2,5-furan dicarboxylic acid, glycerol, 3-hydroxy butyrolactone, xylitol/arabinitol, diacids (fumaric, malic, and succinic), glucaric acid, aspartic acid, glutamic acid, and levulinic acid can also be produced from sugars generated biodegradable fractions of MSW. Among these bio-based chemicals, the production of succinic acid increases dramatically in the market because this chemical can be used as a raw material in different applications (57%), food and beverages (13%), and pharmaceuticals (16%) as well. Moreover, it can replace high-value chemical products like maleic anhydride, adipic acid, and phthalic anhydride (Nanni et al., 2021).

For years, succinic acid was produced from the petrochemical oxidation of butane. However, succinic acid production from a bio-based resource like MSW is economically attractive and might meet the demand of the world market with a 2020 volume of 710 kilotons. Currently, the production of succinic acid from bio-based is still deficient because most of the production is conducted using pure substrate rather than mixed MSW and genetically modified strains for the fermentation of succinic acid (Li and Mupondwa, 2021). In this respect, further research is recommended to investigate and improve the microbial strains' efficiency and processing to produce high-value chemicals with a higher yield. Meanwhile, the microbial production of succinic acid should be adapted to the different inhibitors from MSW using genetically and metabolically modified yeast (Menon and Lyng, 2021).

4.2. Thermal processing of MSW

Thermal processing of MSW into high-value fuels and valuable products through torrefaction, gasification, and pyrolysis is shown in Fig. 5. Compared with the biochemical conversion process, the thermal process, operating at high temperatures, can lead to a high conversion energy rate (Martinez et al., 2021). In addition, this process converts different types of MSW material into residuals of unsorted waste with high energy potential (Paukov et al., 2019).

4.2.1. Gasification

Gasification is one of the essential thermochemical routes to producing syngas from MSW. It is operated at a temperature range of 800–1200 °C in the presence of CO_2 or steam as a gasification agent with a lower oxygen supply (Motta et al., 2018; Parvez et al., 2020; Siwal et al., 2020). This process efficiently converts MSW-containing carbon-based material into syngas and co-products such as CH_4 and CO_2, slag, bottom ash, and some impurities other than the syngas. However, it produces harmful substances such as alkaline compounds, SO_2, halogens, and tars, which can cause technical problems during installation. These toxic substances generate severe environmental and health problems compared with steam gasification (Jahangiri et al., 2021; Pieta et al., 2018).

The syngas produced from the gasification process can generate heat

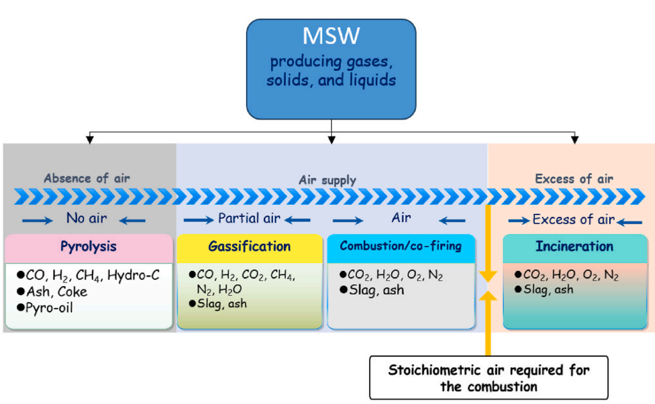

Fig. 5. Thermal processing of MSW into fuels and other valuable products.

and electricity for cities. It can also be used as a raw material to produce high-value chemicals and fuels (Liu et al., 2017). MSW gasification in terms of energy was studied by Ibikunle et al. (2021) in Nigeria, who found that 280 tonnes/day of MSW with a low heating value of 19 MJ kg^{-1} could generate 1478 MWh heat and 18 MW electrical energy. MSW gasification for maximum char yield and optimal conversion has been achieved at an equivalence ratio (ER) of 0.25–0.35 (Seo et al., 2018). High temperatures enhanced gasification performance and hydrogen-rich syngas production (Zhao et al., 2014).

Some challenges are limited to applying it at a larger scale. One of the main challenges is the creation of tar, which leads to corrosion, fouling, blocking, and production of different syngas CO ratios such as H_2 and gives a low performance in the conversion of the MSW into syngas (Akhlisah et al., 2021; Mendiara et al., 2018). Carpenter et al. (2010) reported that using MSW-derived material could produce high-yield syngas with a low formation of tar gas using downstream and catalytic gasification processes. Han and Kim. (2008) also reported similar results using catalytic decomposition to reduce the formation of tar and other organics emitted from the raw gas. They also increased the syngas performance by reforming methane and separation efficiency before cooling and removing other gas impurities. Giuliano et al. (2020) reported that converting the MSW materials into syngas must follow two necessary sequential processes for effective production. The first is converting MSW materials into char and other volatile gases through the pyrolysis process below 900 °C. The second sequential process uses pure air and high pressure, which leads to the production of pure oxygen and a mixture of H_2 and CO with no nitrogen. This integrated pyrolysis process with gasification is less cost-effective and highly applicable for selected wastes. Due to higher landfilling fees, diversification in power generation, and limited environmental regulation, researchers and policymakers have now paid more attention to developing a sustainable gasification process such as plasma that solves the problems mentioned earlier (Ooi et al., 2021).

Plasma gasification is a process that converts MSW material into high-value substances and energy. It produces syngas and electricity more efficiently than conventional gasification (Perkins, 2020). Low gas emissions characterize this process. It necessitates a large investment due to the high operating temperatures required to produce syngas and other pure slags (Higman, 2008). Similar findings were also reported by Ashok et al. (2020). They reported that the plasma process combined with heterogeneous catalyst plasma gasification is more effective in converting the MSW material into a high-value product than the plasma process. That's because the catalysis that comes with the plasma process lowers the activation energy and makes it easier for the MSW material to be turned into useful products quickly.

4.2.2. Pyrolysis

Pyrolysis is a thermal process that can convert MSW materials into chars and other gases at a temperature range of 300 °C–950 °C. These gases can be converted into other valuable products such as CH_4, H_2, CO_2, and CO (Jouhara et al., 2018; Nanda and Berruti, 2021; Veses et al., 2020). In the past few decades, many developments have been made in the characterization of products formed from pyrolysis and in enhancing the pyrolytic process's overall efficiency in producing char, oil, and other syngas from different fractions of MSW material (Hasan et al., 2021). Wang et al. (2017) reported that the products of the downstream process in fixed reactors, such as char, pyrolysis oil, and syngas, could enhance the reforming of volatile gases and lead to an increase in the production of dry syngas, energy content, decreased moisture content, and molecular weight of the pyrolysis oil of about 40%. Another study conducted by Bhatt et al. (2021) shows that for the effective and controlled conversion of MSW materials through a pyrolysis process, the composition of the MSW material must be consistent, which needs integration with pre-processed steps such as sorting and processing of the MSW.

Thermal processing is a promising technology for converting MSW materials into high-value chemicals and fuels. However, there are still some challenges; these are (i) the durability of the catalyst, (ii) emissions of harmful gases such as H_2S, HCl, SO_2, and other hydrocarbons, (iii) the cleaning of the products gases, tars, and ash. There is a need to carry out more research to develop innovative technologies (Munir et al., 2019). The issues related to catalyst durability, tars, and ash cleaning must be improved through advanced designs. Current MSW incineration plants combined with selective catalytic converters help control NOx and SOx pollution in a circular economy context. To increase recycling in a circular economy, pre-processing and after-processing of MSW must be increased (Gilbert et al., 2009; Yan et al., 2018).

To produce gaseous, liquid, and solid fuels, biological and thermochemical conversion pathways are viable options. Due to their separate limits, however, process integration approaches are necessary. Hence, an integrated biorefinery could help economic viability and resource recovery.

4.3. Advanced oxidation processes (AOPs) for MSW treatment

Several heterogeneous and homogenous AOPs have been employed to treat landfill leachates. The efficacy of these processes depends on their setup complexity, cost, degradation rates of the recalcitrant pollutants, sustainability, and environmental friendliness. Several emerging AOPs technologies for MSW valorization, such as photocatalysis, Fenton, and ultrasound, are reviewed and presented in a subsequent section.

4.3.1. Photocatalysis

Photocatalysis is a light-driven chemical process that utilizes oxidation and reduction reactions via the generation of electron-hole pairs on the surface of a solid photocatalyst (Rtimi, 2017; Hassani et al., 2023). Photocatalytic biomass valorization has received substantial attention because of its excellent, efficient, green alternative route over conventional methods for biomass transformation into valuable products (Chauhan et al., 2022; Hassani et al., 2021; Mamba et al., 2022). Furthermore, photocatalytic biomass reforming is desirable due to the ambient operating conditions and the potential to utilize renewable energy (e.g., solar) with a wide variety of biomass resources (Skillen et al., 2022). Studies on photocatalysis using ZnO, Fe_2O_3, SnO_2, TiO_2, CeO_2, WO_3, CdS, and MoO_3 have been reported in the literature (de Assis et al., 2021; Mamba et al., 2018; Dileepkumar et al., 2022). TiO_2 is the most studied semiconductor due to its high stability, low cost, and low toxicity (Zeghioud et al., 2018). Many studies have been devoted to TiO_2-based photocatalytic biomass valorization producing fine chemicals like furfurals, methyl furfural, vanillin, furanic and aromatic alcohols (Wu et al., 2020).

Photocatalysis deployed for biomass conversion via photo-reforming showed that the carbon chains of compounds such as starch, sugar, and cellulose were oxidized via direct oxidation at the valence band (VB) of the photocatalyst, which subsequently generated CO_2 and protons. Electrons then reduce the protons at the conduction band (CB) to produce H_2 (Skillen et al., 2022). Chong et al. (2014) demonstrated the photocatalytic conversion of glucose to arabinose and erythrose in water (at 288 K) and reported 91% 65%production of arabinose and erythrose, respectively, using TiO_2 rutile. Roongraung et al. (2016) showed the photocatalytic conversion of glucose using a TiO_2 and reported that gluconic acid, arabinose, xylitol, and formic acid were 8.6, 26.0, 3.7, and 33.9%, respectively. Wu et al. (2017) synthesized WO_3/gC_3N_4 (4.7% of WO_3) and used it for photocatalytic oxidation of 5-HMF into 2,5-diformylfuran (DFF). The catalyst showed the conversion of 5-HMF (27.4%), with a DFF selectivity of 87.2%, under irradiation with visible light (>400 nm). Khan et al. (2021) showed that under visible light ($\lambda = 515$ nm), 59% of HMF conversion to DFF with 87% of selectivity by oxidation. However, photocatalytic technology for MSW valorization still faces some challenges, such as low selectivity because of the non-selective photo-produced reactive oxygen species, which may lead to oxidizing the wanted products. In addition, pretreatment approaches to dissolving MSW are still under investigation to promote mass transfer, as the photocatalyst occurs mainly on the surface of the photocatalyst.

4.3.2. Fenton process for biomass conversion

The Fenton reaction is an exothermic process at a temperature higher than the ambient temperature. It is commonly applied as a pretreatment process for wastewater, biomass, and MSW. Fenton chemistry made cellulose more bioavailable to enzymes and microbial species (Ahmadi et al., 2021). Magare et al. (2020) studied an integrated process of value addition to citrus waste and the performance of the Fenton process for its conversion to biogas. They showed that pre-treatment of leftover de-oiled biomass with 30% of Fenton's reagent treatment gives higher biogas and methane production up to 322.63 mL biogas/g VS feed and 122.48 mL methane/g VS feed, respectively, under the mesophilic condition, which is superior to conventional treatment. Zhang et al. (2022) estimated the operating cost of the Fenton oxidation process at 2.17 €/kg COD elimination, and biogas production was increased by 81% after the Fenton oxidation using wastewater. Kato et al. (2014) used solution-phase Fenton chemistry (10 g biomass, 176 mmol H_2O_2, and 1.25 mmol Fe^{2+} in 200 mL of water) for different biomass feedstocks. Enzymatic saccharification of Fenton pretreated biomass showed a 212% increase over the control. In addition, fermentation of Fenton pretreated biomass showed higher gas production. Results demonstrate that solution-phase Fenton chemistry is a viable pretreatment method to make cellulose more bioavailable for fuel and chemical conversion.

4.3.3. Ultrasound for biomass conversion

Ultrasound waves with the frequency of 10 kHz to 20 MHz combined with proper solvents allow the destruction of the recalcitrant lignocellulosic structure and components fractionation of biomass (Meroni et al., 2021). Furthermore, ultrasound energy stimulates biomass conversion through its acoustic cavitational effects. Acoustic cavitation generates micro-bubbles (cavities) in fluids that can induce chemical and physical impact and increase efficiency in the biomass valorization process. Zeng et al. (2010) observed that increased accessibility of cellulose is directly proportional to the time of ultrasound pretreatment between 0 s and 150 s. Ultrasound pretreated at 150 s with the power of 500 W significantly increased the biomass enzymatic accessibility and enhanced sugars, ethanol, and biogas yields by 10–300% (Luo et al., 2014; Zeng et al., 2010). In addition, ultrasound wave promotes esterification and transesterification in biodiesel synthesis and reduces reaction time by 50–80%, lower reaction temperature, amounts of solvent, and catalyst required in reaction systems.

4.3.4. Combined photocatalysis-ultrasound processes for biomass conversion

The combined use of sonochemistry (ultrasound power) and photocatalysis (light irradiation), called sonophotocatalysis, is an advanced oxidation process (AOP) that recently found innovative applications in organic compounds reactions and biomass conversion (lignin, chitosan, etc.) in high-added-value intermediates. Sonophotocatalysis starts to be applied to organic pollutants degradation and could represent an innovative way to valorize biomass into fuels or platform molecules (Chatel et al., 2017). In addition, Sonophotocatalysis can produce a synergistically high yield of reactive oxygen species (breakdown of water molecules by cavitation effect and oxidation/reduction of water or oxygen by e^-/h^+ pairs).

On the other hand, ultrasonic waves can enhance the mass transfer in the medium through their physical effect. On top of that, the cavitation waves can form hot spots up to 5000 °C on the surface of the photocatalyst, leading to in situ regeneration. Researchers have used sonophotocatalysis in various investigations, i.e., highly concentrated, and toxic non-biodegradable organic matter degradation (Zewde et al., 2019). Giannakoudakis et al. (2021) applied an ultrasound-assisted ultra-wet (US-UWet) impregnation synthetic approach using TiO_2–CuOx, to report high efficiency for biomass-derived model platform chemicals/building blocks, 5-HMF, and benzyl alcohol to value-added chemicals 2,5-diformylfuran and benzyl aldehyde, respectively. It is essential to mention that ultrasonic waves can improve mass transfer in terms of photocatalytic biomass conversion or/and allow the use of water as a green solvent instead of harmful organic solvents.

In many cases, the presence of organic solvents inhibits the accurate conversion of biomass because they might play the role of the hole or reactive oxygen species scavenger. In addition, by-products produced from the oxidation of organic solvents and side reactions (between solvent and wanted biomass products) may lead to lower product quality. Table 2 summarizes the different chemical, biological, and thermal processes, as well as hybrid and integrated thermo-bio-chemical conversion technologies, that can be used to valorize MSW into high-value chemicals and fuels. This table also details the type of Feedstock, type of MSW source treated, type of treatment used, type of chemical or fuel produced, and their yield as reported in the literature. Carbohydrate-rich material results in higher yields, whereas protein-rich material and fats result in significantly lower yields in the production of methane and hydrogen; moreover, the utilization of the organic fraction of municipal solid waste as a renewable feedstock and its biological conversion into biofuels and/or value-added chemicals render the organic fraction of municipal solid waste management sustainable.

5. Hybrid/integrated thermo-chemical and biological conversion

Hybrid/integrated thermo-bio-chemical process conversions have been recently proposed as a new concept. Many processes have combined AD with thermal processes to improve biomass energy recovery (Monlau et al., 2015). In a study with an AD process, pyrolysis increased electricity returns by 42%, with €1168 per day of extra income (Monlau et al., 2015). Liang et al. (2015) studied bio-oil production by biomass pretreatment before pyrolysis. They reported significant improvements in pyrolytic oils and biochar quality. Opatokun et al. (2016) performed pyrolysis of raw food waste with the AD process and reported improvement in 7.4 wt % biogas and 60.3 wt% bio-oil yields. Yang et al. (2020) presented a novel approach that integrates AD, pyrolysis, and syngas processes to maximize energy recovery from food waste. A recent analysis showed that pyro-liquid oil obtained from pyrolysis could be recycled through the integrated AD-pyrolysis process. Also, biochar produced from the integrated AD-pyrolysis process could be a source of plant nutrients (Fagbohungbe et al., 2017). The pyro gas fuel that comes from pyrolysis or combustion must make sure that the process meets very strict emission regulations (Couto et al., 2020).

Combining hydrothermal liquefaction (HTL) and AD processes can improve the recovery of valuable liquid fuels from biomass waste. Hoffmann et al. (2013) presented a conceptual design to integrate AD with HTL using animal waste and reported high-quality diesel fuel with a heating value of 43.1 MJ kg^{-1} with energy recovery in the range of 62–84% by the integrated plant. In another experiment, Eboibi et al. (2015) combined the AD and HTL processes and reported 3.9–22.6 m^3/kg VS biogas generation and 20–42 wt% bio-crude yields. Zhou et al. (2015) combined AD and post-HTL processes by adding activated carbon and reported 53% energy recovery, with 500 mL/g biogas yield during wastewater digestion. Fernandez et al. (2018) used the algae Tetraselmis and Chlorella to combine a semi-continuous AD process with HTL, yielding 327 mL/g VS and 263 mL/g VS methane yields, respectively. Parmar and Ross (2019) performed a study by integrating AD with HTC for sewage sludge valorization at temperature ranges of 180–250 °C and reported a high heating value for the biochar. Zhang et al. (2018) compared the fuel properties of HTC-derived biochar and AD process-created corn stalk digestate. They reported that cornstalk digestate has a lower combustion rate than digestate-derived biochar.

HTL and fermentation also reported a promising technology to produce crude oil-like petroleum (Watson et al., 2020), which has many economic and environmental benefits. Ponnusamy et al. (2014) conducted an LCA study and reported that 0.6 kg of CO_2 was saved for every 1 kg of biodiesel produced integrated with the AD of the HTL process. Zhu et al. (2019) analyzed the economic viability of HTL gasification and the AD process. They reported that an integrated approach would require substantial financial and operating costs. Kassem et al. (2020) examined the techno-economic assessment of integrated AD and HTL processes to valorize dairy waste effluents and an estimated 22 million MJ of natural gas annually. Medina-Martos et al. (2020) reported that combining HTC with the AD process has a 14% increased energy efficiency with a treatment cost of €66.2 per ton of sewage sludge compared with HTC + AD (€94.3). Xiao et al. (2020) studied microalgae integrated solar-driven thermal treatment and AD process economics. As a result, they reported fewer greenhouse gas emissions and lower energy costs in biogas production. Benalcázar et al. (2017) demonstrated that hybrid gasification–syngas fermentation produces less CO_2 and has lower financial requirements than fossil fuels.

The various integrated processes for converting MSW into high quantities of chemicals and fuels appear to be highly promising from both an economic and technical standpoint. As a result, more research and investigation are needed in the future to understand the composition of waste biomass, microorganism behaviour, experimental approaches, and simulation, as well as machine learning models for process prediction, optimization, controlling, and real-time monitoring of product quality and yield during hybrid processes.

6. Environmental and economic sustainability of MSW valorization

As previously stated, the growing population, increased urbanization, and a faster-growing global economy generated a massive amount of waste. Its unsafe disposal has created a major global environmental issue. The disposal of waste also needs large spaces for landfilling. There are several negative impacts associated with landfill sites. The most critical environmental problems with landfills are toxins formation, greenhouse gas emissions, and leachate from the MSW dumping ground (Vaccari et al., 2019). Landfill sites are closer to residential areas, raising health concerns among residents. These problems can be overcome by taking advantage of waste management by converting it into high-grade fuels, gas, and chemicals using a cascade approach within a circular economy context. In order to ensure the economic sustainability of the valorization of MSW, the analysis of their techno-economic potential and the life cycle assessment (LCA) based on modeling and simulation studies must be considered during the valorization of MSW plants for a circular economy in determining their technical feasibility. Modeling and simulation studies can also be applied to compare results for various energy production systems. Simulation-based life cycle assessment (LCA) studies can significantly reduce the environmental impact (Corrado and Sala, 2018).

6.1. Life cycle assessment (LCA) of waste valorization

Life Cycle Assessment (LCA) is an international standard methodology (ISO 14040, 2006) that can be used for assessing the environmental impact of different processes, products, and service life cycles (ISO, 2006). This approach also applies to other products, consisting of three stages. The first stage is conducting an inventory related to material and energy inputs and environmental releases. The second stage calculates the environmental impact potential of the identified release and inputs. The final step is to interpret the result for decision-making, and that can be mainly applied to evaluating the environmental impact of MSW technologies and energy recovered, which includes pyrolysis, anaerobic digestion, gasification, incineration, and the landfill (Bernstad and la Cour Jansen, 2012; Cherubini et al., 2009; Khandelwal et al., 2019). Besides its many advantages, the LCA methodology has some

Table 2
Conversion of MSW into high-value chemicals and fuels through different emerging technologies.

Feedstock	Type of MSW source	Type of treatment	Type of chemical/fuel produced	Yield	Reference
Leather processing sludge	Sludge	Acidification and ultrasonic bath	Biodiesel	34.5	Kech et al. (2018)
	Sludge	Transesterification	Biodiesel	8.1	Choi et al. (2014)
	Municipal sludge	Acidification	Biodiesel	90	Olkiewicz et al. (2016)
	Mixed sludge	SO_4^{2-}/Al_2O_3–SnO_2 catalyst	Biodiesel	73.3	Wang et al. (2020)
Municipal solid waste	Food waste from different sources	Anaerobic digestion	Methane	300–570 ($mLCH_4/g$ VS)	Davidsson et al. (2007)
	Organic fractions of MSW (OFMSW) rich in paper waste	Anaerobic digestion co-digestion with cow manure	Methane	172	Macias-Corral et al. (2008)
	Fruit waste by incorporating additives such as sewage sludge biochar	Anaerobic digestion incorporating sewage sludge biochar	Methane	285.7	Ambaye et al. (2020)
	Industrial kitchen waste	Anaerobic digestion pretreatment with pressurize-depressurize	Methane	520	Ma et al. (2011)
	MSW from yard	Anaerobic digestion co-digestion with domestic sewage	Methane	360	Elango et al. (2007)
	Food waste co-digestion with lipids	Anaerobic digestion	Biomethane	3.55 L $L^{-1}d^{-1}$	Ren et al. (2022)
	Waste peanut crisps and cereals	Pyrolysis (750–800 °C)	Hydrogen	66 (%)	Grycová et al. (2016)
	Municipal solid waste	Pyrolysis (600–900 °C)	Hydrogen	18.3–22.4%	Luo et al. (2010)
	Pinewood	Pyrolysis (310–450 °C)	Bio-oil	5–90%	Remón et al. (2016)
	Polypropylene waste	Pyrolysis (450–600 °C)	Liquid product under atmospheric and vacuum condition	81–93%	Parku et al. (2020)
	Rice husk	Torrefaction (250–300 °C)	Solid fuel	50–80% mass yield	Thengane et al. (2020)
	Yard waste	Torrefaction (170–300 °C)	Solid fuel	88.5–62.3%	Jaideep et al. (2021)
	Lignocellulosic biomass	Torrefaction (200–500 °C)	Aromatic carbon	60%	Park et al. (2013)
	Food waste, leaf litter, fruit waste, non-recycled plastic, and vegetable waste	Torrefaction (150–225 °C)	Solid fuel	82.8–61.4%	Triyono et al. (2019)
	wood chips and Wood pellets	Gasification (800 °C)	CO	18.8%	Bandara et al. (2021)
	Softwood pellets	Gasification (700–800 °C)	Hydrogen	36.5%	Von berg et al. (2021)
	Coconut shell	Gasification (700–900 °C)	Hydrogen	9.41%	Yahaya et al. (2020)
	Palm kernel shell	Gasification (700–900 °C)	Hydrogen	9.90%	Yahaya et al. (2020)
	OFMSW	Gasification (500–900 °C)	Syngas yield	84%	Shehzad et al. (2016)
	Polyethylene terephthalate	Photocatalysis using CdS/CdOx under Visible light	Hydrogen	278.2 mmol/g	Uekert et al.(2019)
	Low-density polyethylene	Photocatalysis using ZnO under UV light	Carbon dioxide	–	Kamalian et al. (2020)
	Polyethylene terephthalate	Photocatalysis using carbon Nitride/ Nickel phosphide catalysts under solar light	Hydrogen	77.2 μmol/g	Uekert et al. (2018)
	Low-density polyethylene	Photocatalysis using polyacrylamide grafted TiO_2 under UV light	Carbon dioxide	–	Liang et al. (2013)
	Polyethylene	Photo-Fenton using $FeCl_3$, H_2O_2 under UV–Visible light	Carbon dioxide	>99%	Chow et al. (2018)
	Low-density polyethylene	Fenton using $FeCl_3$, H_2O_2(no light)	C1–C4 acids	62.4%	Chow et al. (2016)
	Polystyrene	Photo-Fenton using $FeCl_3$, H_2O_2 under UV–Visible light	Carbon dioxide	89.0%	Feng et al.(2011)
	Polyvinyl alcohol	Electrocatalysis using catalyst H_3PO_4 and external voltage = 0.55 V	Hydrogen	9.5 μmol/min	Hori et al. (2020)
	Polyvinyl chloride;	Electrocatalysis using TiO_2/graphite cathode and external voltage = −0.7 V	Carboxylic acid	75.0%	Miao et al.(2020)
	Polystyrene	Catalysis using SiO_2/Al_2O_3	Liquid oil	59.6%	Owusu et al. (2018)
	High-density polyethylene;	Catalysis using $CuCO_3$	Liquid oil	94%	Singh et al. (2018)
	Low-density polyethylene;	Catalysis using Cu@TiO_2	Liquid oil (C13–C19)	86.4%	Ukarde and Pawar (2021)
	Polyethylene	Using the catalyst of sugarcane bagasse	Bio-oil	31.5%	Baloch et al. (2020)
	Food waste	Anaerobic digestion with acidification and fermentation using *Lactobacillus*	Lactic acid	0.46 g g^{-1}	Tang et al. (2016)
	Food waste	Mesophilic fermentation using *Lactobacillus amylolyticus*	Lactic acid	0.57 g g^{-1}	Yang et al. (2022)
	The organic fraction of municipal solid waste	fermentation using *Yarrowialipolytica*	Succinic acid	54.4 g L^{-1}	Stylianou et al. (2021)
	sweet potato waste	Anaerobic digestion using *Escherichia coli*	Succinic acid	18.65 g L^{-1}	Huang et al. (2019)

drawbacks, especially during inventory.

In most LCA inventories, MSW data used is from the generic region or represents only developed countries. It is primarily used in the upscale stage and is rarely applied in the early stages of research. It is impossible to get information during the design. Therefore, there is a need to use another technological approach that solves the problems mentioned above. Corona et al., 2018 conducted a study, especially for MSW, using LCA integrated with process flow sheet simulation (PFS) for early decision support for bio-refining. The authors showed that it still needs further investigation for its validation. Another study by Vega et al. (2014) reported similar findings by comparing the environmental performance of different manure residues using LCA. Further, the LCA methodology does not evaluate the environmental performance of some long-term wastes, such as plastic pollution, under limited data.

Territorial Metabolism (TM) is another method for evaluating MSW and other agricultural residues. Kennedy et al. (2007) can quantify the energy and material flow across specific regions and cities that produce specific waste products. Goldstein et al. (2014) showed that this methodology could evaluate different agricultural residues' energy and materials flow. However, the authors reported that regardless of the provenance (urban or rural), the materials-energy balance appeared to be similar, making it hard to figure out how agricultural waste affects the environment.

A new methodology was developed by integrating LCA with TM to solve the above-mentioned problem. The investigation finding of this methodology showed that the material flow from urban and rural areas was converted into the standard of different sets of environmental impact indicators and assessed the environmental performance of MSW in any region (Balkau et al., 2021; García-Guaita et al., 2018; Ohms et al., 2019). Furthermore, Sohn et al. (2018) conducted a study to assess lifecycle-based dynamics coupled with multiple-criteria decision analysis. The authors showed that the developed multi-criteria evaluation with cross-disciplinary tools provides a suitable platform for stakeholder discussion to support solid waste management decision-making. This integrated approach was also claimed to predict and simulate MSW's future environmental performance under various scenario analyses in circular solid waste management. Therefore, applying this integrated approach in the initial stage of the MSW can enhance the innovation of the research design. In addition, it can address the sustainability pillars, such as the United Nations' environmental, social, and economic goals. However, this methodology needs more research to upgrade its performance as a tool for the decision-making process in circular solid waste management supported by geographic information system applications.

6.2. *Environmental sustainability by preserving the water quality*

Groundwater is one of the vital resources for life. Landfill and MSW dumping sites are direct leachate sources and are critical sources of water pollution if they are not appropriately collected, treated, and safely disposed of. Wastewater is discharged from sewage treatment facilities, and leachate comes from landfill sites, leading to the deterioration of the surface and groundwater quality and disturbance of aquatic habitat life, enhancing human health risk (Naveen et al., 2018; Xiang et al., 2019). Landfill leachate and sewage wastewater discharged can be prevented from infiltrating groundwater resources. The valorization of solid waste materials for the circular economy, as well as their integration with waste to energy and high-value chemicals via cascade technology, would help extend the life of groundwater resources (Johari et al., 2012).

6.3. *Environmental sustainability by mitigating GHG*

The decomposition of organic waste is the primary source of greenhouse gas (GHG) emissions. Landfills containing organic waste release a massive greenhouse gas contributing to climate change. The renewability of converting waste into energy represents an opportunity for the waste and recycling industries to mitigate climate change's impact on society (Lou and Nair, 2009). Kesieme et al. (2019) were able to produce a high value of biodiesel, which can serve as an alternative fuel with high specifications such as a high-octane number and virtually zero emissions of sulfur compounds and aromatic hydrocarbons through Fischer-Tropsch synthesis (FTS) by using by-products of the gas emitted from the incineration. The synthetic fuel, biodiesel produced from FTS, is highly compatible with engines and reduces particulate matter (PM), nitrogen oxide (NOx), and other air pollutant gases, including greenhouse gases (GHG). Technology can also produce high-quality ultra-clean fuel without these compounds (Kesieme et al., 2019). In general consideration of MSW's environmental impact, it is necessary to integrate cascade technology to reduce landfills' carbon footprint and ultimately mitigate climate change. Valorizing solid waste materials for a circular economy and incorporating them into energy can create positive economic growth and a healthy environment (Djellabi et al., 2022).

6.4. *Lowering the risk of spreading diseases and toxic compounds*

Landfill sites become home to many scavengers who carry diseases that may be spread in communities. Besides this, the water discharged from landfills can also contain harmful bacteria, viruses, and other pathogenic elements, including heavy metals, which can cause many health problems (Bhailall, 2016; Hoo et al., 2018; Khalil et al., 2019) The valorization of MSW materials is critical for reducing environmental deterioration, the risk of infection spread, and aesthetic reasons. Bhailall (2016) directed research and found that the water from landfills could be prevented from being infected by different viruses and hatching pests by integrating waste into the energy system. A byproduct of anaerobic digestion (AD) of waste to energy, also called digested slurry, can be used as fertilizer to improve soil fertility, and enhance agricultural yields.

6.5. *Techno-economic sustainability of waste valorization*

The techno-economic sustainability of waste valorization in a circular economy is part of creating wealth and jobs to promote sustainable growth. Key points of the circular economy action plan include reducing MSW, stimulating demand from economic sectors, promoting recycling, and biodegrading hazardous substances (Barros et al., 2020; Ferronato et al., 2019). Over decades, industrial production based on the linear economy has led to several environmental and economic issues. However, a circular economy-based approach can overcome such problems. The EU intends to spend 650 million on the Framework Program for Research and Innovation in the Circular Economy, with EU structural funds providing 5.5 billion for waste management. The EU has targeted the recycling of 65% of municipal waste and 75% of packaging waste by 2030 (SG, 2015). The development of the circular economy is also growing in countries like Denmark, the Netherlands, Germany, the United States, China, Japan, South Africa, India, and many parts of the world dealing with the circular economy as a whole and enthusiastically applying the principle of the 3 R s (Reduce, Reuse, Recycle) (Baker-Brown, 2019).

According to Van Fan et al. (2020), applying a circular economy to waste management systems has the potential to generate 42 €/t of processed MSW. Mabalane et al. (2021) discovered that hybrid-based anaerobic digestion and gasification of MSW for electricity generation are economically viable in South Africa. The manufacture of bioethanol from MSW using *S. cerevisiae* and Z. mobilis is very profitable, with parameters such as autoclave pretreatment, reduced enzyme usage, and greater solid loading influencing profitability (Meng et al., 2021). Vaez et al. (2021) enhanced the production of pectin, ethanol, and biogas from 1 t of orange waste, attaining a maximum yield of 244 kg of pectin, 26.5 L of ethanol, and 36 m^3 of methane.

Integrated municipal solid waste management centers are both economically and environmentally viable, with secondary product replacements offsetting environmental and economic costs (Rajendran et al., 2021). When compared to coal substitution, biogas production from MSW can save 11.8%, 18.9%, and 8.5% of the overall cost (Wang et al., 2020). Gasification and pyrolysis are the next best technology possibilities, with costs of 7 cents per KWH and 12 cents per KWH, respectively (Agaton et al., 2020). Rad et al. (2020) presented a hybrid photovoltaic, wind turbine, biogas generator, and fuel cell renewable energy system with an energy cost of 0.164–0.233 $/kWh for rural areas in northwest Iran.

Anaerobic digestion and Incineration are two processes used in facilities worldwide to process solid waste energy for fuel and energy production (Ghumra et al., 2022; Rajendran et al., 2021). However, these technologies produce low-value products and are limited in their ability to continue treatment procedures over time. A strategy is required to achieve significant changes in the MSW management structure, including goals and objectives as well as stages during system execution (Ghumra et al., 2022; Rajendran et al., 2021). WTE projects have proven to be a better waste management option, providing cleaner power, heat, and final disposal of MSW (Ghumra et al., 2022; Rajendran et al., 2021).

Because solid waste processing is seasonal and dependent on the socioeconomic classes of producers and consumers, selecting a suitable WTE technology might be problematic. Assessing the techno-economic viability of WTE developments at the national level is critical (Ghumra et al., 2022; Rajendran et al., 2021). Process simulation models for WTE technology provide for pre-feasibility and optimization assessments, which aid in design decisions (Lorenzo Llanes and Kalogirou, 2019). The Aspen Plus® process simulator is frequently used in modeling, design, optimization, sensitivity, and economic studies (Haydary, 2019).

Llanes and Kalogirou's (2019) techno-economic analysis of waste to energy in Havana discovered that the lower the moisture content and inert material, the greater the cycle efficiency. For the WTE project to be profitable, the energy price for a fixed gate fee should be between US$60 and $150 per MWh.

Bankole and Robinson (2012) discovered that an MSW plant that recovered glass, metals, and plastics and produced 26 million liters of ethanol per year would have an internal rate of return of 27% and a net reduction in greenhouse gas emissions of 137% in their study on the economic and environmental performance of bioethanol production using MSW produced in the UK.

The biobased biorefinery concept is being considered in solid waste technology assessments. Recycling and composting are the most cost-effective and environmentally friendly options. For example, Sadhukhan et al. (2016) investigated the impact of employing MSW in a biomass-based biorefinery. Various processing scenarios were examined to produce levulinic acid from organic waste. The MSW biorefinery processed 19.98–53.96 tons of MSW per hour. CO_2 emissions per hour ranged from 2.83 to 26.97tCO_2e/h. The discounted payback period ranged from 6.86 to 12.11 years, with an internal rate of return ranging from 15.47 to 24.56%. Furthermore, they claimed that a refinery strategy for levulinic acid production combined with anaerobic digestion with material recovery was the optimum alternative for processing Mauritius' MSW.

Although the emerging concept of MSW valorization into valuable sugars to produce biofuels, biochemicals, and bioenergy has merit, variations in composition, regional and seasonal availability, storage and delayed processing options, and sorting of inorganic wastes from degradable organic material are primary concerns. It is critical to evaluate technical challenges, installation costs, and the environmental effects of treatment and disposal systems when selecting the best solid waste management scheme (Ghumra et al., 2022; Rajendran et al., 2021).

Waste volume, plant capacity, utility costs, and tax and government incentives all play a role in determining the economic viability of turning MSW into high-value chemicals and fuels. The integrated and hybrid processes are considered highly profitable, as they reduce capital costs and energy utilization while providing an appropriate solution for energy recovery and waste disposal (Ghumra et al., 2022; Rajendran et al., 2021).

Despite technological and economic constraints, pre-commercial and commercial instances of thermochemical and biochemical MSW biorefineries exist worldwide (Bhaskar et al., 2020). Enerkem in Canada has developed a breakthrough technology for the thermochemical conversion of MSW to bio methanol and ethanol, whereas companies like Fulcrum Bioenergy and Velocys focus on combining gasification and the Fischer-Tropsch process to produce synthetic crudes, hydrocarbons, or diesel fuel (Bhaskar et al., 2020). IMECAL S.A. is expanding its Perseo Biorefinery in Spain, which focuses on enzymatic hydrolysis, simultaneous saccharification, fermentation, and anaerobic digestion. Bhaskar et al., 2020). Wilson Biochemical and Fiberight Limited have developed and scaled up their patented processes for producing lignocellulosic feedstocks, such as fermentable sugars and biogas (Bhaskar et al., 2020). Further R&D is required to industrialize the enzymatic hydrolysis process. These examples illustrate that thermochemical methods are more mature and commercially viable than biochemical technology in MSW biorefineries. Ghumra et al. (2022); Rajendran et al. (2021).

The increasing amount of MSW presents a tremendous challenge for their handling to minimize their environmental impact. Traditional waste management methods, such as landfills and burning, negatively impact the environment. Recycling, renewing, and reusing precious resources is vital for the circular economy. India is trying to adopt a circular economy across the manufacturing, construction, power, textile, and other industrial sectors to maximize the economic value of waste by turning it into a valuable product or energy. This approach, coupled with the minimization of waste generation, led to the development of no-waste production processes. According to the Circular Economy Mission to India (2018), it can unlock $0.5 trillion for India by 2030 (Pardo and Schweitzer, 2018). The report, led by the Ellen MacArthur Foundation and UNCTAD, focuses on the two most important keys to the Indian economy and society: employment (construction, food, agriculture, and mobility and vehicle manufacturing), and this study's findings show that adopting a circular economy pathway would bring India annual benefits of USD 624 billion in 2050 and reduce negative externalities compared with the current development path, which is equivalent to 30% of India's current GDP. It would also reduce GHG emissions, be 44% lower by 2050 than the present scenario, and congestion and pollution would fall significantly, leading to health and economic benefits for Indian citizens (Ellen Macarthur Foundation, 2016).

7. Municipal solid waste (MSW) policy and regulatory challenges

Municipal solid waste (MSW) management is a substantial international challenge, especially in developing nations. However, different policy and regulatory framework has been created worldwide. At the nationwide level, all nations have the MSW policy for eco-friendly waste management, which include recycling, reusing, and recovering energy and valuable chemicals from them. To handle the MSW-related issue, various tax and subsidy schemes are enforced worldwide. Large amounts of subsidies are provided for buying relevant instruments, which are extremely useful in decreasing the cost of MSW collection and its safe disposal. Economic research has recognized numerous combinations of these policies that can enable efficient MSW management practices (Zhao et al., 2020). Enforcing policies and programs sought to improve MSW management has been investigated in various nations. In Ethiopia, the management of MSW is distinguished by colossal waste generation and unbalanced management. The government has executed legal frameworks concentrating on waste collection, transportation, and safe disposal. However, challenges such as lack of policy enforcement, inadequate capacity, and lesser stakeholder association and cooperation restrict effective MSW management (Hirpe and Yeom, 2021). Togo has enforced policies and incentive systems to encourage waste reduction, reuse, and recycling, but challenges remain in enforcing and spreading these policies (Beguedou, 2023). Kosovo has encountered fast growth in MSW production due to population expansion and economic growth (Spahiu et al., 2021). For the effectiveness of MSW, management they have also enforced policies to address these problems. Under National Environment Policy 2006, India has several provisions for controlling various forms of environmental pollution, emphasizing efficient collection and treatment systems for MSW by its recycling and safe disposal. The government focuses on circular economy, greenhouse gas reduction, adopting LCA, and promoting waste-to-energy projects for effective MSW management. However, the implementation of MSW policies is also facing challenges related to monitoring and infrastructure (Goswami et al., 2021).

As a rapidly urbanizing country, China also encounters consequential challenges in MSW management. For example, the Healthy Cities policy in China has been evaluated by employing the Difference-in-Differences (DID) approach, which demonstrated the impact of pilot policies on domestic pollution sources and MSW management (Ma et al., 2022). China has also enforced policies and programs, such as the Municipal Solid Waste Source Separation Program, to address the issue of MSW (Zhao et al., 2020). Shanghai's compulsory MSW classification policy has been assessed using a three-stage DEA model, which showed that the policy was implemented reasonably well, with an average efficiency of 0.906 (Chu et al., 2023). Brazil, specifically the Recife Metropolitan Region, helps to meet the National Solid Waste Policy provisions (Jucá et al., 2020). MSW management encounters policy and regulatory challenges globally. However, nations enforce various policies and programs to manage these challenges and enhance the MSW management system. Stakeholder engagement, proper waste collection system, best waste disposal practices, and the enactment of legal frameworks are essential for adequate MSW control. The enactment of policies and programs to enhance MSW management has been investigated in various countries, underlining challenges and practical solutions. Evaluating the efficacy of MSW management policies provides insights for policymakers to take the right decision at national levels.

8. The challenges in adopting a circular economy and future perspective

The current MSW management practices for both high-income countries and other countries share similar distributions dominated by landfill disposal, and adopting a circular economy can reduce waste, minimize the continent's heavy dependence on imports of raw materials, and achieve sustainable goals. The European Economic Area also draws attention to the benefits and challenges of such an economic transition. However, the valorization and recycling of MSW materials have a significant advantage in producing high-quality chemicals, fuels, energy, and environmental protection. The recycling and conversion of MSW into high-value chemicals and fuels through the cascade process depends on the complete separation and collection of biodegradable waste, recycling, and recovery of different types of MSW. Determining the exact composition of municipal solid waste still poses a challenge and needs a sustainable, effective solid waste management system to be applied on a large scale. The following research areas should be carried out in the future.

One of the approaches is that it can be used in integrated pretreatment with the biological process in real conditions. Integrating the pretreatment process with biological anaerobic digestion demands higher operational capital than adequate fuel and chemical returns (Budde et al., 2016). Researchers have compared the energy requirements for pretreatment processes such as ultrasound, milling, and grinding on methane production. They have shown that the pretreatment process demands more energy than the yield production of methane (Barakat et al., 2014; Dumas et al., 2015).

Carrere et al. (2016) conducted trial experiments to enhance biogas production by applying chemical pretreatment. They found that chemical pretreatment can increase methane production with less energy than without pretreatment. Using chemical pretreatment can lead to hazardous chemical formations such as phenolics and furans, inhibiting biological activities and decreasing methane yield. Wang et al. (2016) studied the effect of enzymatic pretreatment on methane production from MSW and found a significant enhancement in methane production. Therefore, it concluded that it could be used as an alternative process for biological pretreatment. In general, all the pretreatment processes can be integrated with the various biological and thermal conversions of MSW into high-value chemicals and fuels, but it needs further investigation of its cost-benefit analysis to be applied on a larger scale.

Another point to be considered when converting MSW to high-value energy is the adsorption of CO_2 and H_2S to produce a high methane content (>90% CH_4) using low inputs (Ambaye et al., 2021b; Angelidaki et al., 2018; Nizami et al., 2017a). These studies claimed that integrating AD with scrubbing materials such as water and silica gel could upgrade the methane content by about 95%, which can be used as a substitute for natural gas and automobile fuels. Furthermore, Andriani et al. (2014) reported that implementing AD with Microbial electrolysis cells (MEC) could decrease the refining process for CO_2 and H_2S. On the other hand, a considerable volume of MSW material is converted into high-value chemicals and fuels using the thermal process. This process is characterized by higher gaseous pollutants that increase environmental risks. So, in the future, there is a need to conduct more research on the design and installation of air control devices and gain further insight into the optimization and syngas production efficiency using advanced Fischer–Tropsch technologies.

A lot of research and efforts have been made in the past to develop sustainable and effective methods of converting MSW into high-value chemicals. MSW can be turned into fuels and chemicals that have much value if combined with biological, chemical, and thermal processes. Future research should focus on developing an innovative integrated approach to waste management in terms of its waste classification and using a product-centric method that looks at the specific components of a product with the transition to a more circular economy and ways to separate a product. MSW valorization technologies for sustainable production of chemicals, materials, and fuels in a circular economy will make greater use of MSW resources within the competitive economy and reduce environmental footprints. It also minimizes waste generation at the source and reduces primary resource input dependency.

The difficulty of comparing different production paths using environmental metrics is one of the most significant drawbacks of LCA investigations. Because the LCA framework requires different system boundaries and data availability, this is the case. Moreover, during the LCA studies, researchers consider various types of biomasses (feed materials) and various goal products. As a result, a consistent method for comparing various production methods and environmental parameters should be devised. As a result, more research and analysis are required at the technology readiness level of each valorization pathway to assess maturity and commercialization potential. It is important to note that determining the technological readiness level is lengthy and involves a more complicated process. In a technology readiness level evaluation, the interpretation and use of definitions are subjective, and it might not be easy to use them consistently.

9. Conclusions

This study reviews recent research on fuel and chemical production using MSW as a substrate. Despite extensive research, this topic remains a growing area in resource recovery research for fuels and chemicals due to the growing population, urbanization, and faster economy worldwide that generates a vast amount of municipal solid waste. Unsafe waste disposal has negatively impacted the environment and human health and requires large landfilling spaces. These problems can be overcome using a cascade approach within a circular economy context. In a paradigm shift toward the circular economy, MSW can no longer be viewed as the culprit of environmental pollution but rather as a source of valuable resources, including high-value chemicals and fuels. The valorization of waste for energy generation represents a sustainable utilization of unused resources and environmental trade-offs. The application of emerging biological, biochemical, and thermal process technologies and their integrated approaches in a circular economy context for converting MSW into high-value chemicals and fuels has a promising future for society worldwide. The hybrid or integrated thermo-bio-chemical biomass waste conversion process has emerged as an efficient energy recovery process with many economic and environmental benefits. Using modeling and simulation studies for preliminary energy analysis and valorization parameters of MSW plants for a circular economy can help determine their technical feasibility. In contrast, simulation-based life cycle assessment studies can play a significant role in assessing the environmental impact. Besides, recent developments and limitations in the production of fuels and chemicals from MSM were extensively discussed. The study pointed out research gaps, such as the lack of studies that show the techno-economic feasibility analysis and LCA of the production of fuels and chemicals for MSM management. This review suggests an urgent need to develop an innovative and cost-effective approach (or combine environmentally friendly approaches) that can lead to sustainable waste management in a product-centric process and transition towards a more bio-circular economic context. The outcomes of the study are supposed to provide valuable insights about resource recovery from MSW in the circular economy concept to produce fuels and chemicals.

Ethics approval and consent to participate

This manuscript does not involve human participants, human data, or human tissue.

Consent for publication

All authors are aware of this submission.

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Authors' contributions

TGA and SR: conceptualization; TGA and RD: first draft of the manuscript, MV and SP: reviewing; MV and SR: supervision; TA and SR: Editing the last version of the manuscript.

Declaration of competing interest

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

Data availability

This is review article

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