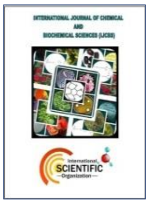
International Journal of Chemical and Biochemical Sciences
(ISSN 2226-9614)

Journal Home page:www.iscientific.org/Journal.html

© International Scientific Organization



Waste valorization technologies and management; A review of traditional and advanced techniques

Bint-e-Zahra*, Amina Qadri and Ghulam Meheuddin

Department of Chemistry, University of Agriculture, Faisalabad-38040-Pakistan.

Abstract

Over population, industrial activities, construction, demolition and over-consumption of resources are the causes of waste production. Waste production is a major problem that is not only contaminating oceans and land, harming human health and environment but also effecting economy. In order to address these issues different approaches that convert waste into useful products (that are both environmentally and economically beneficial) are used. Waste has long been managed using traditional techniques. Due to their limitations, advance techniques such as pyrolysis, gasification, anaerobic digestion and hydrothermal processing are used because they break down waste materials more effectively and with fewer emissions.By introducing emerging technologies like membrane separation, microbial electro-synthesis, plasma gasification, microbial electrochemical processing, and chemical recycling push the boundaries of waste management. These methods create circular economy in addition to conserve resources and lower greenhouse gas emissions. It is clear from comparing the efficiency, influence on the environment, durability from an economic standpoint, and scalability of these various approaches that combining traditional and cutting-edge waste valorization techniques is essential. A circular economy is supported by this integration which opens the door to a more sustainable and profitable future.

Keywords:conventional methods, waste valorization, waste to energy conservation, resource conservation, sustainable waste management, circular economy.

Full length review article

**Corresponding Author*, e-mail: bintezahrainfo@gmail.com

1. Introduction

Sustainable development is a priority for policymakers due to climate change, pollution, resource scarcity, and energy crises accelerated by increasing population and decreasing natural resources. It is our responsibility to teach the following generation about sustainable living practices and other possibilities, and one of the most crucial lessons we can impart to them is about waste management. Waste of many kinds such as food, industrial, and agricultural is produced daily in large quantities, which poses a serious challenge to its management and disposal. Numerous strategies could contribute to sustainable development, these strategies could enhance waste management while simultaneously producing industrially significant materials, fuels, and chemicals [1].

These are a lot of different solid, liquid, or gaseous leftovers that come from the manufacturing process. These are the wastes that come from building, mining, manufacturing, and other business operations. They often hurt people or the environment if they are not treated properly [2]. Industrial wastes like phosphor gypsum, fly ash, red mud, and sludge are major environmental pollutants because they can pollute land, water, and air. Inadequate garbage disposal practices lead to a number of environmental problems, including toxicity to aquatic life, contamination of surface and ground waterways, altered soil quality, contaminated natural waters resources.Because of this, over the past ten years, regulations from around the world have been more stringent on how garbage is handled and disposed of [3-4].Waste valorization is the process of transforming waste resources into goods such as materials, fuels, and chemicals that are more valuable. This procedure keeps a community sustainable and has significant positive effects on the environment [5]. Although this idea has long been around, mostly in relation to waste management. It has recently gained new attention in our society as a result of the rapid depletion of primary and natural resources, the rise in waste production and landfilling around the globe, and the demand for more sustainable and affordable waste management practices. Currently, a number of valuation approaches are demonstrating potential in satisfying industry demands. A potentially effective approach to waste valorization is the utilization of flow chemical technology to convert waste materials into valuable commodities[6].

Waste valorization contributes to maintaining the circular economy and lower the adverse impacts of waste on the environment.The circular economy depends on the transformation of organic wastes and biomass from agriculture into a renewable carbon store that can be used to create a variety of materials and end products, such as feed, fuel, feedstock, chemicals, polymers, and energy. The circular economy boosts the efficiency of resource consumption in order to balance the economic, environmental and societal costs caused the sequential application of resources. As a result, this approach reduces resource depletion, and greenhouse gas emissions and encourages resource efficiency, lowers waste output, and makes it easier for environmentally friendly practices to be used in a variety of industries [7-8]. These techniques must be applied to enhance sustainable growth and better waste management. Waste management involves reusing old materials, recycling those that can be made into new goods, separating recyclables from trash, and figuring out how to turn waste into energy. It also involves establishing safe disposal techniques, cleaning up uncontrolled dumps, and educating the public on appropriate waste management practices [9].

The review emphasizes the critical need of implementing efficient waste management systems to mitigate harmful environmental impacts and encourage the preservation of resources. Global efforts for sustainable development cannot succeed without efficient programs for trash reduction, recycling, and disposal.

2. Traditional waste valorization techniques

Traditional waste valorization techniques are Landfilling, Incineration, Compositing, Recycling and waste-to-energy conversion as shown in Figure1.These methods have been routinely employed to manage garbage by turning it into energy or reusable resources. However, they frequently have serious negative effects on the environment. Improving these techniques is essential to raising sustainability and lowering waste management's environmental impact[10].

2.1 Landfilling:

Around the world, landfilling is the traditional means of disposing different type of wastes including industrial, hazardous, agriculture and municipal solid waste. Furthermore, it encompasses landfilling, where space is provided and usually walled off to avoid leakages where waste is discharged to maintain environmental safety. To minimize air and water quality hazards and odor, layers of debris are compressed and covered with topsoil or some other materials.Leachate (liquid that drains from the garbage) and methane gas emissions are normally controlled in landfills by means of systems like gas extraction and leachate collection, which ensures compliance with environmental rules and minimizes effects on neighboring ecosystems and communities. Landfilling is illustrated in Figure 2 [11]. Landfilling is a more cost-effective and labor-efficient method of waste valorization than others techniques. Furthermore, by using its leachate and landfill gas for energy generation, a consolidated landfill can potentially make money. Based on the distinctive features and hazards connected with various waste kinds, the locations of landfills and treatment facilities are carefully chosen. Household garbage landfills, for instance, are usually sited to minimize odor and traffic disruption, are accessible by collection trucks, and are located well away from highly populated districts. Emergency measures like, the availability of RAIDS (Resources Assured-Secure and Tracked-In-theatre Delivery System), are must deterrents against intentional threats that are mounted against facilities containing radioactive materials, biohazards, poisonous chemicals, and biological wastes. As a general rule, they are situated far away from society and comply with several security measures to maintain the environment and the health of the so-called human beings[12].

2.1.1 Classification of landfilling

Landfilling like open, semi-controlled and sanitary landfilling belongs to the waste valorization category. Each approach has a different environmental impact, as well as different waste treatment methods, which include techniques associated with sanitary landfilling, which features advanced precautions for pollution and health risks. Landfills have to be classified correctly and handled properly for wastage disposal to be more sustainable and to avoid adverse effects on the environment [13].

2.1.1.1 Open dump landfill

A geographical area where solid waste is disposed of in an open area with air contact is known as an open dump landfill. Open dump dumps, which are common in poor nations, dispose of municipal solid waste in open spaces without adequate environmental safeguards or containment [14].This practice gets the waste to air and releases it to unregulated decomposition and leads to other harmful gases including methane and others. Open dumps, which are filthy, often attract scavengers that mean animals or informal waste pickers who will scavenge for a valuable material, but it obviously gives a huge amount of hazard, safety, and health risk due to waste sorting and recycling too in which informal waste workers are involved. Organic waste that is present at uncontrolled open dumps can also attract flies, mosquitoes, rats and other pests, providing the conditions that allow them to proliferate, and pathogenic microorganisms that these pests transmit, this leads to a higher risk of disease transmission[15].

The waste in open dump landfills may undergo anaerobic digestion naturally as there is no oxygen. The remit of this process is the formation of methane gas. Nevertheless, this procedure is rather uncontrolled, resulting in great inefficiency. As a result, there is a great amount of greenhouse gas emissions which leads to ruining the environment. In addition, these environmental issues also extend to health hazards, further pollution, and wastage of resources.Transitioning towards modern waste management systems, such as sanitary landfills with engineered liners and gas collection systems, can help mitigate these challenges and promote sustainable waste disposal practices [16].

2.1.1.2 Semi-controlled landfills

Semi-controlled landfills are situated in specific dumpsites where solid waste is sorted, shred, and consolidated on the spot before being disposed of. Bulldozers or crawlers are used to crush and level the disposed-of thrash piles, and a layer of topsoil is applied every day to prevent annoyances like the growth of scavenging birds, animals, vermin, and microbes. Due to topsoil cover, semi-controlled landfills have comparatively less odor, butthese landfills are not made to regulate leachate outflow and gas emissions.[17].

2.1.1.3 Sanitary landfills

Sanitary landfills are more advanced. They perform on-site solid waste sorting, segregation, size reduction, densification, and topsoil covering procedures. Additionally, they have equipment made to collect landfill gas emissions and liquid leachate.Cover soil is regularly applied on top of recently disposed of wastes in sanitary landfills, which are suitably designated inside a regional border and away from residential areas. This decreases odor, disease vectors, fires, and waste scavenging [18]. In prosperous countries, these landfills are typical and have leachate treatment and interception systems. Sanitary landfills are also intended to expand geographically through the excavation of additional dumpsites following the saturation-capping of current ones.

2.2 Incineration:

A complex waste treatment technique called incineration breaks down the organic components of garbage and reduces its volume by using high-temperature thermal breakdown by thermal oxidation, which usually reaches temperatures above 900°C. Process of incineration is shown in the figure 3. Wastes with a significant organic content or combustible wastes respond best to this method [19]. But in legal terms, it can burn any trash containing as little as trace amounts of potentially hazardous organic materials. This use of toxin oxidation means diminishes or takes out the negative impacts of natural contaminants, which makes incineration a suitable choice for a few waste sorts (e.g., threat, restorative, toxic, or dangerous waste-including carcass), so it seems to be as it were common that the world serves a statistic of large clinical incinerators. Incineration, however, is a valuable method of minimizing waste retention and emissions, but it must be well-controlled to minimize emissions as well as to satisfy all environmental regulations [20]. The kind of waste that is being processed decides the size and the working parameters of the combustion chamber. This will include factors affecting the design of air pollution control systems and ash and residue management, i.e., temperature, excess air, flow rates etc. The elemental composition and moisture content of the waste is vitally important, as this data drives the determination of the required quantity of combustion air and an estimate of the composition of combustion gases. These are important factors to decide the best level of combustion temperature, residence time and air, fuel and waste mixing efficiency in the incinerator. They also serve as guides for the selection and sizing of equipment used for abatement of air pollution, it ensures compliance with environmental regulations [21].

2.2.1 Impacts of incineration

There are a variety of different effects of incineration on ecosystems and on human health. Studies have shown that incineration releases air pollutants (air pollution) containing heavy metal, dioxins, and acid gas, causing restitution effects on human health nearby areas. It also leads to global warming as incinerator emissions emit methane and carbon dioxide that are greenhouse gases that exacerbate the negative identify of climate change on ecosystems [22]. Combat the above-discussed environmental problems; it is essential to minimize incinerator emissions and enforce latest pollution control devices for sustainable waste management technique. This sector still lags behind, however more work is needed to find an equilibrium in terms of avoiding environmental repercussions whilst taking full advantage of the benefits of waste minimization [23].

These plants designed to obtain maximum benefits of combustion, such as power generation and waste-to-energy, which helps to increase waste utilization. And they are facilities that, in reducing their detrimental outputs, such as emissions and remaining bottom ash, also produce lower outputs from those of comparable facilities in the region. This particular approach stresses the need to design waste management strategies that prioritize resource recovery and pollution control; American Standard Code for Information Interchange (ASCII) format as they focus on maximizing the amount of benefits that can be optimized at the same time as minimizing deleterious effects on the environment[24].

2.3 Recycling:

Recycling is a fundamental method that collects materials, and processes them to create new items, preventing them from being thrown into the garbage. This process reduces the impact of waste disposal on the natural environment and the surrounding nature as the resources are hydrated and less energy is used. A demonstration of process of recycling is shown in the figure 4. It is the process of converting waste materials into new materials and objects. For example, doing the sorting, cleaning of the waste plastic to produce reusable raw materials recycling plastics such as soda pulp, beverage bottles, food containers, etc. [25].The reprocessing of materials back into useful resources also advocates a circular economy, in which recycling materials is treated as a closed-loop and not linear. Recycling is a core part of waste management and helps deflection of rubbish from landfill, preserving raw materials, reduces greenhouse gases from mining and manufacturing, allows products to be re-used many times, promotes sustainable consumption which seals the loop between post-consumer waste and industry usage getResponse Headers Recycled Products (RHRP)[26].

Developing cutting-edge recycling technologies are crucial for fostering environmental sustainability and lessening the effects of trash production.

2.3.1 Methods of recycling:

Different types of recycling, such as chemical, mechanical, and thermal recycling, are used to turn trash into something useful. These methods turn trash into useful resources, which cuts down on the need for new materials and the damage they do to the earth. Recycling helps keep resources healthy and the economy going round because it gets rid of trash well [27].

2.3.1.1Mechanical recycling

During mechanical recycling, used plastics are gathered, sorted by type, and then put through tools that shred, melt, extrude, or inject mould them so that new things can be made. One issue is keeping the quality and mechanical features stable, since the material could break down during recycling [28].Some polymers, like glass fiber-based polyamide composites, can be recovered mechanically and keep or even improve their properties. But over time, problems like heat oxidation and fiber shrinking can make materials less effective. Even with these problems, increasing the number of people who recycle plastic by machine is necessary to cut down on plastic trash and the damage it does to the environment. This will also encourage a more eco-friendly way to make and use plastic[29-30].

2.3.1.2 Chemical recycling

Chemical recycling is an effective method for addressing the global issue of plastic waste since it transforms discarded plastic into valuable organic substances. This novel technique employs pyrolysis, gasification, and de-polymerization, among other processes, to convert polymers into valuable chemical commodities [31].The use of recycled polymers as raw materials in industrial processes could help create a circular economy through chemical recycling. This would make a big difference in how much plastic trash built up. This technology can work with plastics that are hard to recycle the old way because they are contaminated or have complicated constitutes.Apart from that, mechanical recycling might be combined with it. As more research and development is done in this field, chemical recycling techniques could help achieve sustainability goals and reduce the harm that discarding plastic trash contributes to the environment [32].

2.3.1.3 Thermal recycling

By the help of thermal treatment waste can be converted into energy which involves subjecting waste to high temperatures and purifying it, often by combustion [33].By employing this approach quantity of waste is reduced. Thermal recycling is effective for materials such as plastics and alloys that are difficult to recover using conventional mechanical processes [34]. Research on glass fiber composites has also revealed that the when recycling occurs at temperatures close to 600°C mechanical properties of the material can be largely preserved [35].

2.4 Waste to energy conversion:

Waste-to-energy conversion is the process in which waste materials is turn into energy which is essential to sustainable waste management. A variety of technologies are used in this process i.e. combustion, gasification, pyrolysis etc. In controlled combustion garbage is burn to produce heat that is subsequently transformed into energy using steam turbines or other power-generating devices [36]. The other method is gasification which involves heating garbage in a low-oxygen atmosphere to create synthetic gas, or syngaswhich can be used to generate heat or power. Another technique for using biodegradable trash to produce biogas, a renewable energy source for power generation or heating, is anaerobic digestion [37-38].

By lowering greenhouse gas emissions, diversifying energy sources, and decreasing landfill volumes, these waste-to-energy systems provide substantial advantages. However, in order to guarantee environmental sustainability and community involvement, issues including emissions control, ash management, and public acceptance must be resolved[39]. Waste-to-energy conversion is a key component of the shift towards a more circular economy and cleaner energy production, and it is constantly evolving along with technological and legislative developments [40-41].

2.5 Compositing:

In waste valorization, composing is carefully combining different waste elements to produce a worthwhile final product. The goal of this method is to minimize damage to the environment while improving the return of resources. The first step in the process is generally collecting and sorting different kinds of trash, like plastics, garbage, and organic matter. Then, they are cleaned up and made ready to be combined [42]. After being processed separately, the waste streams are mixed together in exact amounts to give the final combined product of right qualities. This item can be used for numerous purposes, such as making things, getting energy, or improving the land [43].

3. Advanced waste valorization techniques

Advance waste valorization techniques are Pyrolysis, Anaerobic digestion, Gasification and Hydrothermal Processing as shown in the Figure 5. These techniques are more efficient and environmentally friendly alternatives to traditional methods. These technologies significantly reduce pollution and the loss of natural resources by turning waste into energy and materials that are valuable. They represent a critical first step toward sustainable waste management and a circular economy[44-45].

3.1 Pyrolysis:

Pyrolysis is a sort of thermal breakdown in which waste materials (like polymers used in multilayer packaging, tires, and biomass)are heated in the absence of oxygen to break them down into smaller molecules. It is a type of thermal breakdown in which waste materials are burned to lower their molecular weight [46]. Three main products are obtained from the pyrolysis of waste materials are shown in Figure 6[47]; pyrolysis oilis a liquid hydrocarbon mixture, syngas also known as synthesis gas which is a combination of hydrogen, carbon monoxide, and other gases and Bio-char which is a solid residue rich in carbon [48]. Beyond temperature and catalysts, a number of other critical elements also play a vital role in the pyrolysis of garbage. The kind of plastic feedstock used, the pace of heating, and the duration of the reaction all affect the amount and caliber of bio-oil that is produced. The pyrolysis performance of several plastic kinds, including polyethylene, polypropylene, and polystyrene, is affected by differences in chemical compositions and thermal behaviors. The kinetics of decomposition are influenced by the heating rate; higher heating rates often provide higher yields of bio-oil, but at the expense of possible inferior quality [49].

In order to provide the feedstock enough residence time to completely decompose and generate the product, reaction time is also essential. In waste pyrolysis operations, optimizing these parameters is crucial to maximize the quality and efficiency of bio-oil production, advancing sustainable waste-to-energy technologies. The necessity for post-treatment techniques to increase the products' the suitability for certain applications is highlighted by the use of pyrolysis products in many sectors[50]. Refinement, purification, and chemical processing are some of the techniques used to improve the pyrolysis oils, gasses, and char's qualities and characteristics. Waste pyrolysis operations can become more sustainable and efficient through the optimization of post-treatment techniques. This allows for the creation of useful resources from waste materials while adhering to industry norms and regulations [51].

3.2 Gasification:

Gasification is a process that turns biomass such as wood, trash, or agricultural residues into syngas[52]. The process of gasification is shown in the Figure 7. Complete combustion is prevented by the high temperature and low oxygen content of this process. Because gasification creates syngas while releasing less dust and hazardous gases like nitrogen oxides and sulfur dioxide, it has advantages over traditional combustion. It's a more environmentally beneficial way to use biomass resources because the syngas produced during gasification may be used as fuel for heat, power, or biofuels [53]. Gasification is a process that may be used to a variety of materials, including coal, to create a hydrogen and carbon monoxide gas mixture. Syngas is a gas that can be processed further to produce useful chemicals or fuels [54]. A particular kind of gasification used on coal resources located far below the surface is called Underground Coal Gasification(UCG). Without the need for mining, controlled underground reactions in UCG turn coal into syngas. When comparing this synthetic gas to conventional coal combustion processes, the emissions of pollutants are reduced. UCG contributes to greener energy production methods by providing a method for more effectively and environmentally friendly energy extraction from coal resources [55].

The process of gasification involves adding a feedstock, such as coal or biomass and gasifying agent, such as air to a reactor vessel. Carbon monoxide and hydrogen are combined to form synthesis gas (syngas), which is the result of controlled chemical reactions occurring inside the reactor. Certain process parameters, the type of feedstock used, and the gasifying agent used all have an impact on the quality and content of the syngas [56].

The technology of gasification has advanced dramatically over time. In the past, it was employed to turn coal into town gas in the 1800s. It can now effectively convert a variety of feedstock, such as biomass and alternative fuels, into syngas that is high in energy. One noteworthy application is the gasification of biomass to produce hydrogen, which has advantages like flexible feedstock and low emissions. Because it makes it possible to convert a variety of materials into usable energy resources with less of an impact on the environment, gasification technology is still essential to the generation of sustainable energy [57-58].

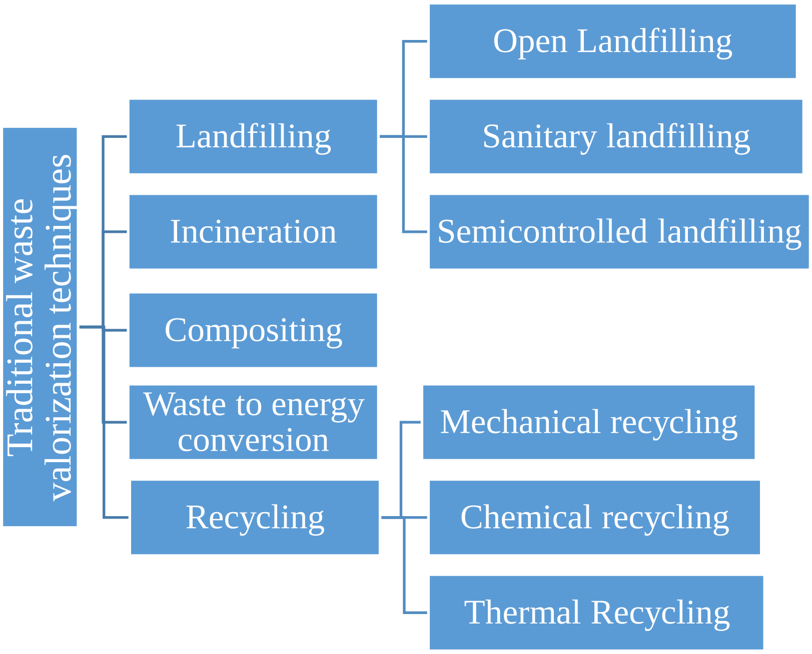


Figure 1: Traditional waste valorization techniques

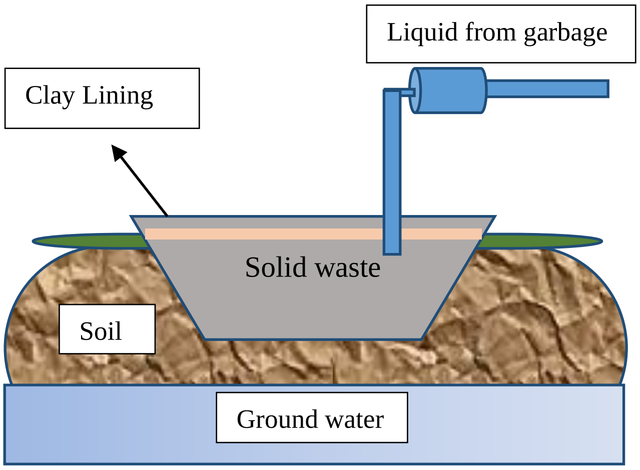


Figure 2: Landfilling

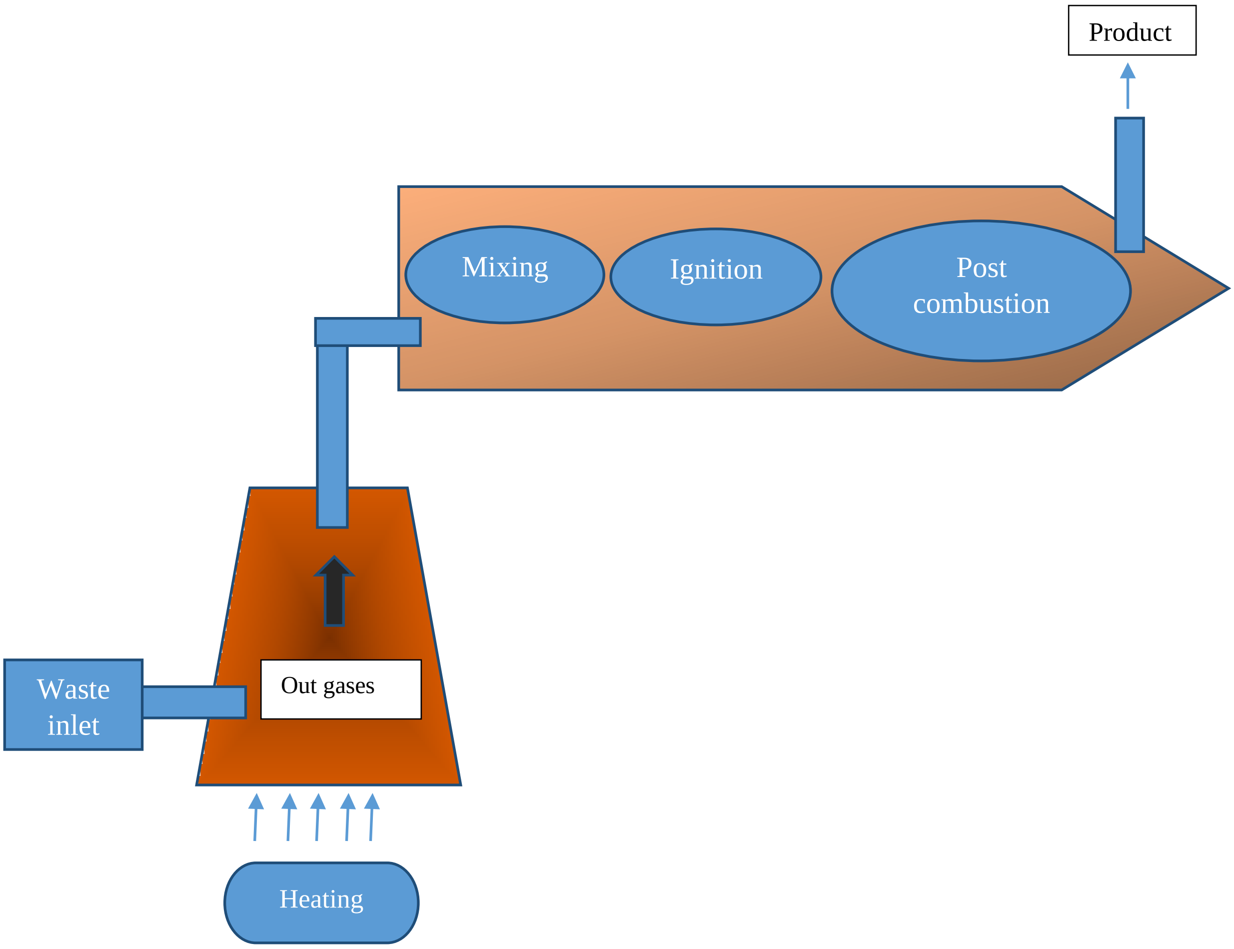


Figure 3: Incineration

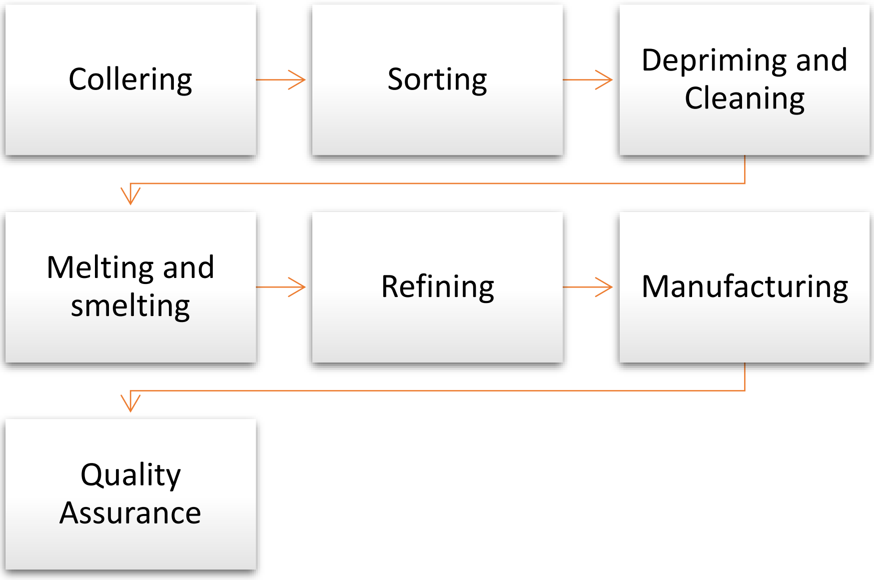


Figure 4: General process of recycling

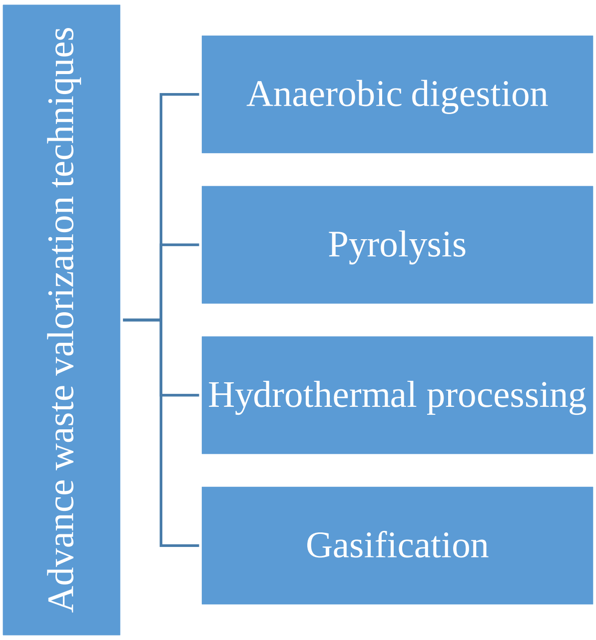


Figure 5: Advance waste valorization techniques

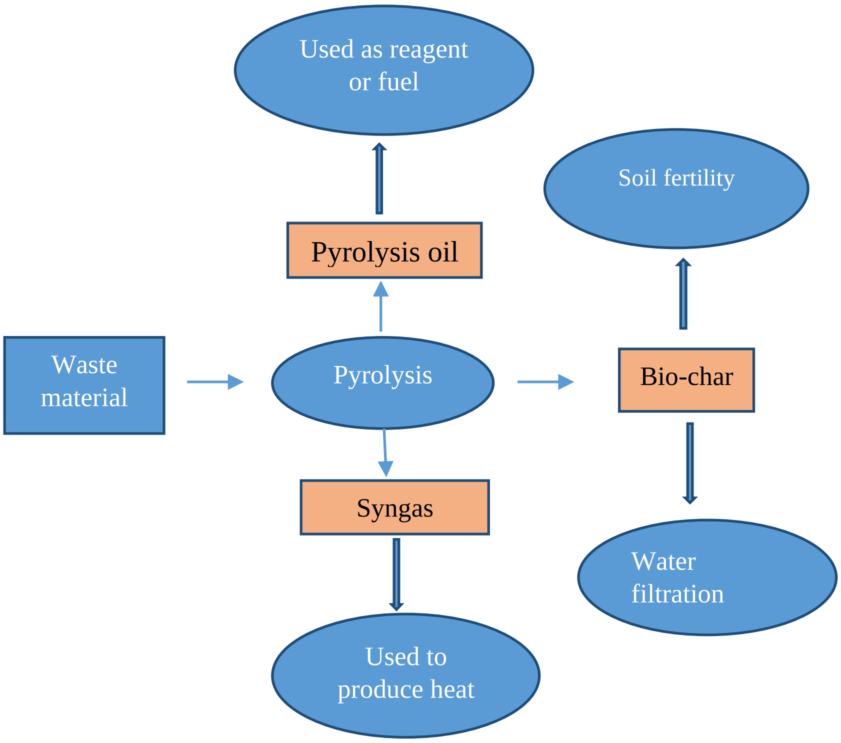


Figure 6: Products and uses of Pyrolysis

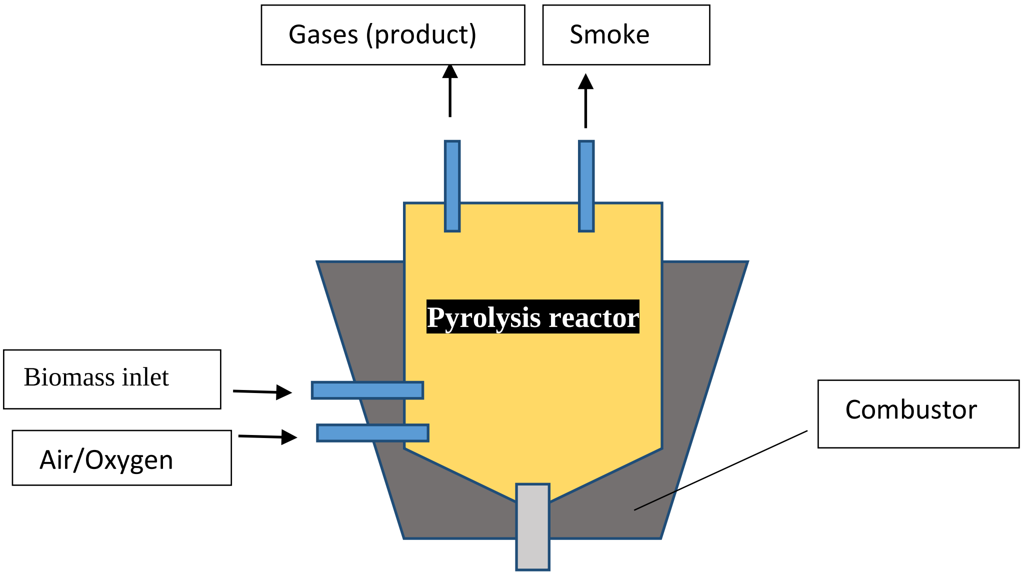


Figure 7: Process of Gasification

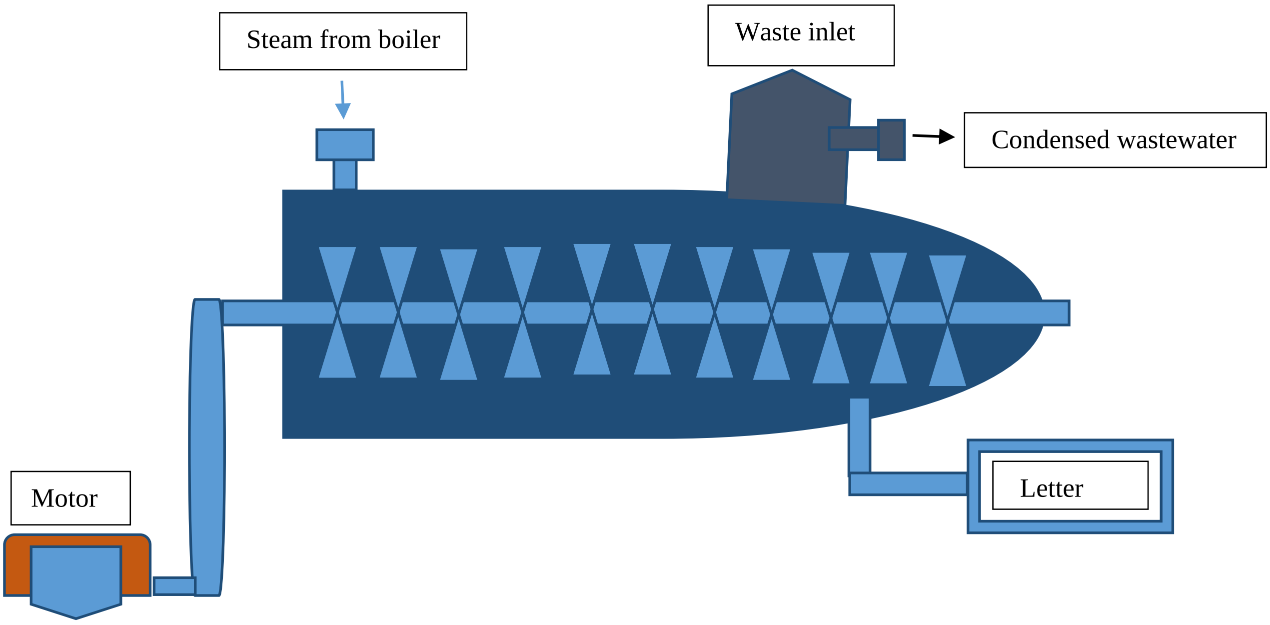


Figure 8: Hydrothermal processing of waste

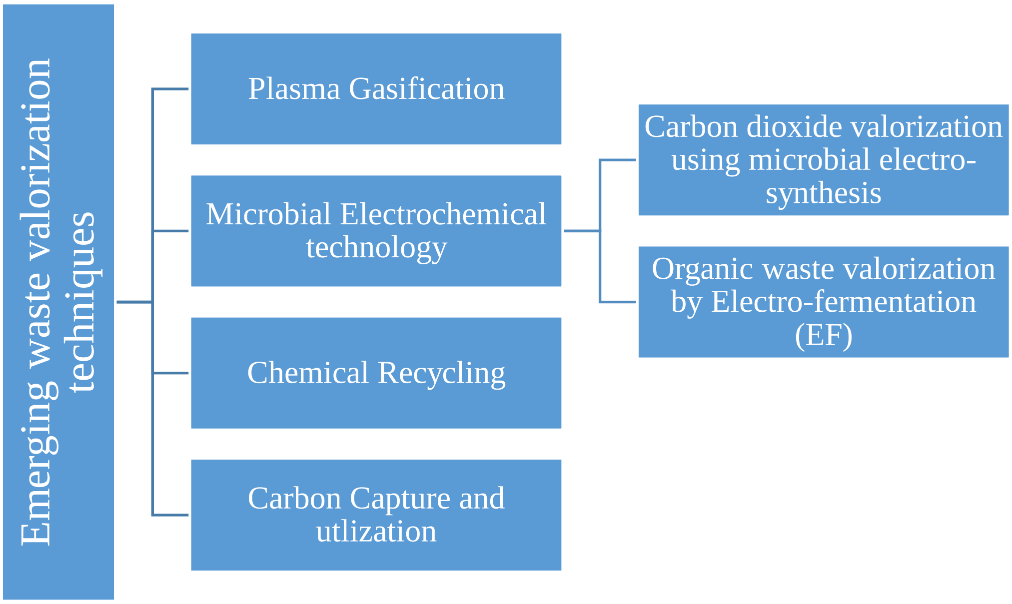


Figure 9: Emerging waste valorization techniques

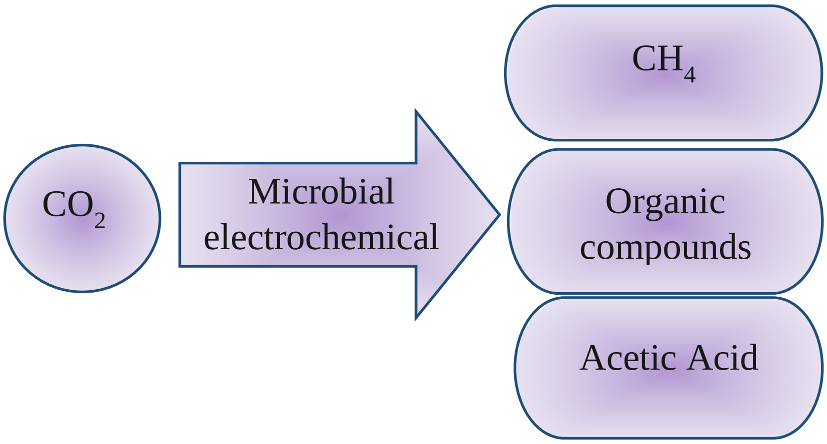


Figure 10: Products of CO$_2$valorization using MES

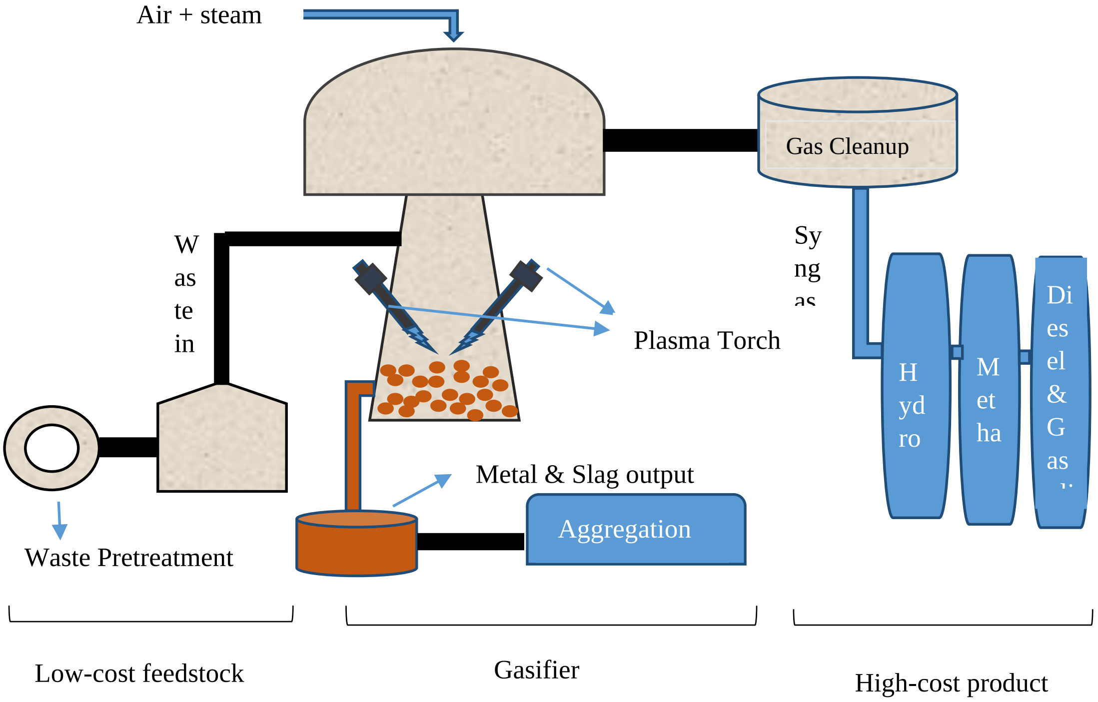


Figure 11: Process of Plasma Gasification

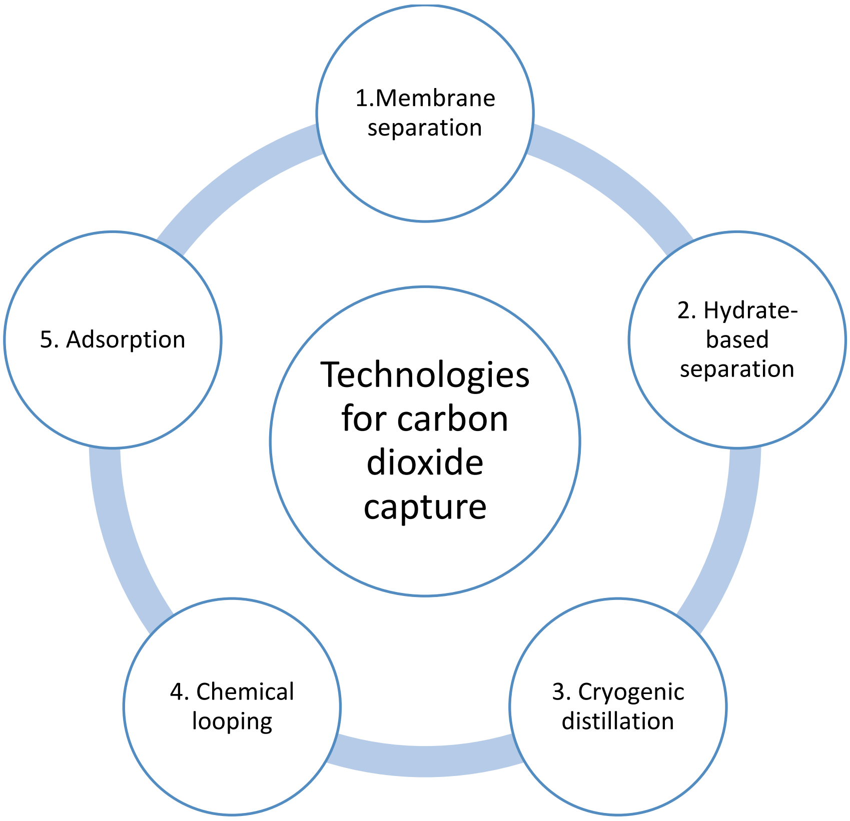


Figure 12: Technologies for carbon dioxide capture

Table 1. Benefits of anaerobic digestion (AD)[59]

Sr.#	Benefits	Description
1	Efficient waste management	Anaerobic Digestion (AD) treats organic waste efficiently, reducing waste volumes and preventing environmental pollution.
2	Renewable energy production	Biogas generated through AD provides a sustainable energy source, contributing to energy security and reducing carbon footprints.
3	Nutrient recovery	The digestate produced during AD is rich in nutrients, making it an excellent natural fertilizer for agriculture.
4	Job creation and economic growth	AD facilities create employment opportunities and stimulate local economies.
5	Mitigation of climate change	AD helps reduce greenhouse gas emissions by capturing methane.

Table 2. Comparison between Traditional and Advanced Techniques

Benefits	Traditional Techniques	Advance Techniques	Reference
Efficiency	Advanced waste valorization techniques, such as pyrolysis, gasification, and anaerobic digestion, are generally less efficient in converting waste into energy or other products than traditional incineration and landfilling.	Advanced waste valorization techniques, such as pyrolysis, gasification, and anaerobic digestion, are generally more efficient in converting waste into energy or other products than traditional incineration and landfilling.	[60]
Environmental Impact	Traditional methods often lead to greater environmental degradation, including emissions and leachate production.	Advanced methods are designed to minimize environmental impact through controlled processes and better emissions management.	[61]
Economic Viability	Traditional methods typically involve recurring disposal costs	Advanced valorization techniques can transform waste management from a cost center to a revenue-generating activity. Producing biogas from organic waste, for instance, can reduce energy costs and provide a new revenue stream.	[62]
Scalability and Adaptability	Traditional methods are less flexible and often require significant space and infrastructure	Advanced techniques are more adaptable to different types of waste and can be scaled based on volume and nature.	

3.3 sAnaerobic digestion (AD)

The production of large amounts of garbage in modern life is a major hazard to the environment and the health of people and animals. In order to address this, a variety of waste treatment and disposal techniques are used; the choice of any particular technique depends on the requirements for optimum safety, the least amount of environmental damage, and the importance of recycling end goods and maximizing waste value. Reducing the quantity of garbage delivered to landfills and substituting organic material recycling and plant nutrient return into the soil are important components of contemporary waste management systems. In addition to promoting waste reduction, AD has the ability to lower energy usage and even produce net energy. This procedure highlights the move toward environmentally and energy-friendly sustainable waste management techniques [63]. Using cutting-edge technology, anaerobic digestion (AD) converts organic waste into useful bioenergy by utilizing the power of microbes. This environmentally beneficial method reduces garbage disposal issues and produces a renewable energy source, benefiting both the economy and the environment. In the absence of oxygen, organic matter is broken down by the AD process, resulting in the production of digestate rich in nutrients and biogas, a combination of methane and carbon dioxide. By using this biogas as a clean-burning fuel for transportation, heat production, or electricity generation, greenhouse gas emissions can be reduced and dependency on fossil fuels is decreased[64].

This method is very effective because it uses little energy and makes less waste, which is in line with world goals for green energy. Several things, such as operating conditions, co-digestion (mixing different feedstocks), and pre-treatment methods, can make AD work better by increasing its efficiency and dependability. Because it is cheap and good for the environment, AD looks like a good way to make energy from biological waste. Biogas can be used as a clean energy source, which cuts down on the use of fossil fuels and lowers greenhouse gas pollution. Overall, AD helps make the energy scene more sustainable by turning biological waste streams into useful energy supplies. This supports the ideas of the circular economy and environmental responsibility. In conclusion, anaerobic digestion is a revolutionary technology that solves problems with garbage management while also making clean energy and supporting long-term growth. For a periodic economy and a better, greener future, it is very important that people use it [65].

3.4 Hydrothermal Processing:

Warm squished water is used in hydrothermal processes to turn biomass feed stocks into solid, liquid, and gaseous products. Biomass is broken down into useful products by heating and pressurizing it to temperatures and pressures that are generally higher than the boiling point of water. Bio-char or activated carbon are examples of solid products. Bio-oils that can be used as chemicals or fuels are popular examples of liquid products. Along with solids, gases like methane and hydrogen are also formed. Hydrothermal process is shown in figure 8. Hydrothermal processing is a versatile and useful way to turn biomass into useful products that can be used in chemistry and energy processes [66]. For an environmentally friendly use of biomass, hydrothermal processing is essential because it produces valuable products from a variety of feed stocks. This process creates biofuels as well as biochemical and bio-based products. Lignocellulosic biomass can be transformed into sugars, bio-oils, and bio-char, while algae and food waste can yield biodiesel, biogas, and organic chemicals [67]. Hydrothermal processing supports the circular economy by efficiently converting biomass into useful outputs, reducing reliance on fossil fuels, and mitigating waste. It also contributes to soil health and carbon sequestration through the production of bio-char. As industries seek sustainable alternatives to conventional resources, hydrothermal processing plays a key role in advancing the bio economy and promoting environmentally friendly practices [68].

5.Emerging technologies

Innovative techniques like plasma gasification, microbial electrochemical processing, and advanced chemical recycling are examples of emerging technology in waste valorization. These technologies are shown in the Figure 9. These cutting-edge technologies provide ways to improve resource efficiency, lessen environmental effect, and turn waste into useful goods. They clear the path for a more sustainable and circular economy by going beyond the bounds of conventional trash management[69].

5.1 Microbial electrochemical technology

Microbial electrochemical technology (MET) is a hybrid technology that converts waste carbon sources into energy and products by using electroactive microorganisms to accelerate bio electrochemical processes. Because the electrodes on this special platform may function as both the cathode (an electron donor) and the anode (an electron acceptor. Cheng et al. introduced electro-methanogenesis, an early MET method that uses Methanobacterium palustre to convert waste carbon into methane [70]. The phrase "microbial electro-synthesis" (MES) was first used in 2010. MES defined as "the reduction of carbon dioxide to multicarbon compounds with electrons donated from an electrode as the electron donor" [71].Soon after, Rabaey and Rozendal released a full assessment in which they covered in great detail the MES's guiding ideas, difficulties, and opportunities. Additionally, they introduced electro-fermentation (EF) in that review, which is an electrochemical method that uses electrical current to modulate fermentation pathways [72].

5.1.1 Types of microbial electrochemical process

Following are major microbial electrochemical processes for CO_2 and organic waste valorization;

5.1.1.1 Carbon dioxide valorization using microbial electro-synthesis (MES)

In order to facilitate subsequent reduction reactions, an enriched or atmospheric CO_2 source needs to be collected and solubilized using either biotic or abiotic mechanisms. There are numerous approaches to capture and use CO_2, each having pros and cons, such as a photochemical, biological, electrochemical, and thermochemical methods. In addition to creating economic value by utilizing CO_2 as a renewable carbon feedstock, this approach actively lowers carbon emissions, which has significant positive effects on the environment and society. Using microbial cells to convert dissolved CO_2 into useful organic compounds—particularly those containing multiple carbons—that can be used as building blocks to create beneficial chemicals with additional value or liquid fuels for transportation.Products of carbon dioxide capture using MES are shown in Figure 10. Microbial electro-synthesis is a combination of biochemical and electrochemical process[73]. The unique advantage of MES for CO_2 valorization is the utilization of electrons as the reducing power, which can be generated from natural gas, biogas, solar, or wind power. However, the availability of various electron sources may be variable. Microbe-enhanced solar energy harvesting (MES) has the potential to alleviate the urgent problems associated with the storage and distribution of renewable energy, as microorganisms are 100 times more efficient than biomass-based chemical manufacturing. There are six recognized mechanisms for fixing CO_2 in bacteria and archaea, which are found in many species. Methanogens and acetogens, two of these autotrophic bacteria, have been employed in MES.Using microbial electrochemical technology CO_2 can be converted into useful products as shown in figure 9[74].

5.1.1.2 Organic waste valorization by electro-fermentation (EF)

Although the main objective of electro-fermentation is to control the fermentation pathways (by electrochemistry) in order to transform organic waste materials, such as agricultural and municipal garbage into the more value able products. Fermentation reactors are equipped with solid electrodes that act as endless sources of electron donors or acceptors. It is possible to control mixed culture communities or pure culture fermentation pathways outside [75]. In environmental settings, electroactive bacteria and fermentation bacteria typically engage in syntrophic interactions to carry out the processes. By controlling the Oxidation Reduction Potential and the NAD+/NADH ratio, the electron transfer in electro-fermentation can be controlled. It is anticipated that anodic electron sinks will promote greater AT synthesis whereas cathodic electron sources will influence the synthesis ofNADPH. This suggests that anodic and cathodic EFs may both enhance fermentation efficiency. A recent study employing Corynebacterium glutamicum, a bacteria that produces lysine, provided an example of this [76].

5.2 Plasma Gasification

The process of breaking down raw material molecules into their constituent elements at high temperatures and atmospheric pressures in the presence of gasifying agent such as steam is known as gasification

[77].Using plasma, a high-energy state of matter, plasma gasification is an innovative waste treatment method that turns inorganic materials into vitrified slag and organic materials into syngas, a mixture of hydrogen, carbon monoxide, and other gases. [78-79]. Synthesis gas is produced when the raw material is exposed to a substoichiometric oxygen level. This gas is mostly composed of hydrogen, carbon monoxide, methane, carbon dioxide, branched hydrocarbons, tars, and a very little quantity of nitrogen. This gas can be used, among other things, as a raw material for chemical synthesis, heat generation, and combustion in engines to produce electric energy [80-81].

5.2.1 Process of plasma gasification

Hazardous materials, industrial waste, and municipal solid waste are fed into the gasifier as inputs. An inert gas, like argon, is ionized by a plasma torch to produce plasma. Waste materials are broken down into their most basic molecular components by the high temperatures of the plasma. Syngas is produced from organic materials and mostly consists of carbon monoxide and hydrogen. For use in construction, inorganic elements are melted and solidified to create a slag that resembles glass. Process of Plasma Gasification and products are shown in the Figure 11[82]. By transforming garbage into energy and valuable commodities, plasma gasification provides a sustainable approach to waste valorization. Its environmental benefits and adaptability make it a viable technology for future waste management and energy generation strategies, despite its high costs and energy requirements [83-84].

5.3 Chemical recycling

The act of turning waste materials—especially plastics—into useful chemicals, fuels, or new materials through chemical processes is known as waste valorization through recycling[85]. This technique salvages value from items that would otherwise be thrown away in addition to aiding in waste management. This kind of recycling focuses on reducing plastic solid waste (PSW) on purpose to create smaller compounds that can be used again as virgin polymers and new petrochemical feedstocks. It can recycle diverse plastic feedstocks, doing away with the need for expensive and difficult separation procedures [86]. By putting in place a successful chemical recycling procedure for plastic solid waste, a circular economy can be developed [87].

5.3 Approaches in chemical recycling

The detail of these processes is given below;

5.3.1 De-polymerization

Reversible synthesis reactions, namely hydrolysis, glycolysis, and alcohol hydrolysis, are efficient methods of de-polymerization for condensation polymers, including polyesters and polyamides, like polyester-based nylons and polyethylene terephthalate (PET). De-polymerization, however, can be difficult since it needs high pressure and temperatures [88].

5.3.2 Partial oxidation

One potential recycling technique is partial oxidation which reduces the creation of harmful byproducts from the direct combustion of plastic trash. A mixture of synthesis gas (CO and H_2) and hydrocarbons with varying carbon contents and olefinicity are produced. But the process of gasification requires a lot of funding, and the end products need to be upgraded before they can be utilized as fuel or chemicals [89].

5.3.3 Cracking processes

Plastic has been cracked using techniques like thermal and catalytic cracking to produce useful chemicals and fuels. Thermal cracking breaks down waste plastic solids at a temperature range of 350 to 900 °C, depending on the kind and purity of the plastic. The result is carbonized char and gaseous and liquid products that resemble naphtha, gas oil, and commercial fuel gas [90].

5.4 Carbon capture and utilization

Because CO_2 emissions from fossil fuels constitute a serious danger to the world economy, ecology, natural ecosystems, and public health, CO_2 collection technologies have become increasingly important. Technological developments in carbon capture and utilization have the potential to significantly cut greenhouse gas emissions and pave the way for net zero emissions, which would help achieve a number of Sustainable Development Goals(SDGs)[91]. There are four ways to go about carbon collection, storage, and usage. Eliminating CO_2 from the point source is the first step. Because of membrane-based separation, adsorption, physical and chemical absorption, and other cutting-edge technologies, industrial plants release flue gases, which are regarded as the point source. Technologies used for carbon dioxide capture are shown in Figure 12[92].

Liquid compressed CO_2 is convenient to transport and store. Geo-sequestration is a technique that allows CO_2 to be permanently stored. The choice of location is influenced by the presence of porous rock in the earth. An impermeable layer holds the injected CO_2 in situ from above as it fills the pores within the rocks[93]. The method used here is quite similar to subterranean gas and oil storage. Geological storage of CO_2 can be achieved in both onshore and offshore basins. Captured CO_2 is meant to be used for alkaline remediation, enhanced oil recovery, recovering untapped oil, or converting it into useful compounds.The fuel source for the combustion process is the exhaust gas. Food and beverage manufacturing, as well as the synthesis of synthetic or hydrocarbon fuels containing hydrogen, both need the usage of CO_2[94-95].

5.4.1 Technologies for carbon dioxide capture

The CO_2 that is caught can be used directly for various purposes such as improving oil recovery, creating precious minerals, chemicals, and clean fuels. The synthesis of fuel, carbonates and polycarbonates, and the manufacturing of valuable chemicals such as formic acid, formaldehyde, methane, syngas, ethanol, methanol, dimethyl ether, urea, and salicylic acid are the main areas of current advancement in CO_2 usage technology. The available technologies for CO_2 capture are shown in figure 11 [96-97]. Utilizing CO_2 has developed into a practical carbon-based solar fuel that doesn't interfere with already-built infrastructure. The procedure entails dividing CO_2 into O_2 and CO. The Fischer-Tropsch method can be used to process CO and green H_2 to create a variety of clean fuels and chemicals[98].

5. Environmental benefits and emerging technologies

Waste valorizationprovides numerous benefits in terms of environmental sustainability, greenhouse gas (GHG) reduction, resource conservation, and economic gains. Below is a detailed discussion of these benefits, along with a comparison between traditional and advanced techniques, supported by scholarly references [99].

5.1Environmental Benefits

Waste recycling reduces the quantity of waste that is deposited in landfills, so improving the cleanliness of both land and water. Conventional methods of waste disposal, such as landfilling or incineration, can generate harmful leachate and emissions that have negative impacts on the environment. Advanced valorization techniques can also be employed to process and eliminate hazardous substances present in waste, hence reducing their adverse impacts. Nevertheless, conventional approaches may not effectively manage hazardous waste to prevent environmental pollution [100].

5.2 Greenhouse Gas Reduction

waste valorization, the process of turning organic garbage into biofuels or biogas, lowers the amount of methane that is released into the air by landfills. In comparison with carbon dioxide, methane has a much greater ability to contribute to warm the planet. This is because less fossil fuels are used when trash is turned into energy, which lowers the carbon effect. Instead of just burning things, methods like anaerobic digestion and pyrolysis are much better at lowering greenhouse gas emissions [101].

5.3 Resource Conservation

Waste valorization is the process of getting valuable materials back from waste. These materials can be used again in numerous fields. By using old methods, these things are often lost. Valorization also helps the circular economy by turning trash into secondary raw materials and reducing the need for new resources. Chemical recycling and other more advanced methods are better at recovering materials than easier mechanical recycling [102].

5.4 Revenue Generation

There are many things that can be remade and turned into useful goods that can be sold to make money. The old way of dealing with trash often cost funds without generating revenue. Some of the areas that can use more jobs are engineering, manufacturing, maintenance, and buildings that add value. Most of the time, jobs in new technologies are more valuable and require specific skills than standard waste management jobs [103].

Conclusion:

This study looked closely at both traditional and innovative waste valorization techniques in order to meet the urgent demand for sustainable waste management. Despite their lengthy history, conventional methods including composting, incineration, recycling, and landfilling frequently have detrimental consequences on the environment, including resource depletion and greenhouse gas emissions. On the other hand, more environmentally friendly options are provided by modern methods including pyrolysis, anaerobic digestion, gasification, and hydrothermal processing. Emerging technologies that have the potential to reduce waste and provide useful byproducts include microbial electrochemical processing, plasma gasification, and advanced chemical recycling.

To improve these technologies' effectiveness, scalability, and financial sustainability, more research is needed. The key to increasing resource recovery and limiting environmental effect is process optimization, enhanced economic viability, and cost reduction. Large-scale deployment requires integrated waste management systems, encouraging regulations, more funding, and public-private collaborations. The study highlights how crucial it is to keep coming up with new ideas and investing in waste valorization techniques. By using these cutting-edge technologies, we may realize the full potential of waste valorization by greatly enhancing waste management effectiveness, minimizing environmental impact, and moving toward a more sustainable future.

References:

[1] D.C. Wilson, C.A. Velis, Waste management–still a global challenge in the 21st century: An evidence-based call for action. In SAGE Publications Sage UK: London, England: 2015; Vol. 33, pp 1049-1051.

[2] M. Prathap, N. Balaji, J. Sudarsan In *Experimental study on usage of industrial waste in road construction*, AIP Conference Proceedings, 2020; AIP Publishing: 2020.

[3] P. Roy, M. Ahmaruzzaman, Industrial wastes as novel adsorbents for the removal of toxic impurities from wastewater. In *Sustainable Materials for Sensing and Remediation of Noxious Pollutants*, Elsevier: 2022; pp 129-147.

[4] A. Qadri, M. Alam. Drinking water treatment using advanced technologies.

[5] R.D. Tchonkouang, H. Onyeaka, T. Miri. (2023). From Waste to Plate: Exploring the Impact of Food Waste Valorisation on Achieving Zero Hunger. Sustainability. 15(13): 10571.

[6] Y. Zhang, T. Zhang. (2022). Biowaste valorization to produce advance carbon material-hydrochar for potential application of Cr (VI) and Cd (II) adsorption in wastewater: a review. Water. 14(22): 3675.

[7] P. Roy, A.K. Mohanty, P. Dick, M. Misra. (2023). A review on the challenges and choices for food waste valorization: Environmental and economic impacts. ACS environmental Au. 3(2): 58-75.

[8] E. Capanoglu, F.A. Tomás-Barberán, Introduction to novel approaches in the valorization of agricultural wastes and their applications. In ACS Publications: 2022; Vol. 70, pp 6785-6786.

[9] I. Skenderovic, B. Kalac, S. Becirovic. (2015). Environmental pollution and waste management. Balkan journal of health science. 3(1): 2-10.

[10] R. Castro-Muñoz, E. Díaz-Montes, E. Gontarek-Castro, G. Boczkaj, C.M. Galanakis. (2022). A comprehensive review on current and emerging technologies toward the valorization of bio-based wastes and by products from foods. Comprehensive reviews in food science and food safety. 21(1): 46-105.

[11] A. Siddiqua, J.N. Hahladakis, W.A.K. Al-Attiya. (2022). An overview of the environmental pollution and health effects associated with waste landfilling and open dumping. Environmental Science and Pollution Research. 29(39): 58514-58536.

[12] S. Nanda, F. Berruti. (2021). Municipal solid waste management and landfilling technologies: a review. Environmental chemistry letters. 19(2): 1433-1456.

[13] J. Crawmer, C.-H. Chen, B. Richard, R. Zelinsky, H. Pearlman In *An Innovative Volatile Organic Compound Incinerator*, 10th US National Combustion Meeting, April, 2017; 2017; pp 23-26.

[14] S. Roy, A. Bose, D. Basak, I.R. Chowdhury, Open landfill site and threat to the proximity resident's: Addressing perceived consequences of unscientific solid waste dumping using GIS techniques. In *Urban Environment and Smart Cities in Asian Countries: Insights for Social, Ecological, and Technological Sustainability*, Springer: 2023; pp 237-261.

[15] S. Mohan, C.P. Joseph In *Biomining: an innovative and practical solution for reclamation of open dumpsite*, Recent Developments in Waste Management: Select Proceedings of Recycle 2018, 2020; Springer: 2020; pp 167-178.

[16] S. Mor, K. Ravindra. (2023). Municipal solid waste landfills in lower-and middle-income countries: Environmental impacts, challenges and sustainable management practices. Process Safety and Environmental Protection.

[17] V. Grossule, M.C. Lavagnolo. (2020). OPTIMISED MANAGEMENT OF SEMI-AEROBIC LANDFILLING UNDER TROPICAL WET-DRY CONDITIONS. Detritus.(10): 160.

[18] N.N.R. Nik Ab Rahim, J. Othman, N. Hanim Mohd Salleh, N. Chamhuri. (2021). A non-market valuation approach to environmental cost-benefit analysis for sanitary landfill project appraisal. Sustainability. 13(14): 7718.

[19] P.G. Nidoni. (2017). Incineration process for solid waste management and effective utilization of by products. International Research Journal of Engineering and Technology. 4(12): 378-382.

[20] R. Zhong, C. Wang, Z. Zhang, Q. Liu, Z. Cai. (2020). PCDD/F levels and phase distributions in a full-scale municipal solid waste incinerator with co-incinerating sewage sludge. Waste Management. 106: 110-119.

[21] Y.-Q. Huang, Y. Zeng, J.-L. Mai, Z.-S. Huang, Y.-F. Guan, S.-J. Chen. (2024). Disposable Plastic Waste and Associated Antioxidants and Plasticizers Generated by Online Food Delivery Services in China: National Mass Inventories and Environmental Release. Environmental Science & Technology.

[22] D. Liu, S. Wang, R. Xue, G. Gao, R. Zhang. (2021). Life cycle assessment of environmental impact on municipal solid waste incineration power generation. Environmental Science and Pollution Research. 28: 65435-65446.

[23] B. Dastjerdi, V. Strezov, R. Kumar, M. Behnia. (2022). Environmental Impact Assessment of Solid Waste to Energy Technologies and Their Perspectives in Australia. Sustainability. 14(23): 15971.

[24] K. Petridis, P.K. Dey. (2018). Measuring incineration plants' performance using combined data envelopment analysis, goal programming and mixed integer linear programming. Annals of Operations Research. 267: 467-491.

[25] I. Tsuchimoto, Y. Kajikawa. (2022). Recycling of Plastic Waste: A Systematic Review Using Bibliometric Analysis. Sustainability. 14(24): 16340.

[26] A. Kijo-Kleczkowska, A. Gnatowski. (2022). Recycling of plastic waste, with particular emphasis on thermal methods. Energies. 15(6): 2114.

[27] M.E. Grigore. (2017). Methods of recycling, properties and applications of recycled thermoplastic polymers. Recycling. 2(4): 24.

[28] Z.O. Schyns, M.P. Shaver. (2021). Mechanical recycling of packaging plastics: A review. Macromolecular rapid communications. 42(3): 2000415.

[29] S.F. Zeng, P. Guo, C.Y. Hu, Z.W. Wang. (2023). Effects of mechanical recycling on optical properties and microstructure of recycled high-density polyethylene pellets and bottles. Journal of Applied Polymer Science. 140(6): e53446.

[30] M. Klotz, M. Haupt, S. Hellweg. (2023). Potentials and limits of mechanical plastic recycling. Journal of Industrial Ecology. 27(4): 1043-1059.

[31] D. Frączak, Chemical recycling of polyolefins (PE, PP): modern technologies and products. In *Waste Material Recycling in the Circular Economy-Challenges and Developments*, IntechOpen: 2021.

[32] T. Thiounn, R.C. Smith. (2020). Advances and approaches for chemical recycling of plastic waste. Journal of Polymer Science. 58(10): 1347-1364.

[33] S. Feih, A. Mouritz, S. Case. (2015). Determining the mechanism controlling glass fibre strength loss during thermal recycling of waste composites. Composites Part A: Applied Science and Manufacturing. 76: 255-261.

[34] S. Ono, H.T.S.A. Hewage, C. Visvanathan. (2023). Towards plastic circularity: current practices in plastic waste management in Japan and Sri Lanka. Sustainability. 15(9): 7550.

[35] W. Chen, Z. Huang, K.J. Chua. (2022). Sustainable energy recovery from thermal processes: a review. Energy, Sustainability and Society. 12(1): 46.

[36] C. Ram, A. Kumar, P. Rani. (2021). Municipal solid waste management: a review of waste to energy (WtE) approaches. Bioresources. 16(2): 4275.

[37] B. Patel, A. Patel, P. Patel. (2023). Waste to energy: a decision-making process for technology selection through characterization of waste, considering energy and emission in the city of Ahmedabad, India. Journal of Material Cycles and Waste Management. 25(2): 1227-1238.

[38] J. Ali, T. Rasheed, M. Afreen, M.T. Anwar, Z. Nawaz, H. Anwar, K. Rizwan. (2020). Modalities for conversion of waste to energy—Challenges and perspectives. Science of the total environment. 727: 138610.

[39] S.Y. Lee, R. Sankaran, K.W. Chew, C.H. Tan, R. Krishnamoorthy, D.-T. Chu, P.-L. Show. (2019). Waste to bioenergy: a review on the recent conversion technologies. Bmc Energy. 1(1): 1-22.

[40] A. Tabasová, J. Kropáč, V. Kermes, A. Nemet, P. Stehlík. (2012). Waste-to-energy technologies: Impact on environment. Energy. 44(1): 146-155.

[41] W.A. Qazi, M.F. Abushammala, M.K. Younes. (2018). Waste-to-energy technologies: a literature review. The Journal of Solid Waste Technology and Management. 44(4): 387-409.

[42] M. Iglésias, P. Santos, T.M. Lima, L. Leite. (2023). Thermal Recycling of Glass Fibre Composites: A Circular Economy Approach. Sustainability. 15(2): 1396.

[43] T. Dey, T. Bhattacharjee, P. Nag, A. Ghati, A. Kuila. (2021). Valorization of agro-waste into value added products for sustainable development. Bioresource Technology Reports. 16: 100834.

[44] R.A.D. Arancon, C.S.K. Lin, K.M. Chan, T.H. Kwan, R. Luque. (2013). Advances on waste valorization: new horizons for a more sustainable society. Energy Science & Engineering. 1(2): 53-71.

[45] Z. Usmani, M. Sharma, Y. Karpichev, A. Pandey, R.C. Kuhad, R. Bhat, R. Punia, M. Aghbashlo, M. Tabatabaei, V.K. Gupta. (2020). Advancement in valorization technologies to improve utilization of bio-based waste in bioeconomy context. Renewable and Sustainable Energy Reviews. 131: 109965.

[46] P. Wang, L. Qiao, W. Wang, J. Yu. (2023). Catalytic pyrolysis of waste composite plastics with waste FCC catalyst. Journal of the Energy Institute. 110: 101338.

[47] B. Igliński, W. Kujawski, U. Kiełkowska. (2023). Pyrolysis of waste biomass: technical and process achievements, and future development—a review. Energies. 16(4): 1829.

[48] M. Sekar, V.K. Ponnusamy, A. Pugazhendhi, S. Nižetić, T. Praveenkumar. (2022). Production and utilization of pyrolysis oil from solidplastic wastes: A review on pyrolysis process and influence of reactors design. Journal of environmental management. 302: 114046.

[49] T.R. Ayodele, O. Durodola, A.S. Ogunjuyigbe, J.L. Munda In *Effects of operating factors on the bio-oil produced from pyrolysis of plastic wastes using response surface methodology*, 2019 IEEE PES/IAS PowerAfrica, 2019; IEEE: 2019; pp 527-532.

[50] M.S. Qureshi, A. Oasmaa, H. Pihkola, I. Deviatkin, A. Tenhunen, J. Mannila, H. Minkkinen, M. Pohjakallio, J. Laine-Ylijoki. (2020). Pyrolysis of plastic waste: Opportunities and challenges. Journal of Analytical and Applied Pyrolysis. 152: 104804.

[51] I.M. Maafa. (2021). Pyrolysis of polystyrene waste: A review. Polymers. 13(2): 225.

[52] M. Munir, I. Mardon, S. Al-Zuhair, A. Shawabkeh, N. Saqib. (2019). Plasma gasification of municipal solid waste for waste-to-value processing. Renewable and Sustainable Energy Reviews. 116: 109461.

[53] O. Alves, L. Calado, R.M. Panizio, C. Nobre, E. Monteiro, P. Brito, M. Gonçalves. (2022). Gasification of Solid Recovered Fuels with Variable Fractions of Polymeric Materials. Energies. 15(21): 8139.

[54] O. Alves, L. Calado, R.M. Panizio, M. Gonçalves, E. Monteiro, P. Brito. (2021). Techno-economic study for a gasification plant processing residues of sewage sludge and solid recovered fuels. Waste Management. 131: 148-162.

[55] M. Yerizam, A. Syarif. (2021). Syngas characteristics from UCG gasification process with lignite and subbituminous coal types. International Journal of Research in Vocational Studies (IJRVOCAS). 1(2): 52-58.

[56] J.G. Speight, Chemistry of Gasification. In *Gasification of Unconventional Feedstocks*, Gulf Professional Publishing Location Boston: 2014; pp 30-53.

[57] M. Hossain, P. Charpentier, Hydrogen production by gasification of biomass and opportunity fuels. In *Compendium of hydrogen energy*, Elsevier: 2015; pp 137-175.

[58] M. Sajid, A. Raheem, N. Ullah, M. Asim, M.S.U. Rehman, N. Ali. (2022). Gasification of municipal solid waste: Progress, challenges, and prospects. Renewable and Sustainable Energy Reviews. 168: 112815.

[59] A. Kushwaha, V. Mishra, V. Gupta, S. Goswami, P.K. Gupta, L.K. Singh, C.B. Gupt, K. Rakshit, L. Goswami, Anaerobic digestion as a sustainable biorefinery concept for waste to energy conversion. In *Waste-to-energy approaches towards zero waste*, Elsevier: 2022; pp 129-163.

[60] L. Lombardi, E. Carnevale, A. Corti. (2015). A review of technologies and performances of thermal treatment systems for energy recovery from waste. Waste Management. 37: 26-44.

[61] U. Arena. (2012). Process and technological aspects of municipal solid waste gasification. A review. Waste Management. 32(4): 625-639.

[62] A. Demirbas. (2011). Waste management, waste resource facilities and waste conversion processes. Energy Conversion and Management. 52(2): 1280-1287.

[63] N. Saetang, S. Tipnee. (2022). Anaerobic digestion of food waste from fruits and vegetables to

improve stability and effectiveness. Maejo International Journal of Energy and Environmental Communication. 4(1): 55-60.

[64] J.N. Meegoda, B. Li, K. Patel, L.B. Wang. (2018). A review of the processes, parameters, and optimization of anaerobic digestion. International journal of environmental research and public health. 15(10): 2224.

[65] M. Laiq Ur Rehman, A. Iqbal, C.C. Chang, W. Li, M. Ju. (2019). Anaerobic digestion. Water Environment Research. 91(10): 1253-1271.

[66] B. Zhang, B.K. Biswal, J. Zhang, R. Balasubramanian. (2023). Hydrothermal treatment of biomass feedstocks for sustainable production of chemicals, fuels, and materials: progress and perspectives. Chemical Reviews. 123(11): 7193-7294.

[67] D.C. Elliott *Hydrothermal processing*; Pacific Northwest National Lab.(PNNL), Richland, WA (United States): 2011.

[68] R. Divyabharathi, P. Subramanian, Hydrothermal processing of lignocellulosic biomass to biofuels. In *Zero Waste Biorefinery*, Springer: 2022; pp 95-112.

[69] X. Wang, C. Li, C.H. Lam, K. Subramanian, Z.-H. Qin, J.-H. Mou, M. Jin, S.S. Chopra, V. Singh, Y.S. Ok. (2022). Emerging waste valorisation techniques to moderate the hazardous impacts, and their path towards sustainability. Journal of hazardous materials. 423: 127023.

[70] D. Hou, L. Lu, D. Sun, Z. Ge, X. Huang, T.Y. Cath, Z.J.J.W.r. Ren. (2017). Microbial electrochemical nutrient recovery in anaerobic osmotic membrane bioreactors. 114: 181-188.

[71] K. Nevin, T. Woodard, A. Franks, Z. Summers, D. Lovley, Microbial electrosynthesis: feeding microbial electrosynthesis: feeding microbes electricity to convert carbon dioxide and water to multicarbon extracellular organic. MBio 1, e00103–10. In 2010.

[72] K. Rabaey, R.A.J.N.r.m. Rozendal. (2010). Microbial electrosynthesis—revisiting the electrical route for microbial production. 8(10): 706-716.

[73] X. Li, I. Angelidaki, Y.J.W.r. Zhang. (2018). Salinity-gradient energy driven microbial electrosynthesis of value-added chemicals from CO2 reduction. 142: 396-404.

[74] K.P. Nevin, T.L. Woodard, A.E. Franks, Z.M. Summers, D.R. Lovley. (2010). Microbial electrosynthesis: feeding microbes electricity to convert carbon dioxide and water to multicarbon extracellular organic compounds. MBio. 1(2): 10.1128/mbio. 00103-10.

[75] A. Schievano, T.P. Sciarria, K. Vanbroekhoven, H. De Wever, S. Puig, S.J. Andersen, K. Rabaey, D.J.T.i.b. Pant. (2016). Electro-fermentation–merging electrochemistry with fermentation in industrial applications. 34(11): 866-878.

[76] N. Xafenias, C. Kmezik, V.J.B. Mapelli. (2017). Enhancement of anaerobic lysine production in Corynebacterium glutamicum electrofermentations. 117: 40-47.

[77] N. Couto, A. Rouboa, V. Silva, E. Monteiro, K.J.E.p. Bouziane. (2013). Influence of the biomass gasification processes on the final composition of syngas. 36: 596-606.

[78] A. Ramos, E. Monteiro, A.J.R. Rouboa, S.E. Reviews. (2019). Numerical approaches and comprehensive models for gasification process: A review. 110: 188-206.

[79] A. Sanlisoy, M. Carpinlioglu. (2017). A review on plasma gasification for solid waste disposal. International journal of hydrogen energy. 42(2): 1361-1365.

[80] R.C.J.U.E.d.C. Neves, FEM/dissertação, Campinas–SP. (2013). Reforma de gás de gaseificação por meio de tocha de plasma: ensaios preliminares.

[81] Q. Zhang, L. Dor, D. Fenigshtein, W. Yang, W. Blasiak. (2012). Gasification of municipal solid waste in the Plasma Gasification Melting process. Applied Energy. 90(1): 106-112.

[82] I. Janajreh, S.S. Raza, A.S. Valmundsson. (2013). Plasma gasification process: Modeling, simulation and comparison with conventional air gasification. Energy Conversion and Management. 65: 801-809.

[83] A. Ramos, A.J.R. Rouboa, S.E. Reviews. (2022). Life cycle thinking of plasma gasification as a waste-to-energy tool: Review on environmental, economic and social aspects. 153: 111762.

[84] M. Oliveira, A. Ramos, T.M. Ismail, E. Monteiro, A. Rouboa. (2022). A review on plasma gasification of solid residues: recent advances and developments. Energies. 15(4): 1475.

[85] A. Rahimi, J.M. García. (2017). Chemical recycling of waste plastics for new materials production. Nature Reviews Chemistry. 1(6): 0046.

[86] M.G. Davidson, R.A. Furlong, M.C. McManus. (2021). Developments in the life cycle assessment of chemical recycling of plastic waste–A review. Journal of Cleaner Production. 293: 126163.

[87] N. Fitzgerald, A. Bailey, J. Fitzgerald, G. Bentley, M. Klembara, K. Peretti *Plastics for a Circular Economy Workshop: Summary Report*; US Department of Energy (USDOE), Washington DC (United States). Office of …: 2020.

[88] S. Ügdüler, K.M. Van Geem, R. Denolf, M. Roosen, N. Mys, K. Ragaert, S.J.G.c. De Meester. (2020). Towards closed-loop recycling of multilayer and coloured PET plastic waste by alkaline hydrolysis. 22(16): 5376-5394.

[89] S. Ügdüler, K.M. Van Geem, R. Denolf, M. Roosen, N. Mys, K. Ragaert, S. De Meester. (2020). Towards closed-loop recycling of multilayer and coloured PET plastic waste by alkaline hydrolysis. Green chemistry. 22(16): 5376-5394.

[90] S. Al-Salem, A. Antelava, A. Constantinou, G. Manos, A.J.J.o.e.m. Dutta. (2017). A review on thermal and catalytic pyrolysis of plastic solid waste (PSW). 197: 177-198.

[91] F.M. Baena-Moreno, M. Rodríguez-Galán, F. Vega, B. Alonso-Fariñas, L.F. Vilches Arenas, B. Navarrete. (2019). Carbon capture and utilization technologies: a literature review and recent

advances. Energy Sources, Part A: Recovery, Utilization, and Environmental Effects. 41(12): 1403-1433.

[92] B.R. Patra, A. Mukherjee, S. Nanda, A.K.J.E.C.L. Dalai. (2021). Biochar production, activation and adsorptive applications: a review. 19: 2237-2259.

[93] W. Gao, S. Liang, R. Wang, Q. Jiang, Y. Zhang, Q. Zheng, B. Xie, C.Y. Toe, X. Zhu, J. Wang. (2020). Industrial carbon dioxide capture and utilization: state of the art and future challenges. Chemical Society Reviews. 49(23): 8584-8686.

[94] Y. Jing, A. Rabbani, R.T. Armstrong, J. Wang, Y. Zhang, P.J.J.o.C.P. Mostaghimi. (2022). An image-based coal network model for simulating hydro-mechanical gas flow in coal: An application to carbon dioxide geo-sequestration. 379: 134647.

[95] H.-J. Ho, A. Iizuka, E. Shibata. (2019). Carbon capture and utilization technology without carbon dioxide purification and pressurization: a review on its necessity and available technologies. Industrial & Engineering Chemistry Research. 58(21): 8941-8954.

[96] B.R. Patra, S.P. Gouda, F. Pattnaik, S. Nanda, A.K. Dalai, S.J.C.D.C. Naik, Conversion. (2022). A brief overview of recent advancements in CO2 capture and valorization technologies. 1-16.

[97] T.M. Gür. (2022). Carbon dioxide emissions, capture, storage and utilization: Review of materials, processes and technologies. Progress in Energy and Combustion Science. 89: 100965.

[98] J.A. Okolie, B.R. Patra, A. Mukherjee, S. Nanda, A.K. Dalai, J.A.J.I.j.o.h.e. Kozinski. (2021). Futuristic applications of hydrogen in energy, biorefining, aerospace, pharmaceuticals and metallurgy. 46(13): 8885-8905.

[99] S. Van Ewijk, J. Stegemann. (2016). Limitations of the waste hierarchy for achieving absolute reductions in material throughput. Journal of Cleaner Production. 132: 122-128.

[100] A. Damgaard, C. Riber, T. Fruergaard, T. Hulgaard, T.H. Christensen. (2010). Life-cycle-assessment of the historical development of air pollution control and energy recovery in waste incineration. Waste Management. 30(7): 1244-1250.

[101] M. Nelles, J. Gruenes, G. Morscheck. (2016). Waste management in Germany–development to a sustainable circular economy? Procedia Environmental Sciences. 35: 6-14.

[102] R. Geyer, J.R. Jambeck, K.L. Law. (2017). Production, use, and fate of all plastics ever made. Science advances. 3(7): e1700782.

[103] N. Ferronato, E.C. Rada, M.A.G. Portillo, L.I. Cioca, M. Ragazzi, V. Torretta. (2019). Introduction of the circular economy within developing regions: A comparative analysis of advantages and opportunities for waste valorization. Journal of environmental management. 230: 366-378.