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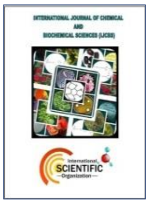

Cleaner Production, products and services: A review of technologies involved

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Abstract

A large amount of waste is produced every year across the world that causes serious environmental problems as well as depletion of the resource reservoirs. Waste management techniques are cutting-edge approaches to managing urban garbage. Due to the limitations of conventional solid waste management techniques that cause leaching of harmful chemicals to the land, advanced technologies are used to minimize the effect resulting in cleaner production. These technologies are more efficient and adaptable. Several areas use catalytic converters, filters and scrubbers for cleaner production by transforming the toxic emissions into less toxic chemicals and gases. Use of bio-pesticides, bio-catalysis and bioremediation has been demonstrated to be highly effective for cleaner production. Moreover, gasification, pyrolysis and anaerobic digestion are also helpful to convert the waste material into energy to get entered the closed loop system of energy and economy. These methods are cost effective but have some limitations. Renewable energy sources, such as solar, wind and hydro are integral to cleaner production as they provide sustainable and environmentally friendly alternatives to traditional fuels. Cleaner production is necessary as it maintains the quality of environment, conserve the dwindling resources and efficiently use them, corporate the market demand, beneficial for health and safety.

Keywords: cleaner production, waste management, waste minimization techniques, catalytic converter, circular economy.

Full length review article

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1. Introduction

Cleaner Production (CP) is a term that usually referred to uninterrupted applications of an environmental, economy related and technology related strategy which is interlinked with processes and products. Its aim is to enhance and improve efficiency while using the raw materials, energy and water by reducing recycling and abstaining from producing waste products by yielding economic and environmental paybacks for process of production. Environmental Management (EM) techniques and CP procedures are the instruments that work hard to maximize efficiency in the manufacturing process, input use, and industrial waste generation. We can define an innovation as the development and representation of innovative and new ideas and CP is an innovation in production methods, which is in the form of service and product and the whole way in which a service or a product can be presented or manufactured [1]. CP is an ongoing approach that can give a business or industrial facility an edge over rivals. To minimize waste, wastewater, and atmospheric emissions while optimizing the efficient use of energy and raw materials and reducing water consumption, the CP methods provide establishments and administrations with workable alternatives for side-by-side implementation in production processes. This is how they benefit businesses both environmentally and economically [2]. CP is a defensive approach in minimizing the effect of products and production on the environment. The major performers of CP are the corporations that regulate the manufacturing processes. These are intensely influenced by their clients, which may be public, private or other firms and legislations (by rules and regulations and taxes). Managing operations of a company in a responsible and environmentally conscious manner is one of CSR's primary responsibilities. Numerous assessments show how crucial it is to promote environmental management techniques and their advantages, especially when implementing EMS in businesses affects the ability of their processes, products, and environmentally friendly supply chains. By encouraging sustainable development, environmental protection policies can benefit society on an economic, sustainable, and social level (i.e., businesses, scientists, authorities, etc.) [3]. Two global environmental management systems, the Eco-Management and Audit Scheme or EMAS and the International Standard ISO 14001, are among the tools used by organizations to minimize their environmental impact. An expansion of this global standard, EMAS is an alternative environmental management system to ISO 14001. The International Organization for Standardization released the ISO 14001 standard [4].

Use of sustainable resources has many benefits, Mitigation and adaptation to climate change is one of the most significant advantages of using natural assets and renewable energy sources. It should be emphasized that the adoption of ISO 14001 as a standard can serve as a springboard for several environmentally beneficial initiatives, such as lowering emissions of SO_2, CO_2, and PM, as well as consuming less energy and losing less heat. Over the last 20 years, there has been an increase in the acceptance of voluntary environmental certifications like ISO 14001 and the Eco-Management and Audit Scheme (EMAS). The effects of implementing these kinds of credentials on performance have been extensively investigated in the academic literature [5]. Investigation is conducted from financial and environmental perspectives concerning formation connected to CP and inter-functional collaboration between environmental and production managers to enhance the overall performance of textile enterprises. The implementation of CP exposed findings from an energy and environmental audit, which showed that a textile company was not adhering to ISO 14000 environmental quality requirements. It was evident from analyzing the connection between China's foreign trade and regional environmental issues that public policy formulation and the use of CP in the textile industry are essential for reducing ecological effects [6]. One of the most important problems modern human society faces is environmental degradation. The ecology is seriously threatened by environmental deterioration and heavy metal contamination. Rapid urbanization and industrialization have resulted in heavy metal pollution. Since the 1940s, there has been a notable rise in the pace at which these metals are mobilized and carried through the environment. The Metal Mining and Finishing Industries use water and many other chemicals in their manufacturing chain that generate both solid and liquid harmful waste. Their major anthropogenic sources are industrial emissions, extraction of metals, smelting, and agricultural practices like the usage of phosphate fertilizers and pesticides. Their natural source is the weathering of rocks which contain metal and volcanic eruptions. Over threshold metal concentrations can lower soil fertility by disrupting the microbial balance of the soil. A thorough analysis of the ecotoxicology and environmental chemistry of dangerous metalloids and heavy metals demonstrates the need for action to reduce these substances' negative effects on the environment and the general population [7]. Therefore, green chemistry and cleaner production is the biggest need of the age. By implementation of green technology and pollution controlling techniques we can achieve cleaner production and serve the environment. The purpose of writing this article is to highlight the importance of cleaner production and to focus on the requirement of advanced technology for CP. This review aims to describe the waste minimization techniques, pollution control technologies, carbon capturing technologies; how waste can be used to produce energy. Also, the sources of renewable energy will be discussed. If there is any barrier while putting these technologies into practice, this review will provide strategies to overcome that barrier.

2. Waste Minimization Techniques

According to the size of production system, larger companies produce more waste than others. As the world gets more industrialized, a lot of nations are developing new industrial products to capture market shares. A significant amount of waste is produced because of the growing global population and rising standards of living. The bulk of manufacturing sectors have been compelled by the tight legal framework and the fast-rising waste creation to discover an appropriate way to manage their waste. Therefore, there is greater need of minimization that waste by the application of CP practices. According to size of the business, an estimation is provided about the implimentation level of CP practices in the figure 1 [8]. The main objective of waste minimization technologies is to reduce or eliminate the generation of harmful and tenacious wastes. These technologies approach redesigning the products, and processes and changing consumption patterns. These techniques provide environmentally resourceful, cost-effective, and economically efficient management of waste. Here the most frequently used techniques are discussed[9].

2.1. Solid waste Management and 4R techniques

In recent years, the terms "solid waste management" (SWM) and "4R" (reduce, reuse, recycle, and recover) are commonplace. SWM is a cutting-edge approach to managing urban garbage that is utilized in many nations to enhance operation quality and accomplish the objectives of the 4R strategy. The source isolation, distribution and processing, storage and recovery stations, management and regeneration, and disposal of ultimate waste are all included in the chain processes. Social resources and waste management technologies support waste flow and recovery at every level. The problems associated with environmental degradation are becoming increasingly serious as the economy and manufacturing sector expand [10]. The local community and government had a big problem with waste disposal. Consumers purchase and utilize products that cause a significant amount of waste. Since garbage generation is significant and the number of consumers has expanded, waste management has become a serious issue. Due to the massive amount of waste that has been produced, massive waste-management measures are required. Because the pace at which waste gets produced depends on a country's level of social and economic development, developed nations typically generate far more municipal solid waste per person than developing and third-world nations. The four R's: Reducing, Reusing, Recycling, and Recovering of the waste are the strategies used to lessen the damaging effects that manufacturing and commerce have on the environment [11]. The Hybridized Intelligent Framework (AIHIF), which is based on artificial intelligence, has been developed now a day to optimize the waste management process through automated recycling. The system uses graph theory and machine learning to optimize waste collecting over a small distance. AI design technological advances, which support various methods tailored to interest groups, gather their data and significantly enhance the functioning, accuracy, and efficiency of planning for the environment and urban management. Artificial intelligence has demonstrated and is expected to be beneficial in the future for managing the environment and pollution, managing industrial waste worldwide, and accomplishing the Sustainable Development Goals (SDGs) established by the United Nations Development Programme (UNDP) [12]. Several critical techniques require being built into an integrated strategy for waste reduction and control to be effective. First, separating garbage at the source lowers the amount and moisture content of waste that is delivered for disposal while also preventing contamination of reusable goods. Maintaining proper inventory and raw material management is essential to maximizing process efficiency and reducing waste. Additionally important are product modification and substitution, such as redesigning goods and packaging to decrease waste and swapping out non-recyclable materials for recyclable or less polluting ones [13]. Waste minimization is further aided by modifying input materials by making improvements to raw materials before they enter into the manufacturing process. Technological innovations that result in more efficient, low-waste manufacturing processes—particularly those involving changes to processes and equipment—are some of the most effective ways to reduce waste. Reusing and recycling materials on-site enhances resource sustainability and reduces the requirement for new raw materials. When combined, these strategies can greatly increase the effectiveness of waste management while minimizing the adverse impacts of industry on the environment [14]. Waste can take many various forms and can be characterized in a number of ways. Every form of trash generated in a nation should be formally classified into one of these groups, according to the national waste disposal strategy, in order to provide an appropriate framework that is sustainable in terms of both the environment and the economy: (i) garbage from cities, (ii) from industry, and (iii) from medical operations. Waste comes in several forms. Among them are wastes from construction and demolition projects, farms, homes, businesses, and mines. Based on their physical properties, waste can be classified into three primary categories: gas, solid, and liquid [15].

2.1.1. Waste of electronic Equipment's

Due to its unique chemical composition and continuous creation, waste of electrical and electronic equipment (WEEE) treatment is considerably more complex than that of ordinary solid waste management. Because electronic equipment depends on electromagnetic fields or electrical currents to function, it is considered end-of-life or electronic and electric equipment waste (WEEE). Computers, laptops, cell phones, photovoltaic (PV) panels, liquid crystal displays (LCDs), and light-emitting diode (LED) displays are the four categories into which waste electrical and electronic equipment (WEEE) is divided. With a recycling rate of 65%, photovoltaic panels are a typical type of silicon-based electrical equipment. Glass and aluminum recovery come first in the recycling process, which is then thermally treated at 650°C [16]. Liquid crystal and light-emitting diode screens make up another type. Moreover, because of their small size and rapid manufacturing pace, which make recycling difficult, mobile phones have the lowest recycling rate. In terms of recycling resources for smartphones and smart batteries, lithium is the most lucrative. It is crucial to the recovery of heavy metals including lead, silver, and gold. The fragments of these outdated devices typically contain elements that may be systematically recovered, such as glass, metals, and plastics, creating an inflow of raw materials. While e-waste does contain some valuable elements, it also contains poisonous compounds. As an outcome, every year more valuable items must be recycled, and the negative effects they have on the environment should be minimized [17].

2.1.2. Clinical waste

Healthcare organizations have grown structurally in response to both the growing population and the rising need for healthcare services. The health sector thus generates more trash associated with healthcare daily. Its resources and efforts are insufficient to deal with the growing number and variety of medical waste. Worldwide, the COVID-19 pandemic has resulted in a significant increase in medical waste production that contained face masks, gowns, gloves, syringes, sharps, etc., primarily from clinics, hospitals, and other healthcare facilities. Efficient handling of medical waste can be achieved through the implementation of targeted protocols such as exact identification, collecting, classification, preservation, transport, handling, and ultimate disposal. Following separation, the trash can be recycled using a rotary kiln burning facility, plasma incineration, high-heat pyrolysis, and other methods [18][19]. Healthcare risk waste (HCRW) is contaminated with chemicals, pathogenic viruses, extremely toxic metals, and bacteria that may transmit disease. Garbage has the potential to harm the ecosystem and cause pollution. Wind-borne pathogens and toxic substances from negligently disposed-of HCRW can infect humans. Using plasma pyrolysis is the safe treatment method for HCRW. It transforms organic waste into beneficial byproducts that are marketable. All the microbes in the garbage are disinfected by the extreme heat generated via plasma. The HCRW is pyrolyzed into CO, H_2, and other gases when it comes into touch with the plasma arc. Hazardous chemicals, radiation, and dangerous bacteria are all present in HCRW due to their contagious nature. As a result, treatment must be carried out before disposal. Nevertheless, HCRW treatment methods harm the environment[20].

2.1.3. Rubber Waste

Because of the great demand in the market, rubber manufacture and production have continued throughout ages. The figure indicates that the quantity of natural rubber (NR) produced in 2015 compared to 2000 has doubled. Because a significant amount of raw rubber—roughly 70% of the yearly output of NR—goes into the tire manufacture industry, old tires are one of the biggest causes of rubber waste in the environment. The European Commission introduced the 4Rs (reduce, reuse, recycle, and recover) disposal approach on November 19, 2008, with the goal of improving the treatment of rubber waste. This approach is now commonly used in trash processing [21]. Rubber waste is reduced and disposed of by combining several tactics that follow the principles of the 4R waste management framework: reduce, reuse, recycle, and recover. Retreading technology is used on end-of-life tyres to decrease waste by replacing worn treads with new ones, allowing the tyres to be reused and reducing the accumulation of waste tyres. Rubber waste may be decreased by designing goods and procedures to improve energy and material efficiency, minimize waste, and maximize reuse. Reuse is the practice of reusing complete tyres without any kind of treatment, although there is a chance that additives and degraded elements will leak into the environment as a result. Retreaded tyres are recycled, which lowers the amount of rubber consumed. Rubber waste may be recycled by grinding it into smaller particles or by adopting de-vulcanization techniques to extract the rubber component, which can then be homogenized or used to produce composite products. Pyrolysis is a process used in recovery that yields a variety of goods, such as steel wire, hydrocarbons, and carbon black. Rubber waste may also be utilized as an alternate fuel or energy source to generate power [22][23].

2.2. Closed loop system

These days, it's acknowledged that creating closed-loop supply chains and reverse logistics for both established and emerging businesses is essential for our civilizations. The volume of publications—particularly those that take into account case studies from a variety of industries—clearly demonstrates an increasing fascination in reversal issues. When it comes to end-of-life (EOL) products, the traditional supply chain methodology—now known as the forward supply chain—claims no accountability. Subsequently, the reverse logistics (RL) or reverse supply chain endeavors to take responsibility for EOL products in the most ecologically sustainable way feasible [24]. Supply chain evolution results in an integrated method that takes into account both forward and reverse supply chains that are concurrently generated as closed-loop supply chains (CLSC). A supply chain that is closed-loop has two primary responsibilities: first, it manages value-added procedures to meet customer needs (as before); second, it attempts to gather end-of-life products (also known as return products) from consumers and ascertains the most efficient methods of accounting for them. To achieve cleaner production, evaluations of hotspot research and process optimization, followed by better design, are crucial. Complex linkages between cleaner manufacturing and social and economic performance are also involved. It contributes significantly to sustainable development [25]. Closed-loop systems that enhance resource reuse in industrial processes while minimizing waste are essential to cleaner production. In an enclosed-loop system, goods and materials are intended to be recycled, repurposed, or remanufactured at the end of their functional lifespan being thrown away as trash. A fundamental tenet of the circular economy is the decoupling of economic growth from resource use and environmental deterioration through the use of closed-loop technology. Closed-loop manufacturing lessens greenhouse gas emissions, minimizes environmental pollution, and conserves natural resources by recycling materials and cutting waste. Collaboration is necessary for the implementation of closed-loop systems at every stage of the supply chain, from raw material suppliers to final consumers. It also entails developing goods, using eco-friendly materials, collaborating with stakeholders, and investing in the tools and technologies that are required [26].

CP encompasses the reusing and rethinking of resources, as well as the repair, refurbishing, and maintenance of items to be recycled back into the supply chain. This goes beyond the traditional "reduce, reuse, and recycle" approach. Closed loop system involves forward and reversal supply process that is indicated in figure 2. In forward process raw material is first sent to the processing unit and then to assembly lines. When the product is formed it is then supplied to the distributer. Consumers can buy their product by visiting the distributer. If there is a fault in the product, the process goes in reverse direction as shown in figure 2[27].

3. End of Pipe Technologies

CP refers to the use of less energy and resources and the replacement of more hazardous goods (for both the environment and human health) with safer alternatives. CP was the industry's response to the WCED (1987) demand for sustainable development, which was further developed in Rio's Agenda 21 (UN, 1992). Over the last twenty-five years, the idea has been implemented. Its methodology, application, and scope all altered during this time. This gave an idea that was first introduced to remind industry of its environmental duties a deeper socio-economic consequence. Generally speaking, automobile emissions of pollutants are modest; but, as more vehicles are used, more environmental pollutants are produced. Transportation contributes about 35% of carbon monoxide, 30% of HC, and 25% of NOx that are released into the environment. These contaminants are harmful to both the environment and public health. Vehicle emissions are often influenced by the air-fuel ratio. Engine modifications, the pretreatment process of fuel, fuel additives, and recirculation of exhaust gases, positive crankshaft ventilation, and the use of catalytic converters are the methods used to control exhaust gas emissions [28].

3.1. Catalytic Converters

Eugene Houdry, a French mechanical engineer, created the catalytic converter for the first time in 1930. An instrument used in cars to reduce pollution is a catalytic Converter. More hazardous pollutants created by car exhaust are transformed into less hazardous pollutants by it.A catalytic converter is an emission control device for reducing the toxic gas emissions from an internal combustion engine. The catalytic reaction is the reaction between catalyst surfaces and remaining toxic gases present in the exhaust. The catalysts are used as a reduction and an oxidation catalyst is present in the ceramic monolith structure and coated with metal support[29][30].

3.1.1. Catalytic Converters in Automobiles

A catalytic converter is a straightforward device that lowers the amount of pollutants released from moving cars through simple redox processes. It transforms the toxic emissions that come from an automobile engine into less toxic gasses. It is made up of an insulating layer-filled ceramic honeycomb interior housed in a metal housing. The tiny wall channels within its honeycomb interior have an aluminum oxide wash finish on them. This coating, which contains Pt, Rh, and Pd among other precious metals, is porous and increases surface area, hence facilitating more reactions. The converter converts the undesirable pollutants by straightforward oxidation and reduction processes. Electrons are lost during oxidation, whereas they are gained during reduction. The fuel injection system is managed by the catalytic converter. To keep the catalytic converter operating at the stoichiometric point and close to 100% efficiency, the engine adjusts the air-to-fuel ratio based on the oxygen sensor's observations of the amount of oxygen in the exhaust stream [31].

$$\textbf{CO + Hydrocarbon + Oxygen} \xrightarrow{Catalyst} \textbf{CO}_2\textbf{+ H}_2\textbf{O}$$

For cars, a catalytic converter is essential because it lowers the ambient temperature of the burning gases, which is necessary to lower NOx emissions while also lowering CO and HC emissions. The catalytic converters increase in the delay period temperature is the cause of the increase in HC, NOx, and CO conversion efficiency. Toxic contaminants are present in fewer amounts as the reaction time gets shorter[32].

3.1.2. Catalytic Converters in Wastewater Treatment

The demand for fresh water is fueled by industrial use, agricultural irrigation, and human consumption, and it is rising as the world's population does. It would be ideal to have more affordable and environmentally friendly ways to treat unfit-for-human consumption water, especially in isolated or rural areas. The possibility to directly transform hazardous chemicals in water into harmless compounds exists because of heterogeneous catalysts. Although heterogeneous catalytic reaction methods are often associated with large-scale industrial chemical production, they can also be applied at smaller scales, such as in automobiles where they are utilized in catalytic converters to break down gaseous pollutants from fuel combustion. Catalytic converters are also used for the reduction of toxic metal ions. Contamination of drinking water with hexavalent chromium ranks as one of the most serious issues caused by industrial effluent discharge[33][30]. Due to its high solubility in water, the metal hexavalent chromium is believed to be demonstrated to be carcinogenic to humans because it can easily permeate cell membranes and form reactive oxygen species, also known as ROS, and many unstable intermediates. Furthermore, mutagenesis and damage to DNA are caused by ROS and hexavalent chromium intermediates. As a result, the conversion of Cr(VI) to Cr(III) is highly advantageous because Cr(III) has no toxicological significance. Particularly considering practical applications for the removal of harmful pollutants from the environment, photo catalysis technology is a very attractive green approach when compared to other widely used methods such as adsorption, chemical reduction, electrochemical method, bioremediation, and ion exchange [34]. Attempts to convert poisonous Cr(VI) to harmless Cr(III) have been made recently in research using a variety of nanomaterials. It should be mentioned that, for the reasons listed below, the elimination of all chromium risks from water may require more than just reducing the hazardous Cr (VI) to Cr (III). Although chromium (VI) oxide is a highly soluble chromium compound with a solubility of 1680 g/L, its reduced product, chromium (III) compounds, are not soluble in water and might accumulate on the surface of Nano-catalysts, potentially impacting their long-term stability[35][36]. In water, the reduced metabolite chromium (III) can also bind to suspended particles that float. The full detoxification of chromium necessitates the removal of all suspended particles from the treated water due to the re-oxidation of Cr(III) to Cr(VI) under diverse natural environment conditions. Another crucial prerequisite for the catalyst's capacity for repeated reduction is its recyclable nature, which has received little attention in the literature[37].

Only 3% of the water on Planet is clean enough to drink, despite the fact that water occupies 70% of the planet's surface. By 2025, half of the world's population will face freshwater scarcity due to rising global population pressures that will put freshwater supplies under unprecedented strain. Water quality affects the useful uses of water in addition to its quantity. The majority of pure water sources are already in use, which means that ever-degraded water quality must be used. Low-molecular-weight organic compounds known as CVOCs, which include vinyl chloride (VC), trichloroethylene (TCE), trichloroethane (TCA), and chloroform (CF), were extensively employed as degreasing agents in the automotive, electronics, and military sectors. At the moment, their application in consumer goods, dry cleaning, and chemical manufacture is restricted. Damage to the brain system, liver, and lungs is among the health impacts on humans. After being consumed, nitrate can be metabolically changed into nitrite, which can then combine to generate potentially cancer-causing N-nitroso compounds[38][39].

3.1.3. Catalytic Converters in Oil Refineries

The fluid catalytic cracking process is widely used to convert gas oil and air wastes into high-octane gasoline. The unit has two reactors: the riser reactor, which handles endothermic cracking and coke deposition on the catalyst, and the regenerator reactor, which uses air to burn off coke. The regeneration process supplies the heat needed for the endothermic cracking events along with reactivating the catalyst pellets. The creation of novel, extremely active cracking catalysts and the addition of additives that significantly increase the catalyst's productivity and selectivity enable the completion of the cracking processes in the riser. By removing steam, the particle separator vessel serves as a disengaging chamber to separate the catalyst from the gaseous products. The complex structure of the FCC unit is attributed to the strong interactions between the riser and the regenerator reactors, in addition to the uncertainty in the kinetics of the cracking, deposition, and burning of coke. The viewpoints of control and process modeling make this complexity clear. The operation and design of the FCC units are the focus of extensive research due to their complexity and the substantial financial benefits they provide [40]. In the refining process, vacuum gas oil is converted into more expensive gasoline blended components and additional products using fluid catalytic cracking catalyst or (FCCCs). The primary recycling method for wasted FCCC, which has been documented in the literature, involves using them as a raw material, partially substituting sand and cement powder, in the manufacturing of concrete and mortar. Their usage as catalysts for the pyrolysis and gasification of plastic and biomass, as well as for the synthesis of synthetic fuels, are some other small uses. These procedures have not been extensively developed at the industrial scale, despite their significance. The primary option for handling is still to dispose of it in a landfill or use it to mix concrete[41].

Spent may be recovered, such as nickel and vanadium. However, because rare earth elements' rarity and limited availability result from their production being concentrated in a few nations, these catalysts are an intriguing source of secondary raw materials in the future. In the process of refining petroleum, replacing inactive catalysts is a substantial expense. Catalysts are therefore renewed and regenerated until the catalytic activity is severely reduced and new catalysts must be used in their stead. Certain cracking catalysts, such as HDC, require regeneration and then rejuvenation in order to be reactivated. While regeneration—which involves calcining coke—usually goes hand in hand with rejuvenation, rejuvenation does not necessarily go hand in hand with regeneration [42]. Rejuvenation eliminates alkali and other metal ions from the catalyst, which raises the proton acidity of the catalyst since these ions are poisoning the metal sites. The most used technique for oxidizing coke is oxidative regeneration. Though research is always being done to enhance the regeneration process and reduce operating costs, these approaches are well-established and widely employed in the oil refining sector. The automotive and construction sectors do not currently have a strong working relationship in terms of technology support, standard equipment investments, training, and knowledge transfer. In actuality, cooperation between a numbers of local players in Malaysia can enable ELV recycling[43].

3.2. Scrubbers and Filters

The level of air pollution has increased significantly in recent years. Annually, the levels of sulfur dioxide (SO_2) and nitrogen oxides (NOx) that contribute to air pollution have increased, significantly affecting human health and industrial output. Wet scrubbing is a gas separation technology that offers significant economic and practical benefits for the simultaneous removal of SO_2 and NOx. With the adjustment of the industrial structure, the emission of particulate matter has been effectively regulated in several locations. However, the atmospheric impact of sulfur dioxide (SO_2) and nitrogen oxides (NOx) has grown more significant. Sulfur dioxide (SO_2), nitrogen monoxide (NO), and nitrogen dioxide (NO_2) are the main constituents found in the flue gas produced by burning coal. According to meteorological data analysis, there is a progressive increase in the fraction of NO_2 in the Earth's atmosphere. Elevated levels of SO_2 and NOX within certain thresholds have significant impacts on both industrial productivity and human well-being, particularly on the respiratory system, especially in vulnerable populations as children and the elderly. The combination of SO_2 and NO_X with water molecules in the atmosphere can produce corrosive acidic compounds that can cause damage to equipment and goods in industrial facilities [44]. End-of-pipe technology, such as wet scrubbers, is frequently employed within industrial settings to reduce air pollution. Using a liquid, generally water, to remove contaminants in exhaust gases before releasing them into the atmosphere, they function as pollution control devices. Both industrial processes and human health are negatively impacted by the accumulation of particulate matter (PM) and small particles. PM is a complicated combination made up of many different kinds of particles, many of which have the potential to have negative effects. The industry uses three distinct forms of fine particles, or dust-catching mechanisms: impaction, interception, and diffusion. Temperature and humidity might be effectively controlled to integrate the cleaning procedure into a single entity whereby toxicity increases with decreasing particle size. Wet scrubbers are mostly employed in foundries to segregate the particle discharge from the furnace. Additionally, wet scrubbers are employed in many sectors such as chemical engineering, cement, textile, mining, and paper mills to effectively remove particle emissions from the air or gas stream. Furthermore, wet scrubbers are employed in the circulating fluidized bed (CFB) burning process to segregate different particulate materials and polluting gases. A schematic diagram of a packed wet scrubber is shown in figure 6 [45]. When the pollutant gas is released from the wet scrubbing system, the exhaust gas contains large amounts of water molecules, and the waste liquid is released right after the solution has absorbed the gas. Because of the high water consumption in the wet scrubbing system—especially in places with limited water resources—the water must be recycled. The high-heat flue gas at the entrance is initially unsaturated during the wet scrubbing operation, and the slurry's moisture will gradually seep into the flue gas. The temperature of the flue gas keeps dropping during the water contact spraying operation, and the moisture content of the flue gas rises until saturation. Following that, the saturated flue gas's temperature keeps dropping, and as a result of super saturation, the flue gas will produce condensed water. Thus, the foundation for determining whether the system saves water is a comparison fig of the evaporated and condensed water. Trade openness has made environmental goods (EGs) more accessible, which presents a chance for a sustainable economy. EGs include a range of goods used for resource management (i.e., preserving and maintaining the stock of natural resources and, thus, safeguarding against depletion), environmental monitoring, and environmental protection (i.e., reducing, preventing, and eliminating pollution and any other degradation of the environment) [46].

Less developed nations may be essential to the worldwide chains of value of EGs, even while wealthy nations still control the majority of EG commerce. A reduction in pollution intensity can be attributed to improvements in pollution abatement technology as well as a move toward cleaner components or processes. According to our theoretical paradigm, EGs will aid in reducing pollution intensity if they can support abatement technologies. In particular, it was also mentioned that a significant portion of China's intensity decline may be attributed to technical advancement. As a result, we must conduct an empirical investigation to see if EGs can encourage technology upgrading. China is a very varied country, and the ways that imported EGs influence the level of pollution may vary according to the unique conditions in each area. As a result, we retested the channels that had an impact on various city groupings [47]. While it is frequently argued to limit the competitiveness of domestic firms and occasionally discourage local employment, the social norm of being environmentally considerate has become widely accepted across societies, making intergovernmental coordination on climate change issues more difficult. Therefore, any regulation that makes it easier for trade unions to unite around climate problems would be a positive step forward and might aid in the industry's internalization of environmental concerns. When it comes to company plans, technology is essential for achieving competitiveness and minimizing environmental effects. The regulatory framework in which the company works also has an impact on these procedures. There is no doubt that different nations have different environmental regulations [48]. It has been less effective in identifying the requirements or the conditions required for innovation in other nations, even while the legislative frameworks of some have provided businesses with the freedom and the incentives to find creative solutions to environmental concerns. During this time, the Swedish pulp and paper sector achieved very extensive reductions, up to 90% of chemical oxygen requiring chemicals, among other things. Furthermore, it is acknowledged that Sweden pioneered the non-chlorine pulp industry, which surfaced towards the close of the 1980s. In addition to significantly reducing emissions, the firm gradually improved process technology, allowing the release of a certain grade of total chlorine-free bleached pulp (TCF) on the market [49]. Through examining this shift, we want to provide historical insights into "black box" processes that pertain to how markets and regulations affect businesses' long-term capacity to develop new technologies and transition to more environmentally friendly production methods. Because of the associated health and odor issues, the atmospheric release of volatile chemicals is becoming an increasingly significant environmental and societal hazard. This makes wastewater treatment plant (WWTP) emissions one of the primary sources of odor emissions. These emissions' composition varies throughout the WWTP, but they usually consist of a complex mixture of low-molecular-weight organic molecules, amines, and reduced sulfur compounds. Ammonia and hydrogen sulfide are the two main inorganic odorous molecules found in these sources, according to several investigations that have concentrated on identifying the key malodorous compounds present. However, the study is more difficult due to the variety of chemical components that cause odors [50]. The efficiency of the technology and cost optimization is taken into consideration while choosing the treatment technique for odor control. The most well-known method of chemical scrubbing on an industrial scale is traditional chemical scrubbing due to its great efficiency at gas contact durations of only one or two seconds. However, there are several significant disadvantages to chemical scrubbing, including high running costs and the use of toxic chemicals to remove pollutants. Wet-scrubbing filtration is used to collect iodine and aerosol. It must be located outside of CV or on the reactor building's rooftop due to its size. The reactor system's gases will travel through three stages of filtration: a metal fiber filter that collects droplets and aerosol that pass past the metal scrubber, an AgX (silver-loaded zeolite) filter that removes the bulk of the elemental iodine and aerosol. To improve filtration, the steam/gas combination is broken up into tiny bubbles during the first step of filtration. To maintain good function, it is vital to limit the pressure drop throughout these stages [51].

4. Eco-biotechnology for Cleaner Production

Eco-biotechnology is the application of engineering and science expertise to repair and revitalize the environment that has been harmed. This field gained prominence and expanded in the 1980s along with the establishment of industry standards, the enforcement of compliance, and the enactment of environmental protection laws. It is not a recently discovered field of study. It has been around for many generations, and we are pretty familiar with some of the older methods, such as compositing and wastewater treatment. Although chemical engineering is essentially where it started, other scientific disciplines including biochemistry, environmental microbiology, molecular biology, and environmental engineering have contributed to its progress throughout time. Since a clean environment is in danger and natural resources are being exhausted as a result of growing industrialization, urbanization, and other developments [52].

4.1. Bioremediation

Because bioremediation contains ecologically beneficial ingredients, it has proven to be authentic and successful. It can be finished in situ or ex-situ, depending on a few different factors. The process of using microorganisms to remove or break down contaminants is known as bioremediation. The microbial cycles involved in bioremediation are usually regular components of respiration, variation, or adaptability and are often linked to the metal redox or carbon cycles. Therefore, bioremediation often occurs without direct intervention; nevertheless, bio augmentation and bio-stimulation are often important for the complete removal of contaminants in a reasonable amount of time. Using a variety of microorganisms, heavy metal bioremediation has been widely used as an alternative to traditional methods. Extremely high salinity levels, high temperatures, heavy metals, and nutritional stress are examples of extreme ecological settings in which microalgae with remarkable biological traits, such as high photosynthetic production, may thrive [53]

4.2. Bio pesticides

Bio-pesticides are a competing subclass of pesticides that are naturally occurring organisms or substances that, except those that disrupt pests' nervous systems, limit the population development and proliferation of pests through a variety of methods of action. Pips, biochemical bio-pesticides, and microbial bio-pesticides are the three classes into which they are divided. Biochemical bio-pesticides are natural or precisely manufactured chemicals with natural active components that control pests without harming humans, the environment, or the target bug. Transgenic plants, or PIPs, are plants that are not appropriate for pest assault. Agrochemical use has increased to achieve sustainable crop production. The long-term use of agrochemicals has changed the ecosystem and non-target animals' health. The environmental effects of various pesticides vary depending on their chemical and physical properties. The characteristics of commercial pesticides that demonstrate how they pollute the environment include their non-target toxicity, sorption-desorption, transformation, persistence, metabolism, and destruction [54].

Table 1. Types of waste along with possible minimization techniques

Type of waste	Components of Waste	Appropriate Waste Minimization Technique
Electronic Waste	Fragments of electronics, home appliances, computers, cell phones, lighting equipment, and communication gadgets.	• Reduce the use of toxic substances • Recycling of plastic and broken glass etc. • Use alternate of toxic substances
Rubber Waste	Old and used tires, other stuff of rubber	Reduce, Re-usage, recycling and recovery of this waste
Industrial Waste	Waste water, solid waste	Recovery before disposal
Clinical Waste	Face-masks, gloves, syringes, sharps, gowns, drip-bottles, used bandages etc.	Recycling is necessary because the world has no alternate to these materials.
Agricultural Waste	Waste from livestock, aquaculture, agriculture-related industries, and crop leftovers	Composting, direct combustion, pyrolysis, production of biofuel etc.
Nuclear Waste	Unreacted substance and byproducts from nuclear reactors, ionizing radiation etc.	• Use minimum quantity of active material, • Pretreatment of unreacted substance before disposal

Table 2. Fuel with the corresponding contaminants and catalyst

Fuel Source	Waste product	Catalytic Substance	Remarks
Petrol engine	NOx, carbon dioxide and hydrocarbons	Pt/Pd/Rh- Al_2O_3 coated on ceramic and metallic monolith	Stoich. Air-fuel ratio
Compression-ignition engine (for light vehicles)	Carbon monoxide, Hydrocarbon compounds, Nitrogen oxides	Pt/Rh/BaO/Pd/Al_2O_3 coated on monolith of metal and ceramic	Switches from oxidizing to reducing conditions
Compression-ignition engine (for trucks and buses etc.)	Carbon monoxide, Hydrocarbons, Nitrogen oxides	V_2O_x/TiO_2 on monolith of ceramic (reduction of NOx), Pd/Al_2O_3/Pt(oxidation of HCs and CO)	It uses NH_3 and $(NH_2)_2CO$ as reducing agent.

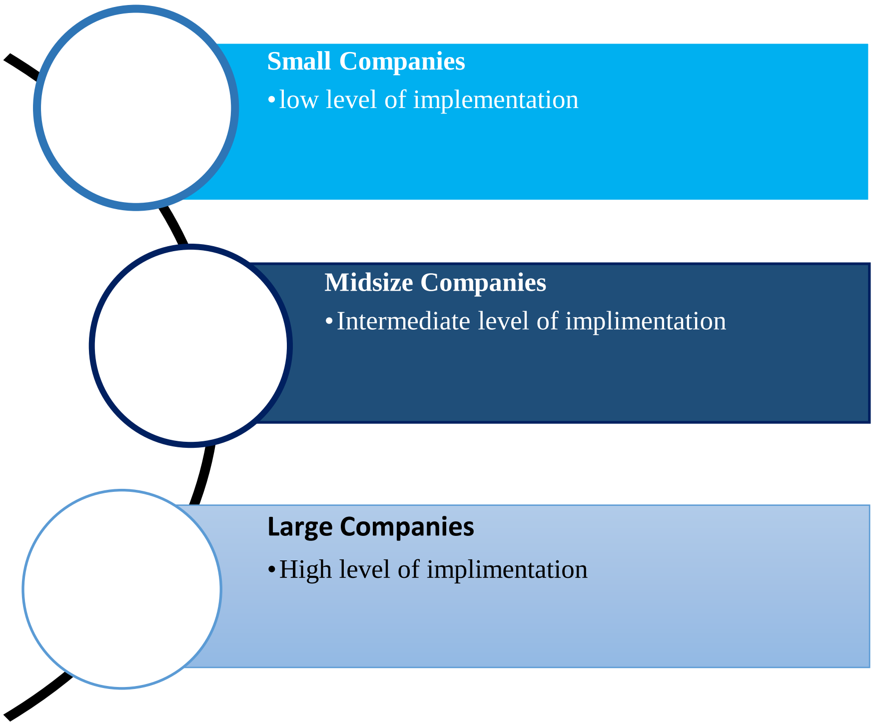

Figure 1. CP practice implementation level according to size of the business

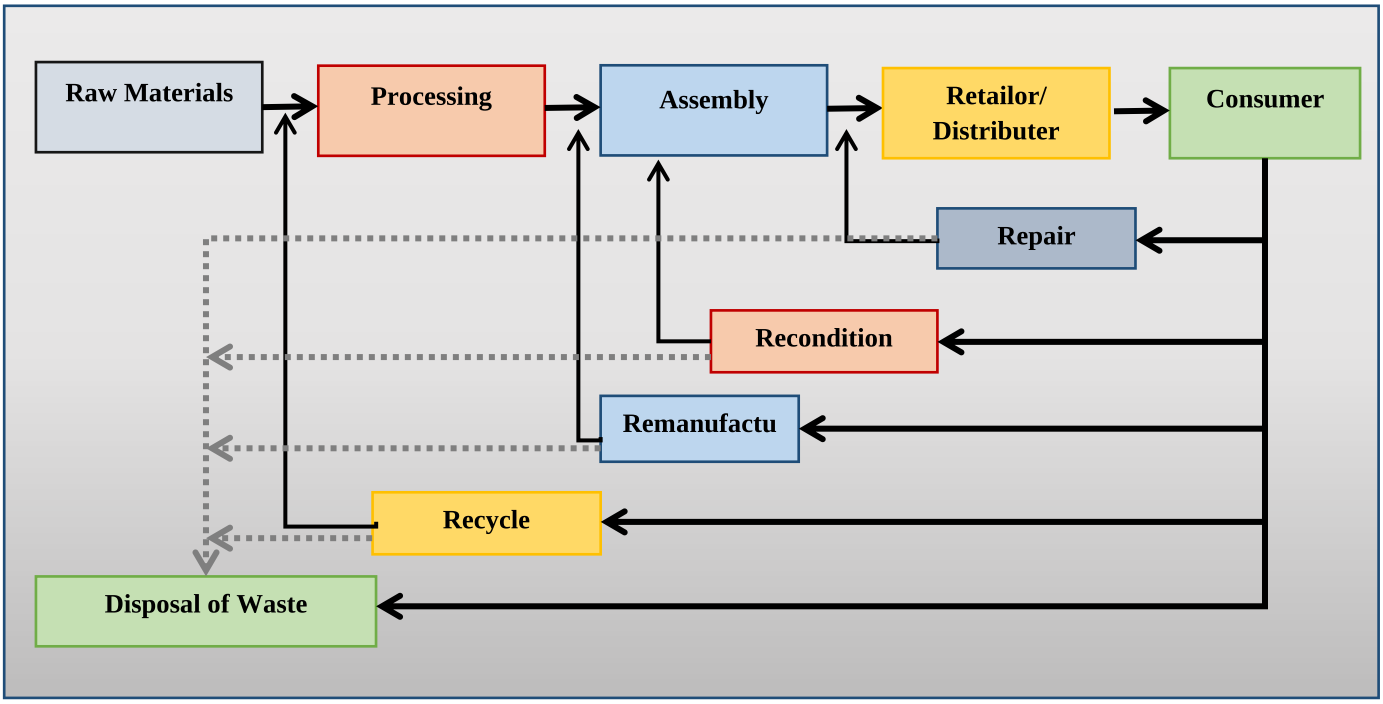

Figure 2: Forward and reversal supply process

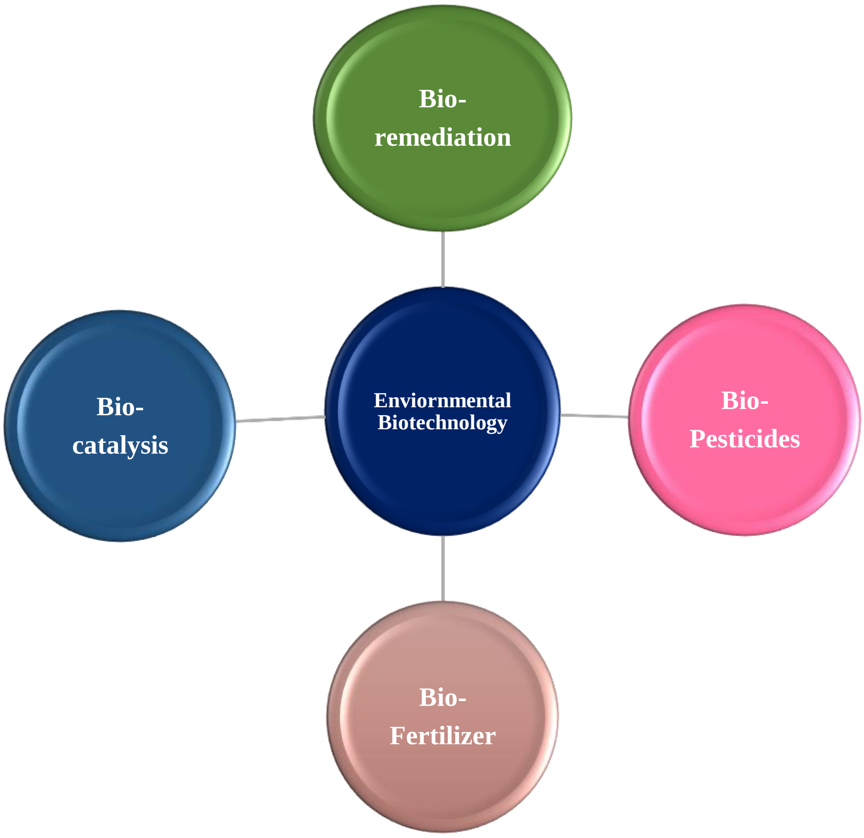

Figure 3: Methods involved for cleaner production

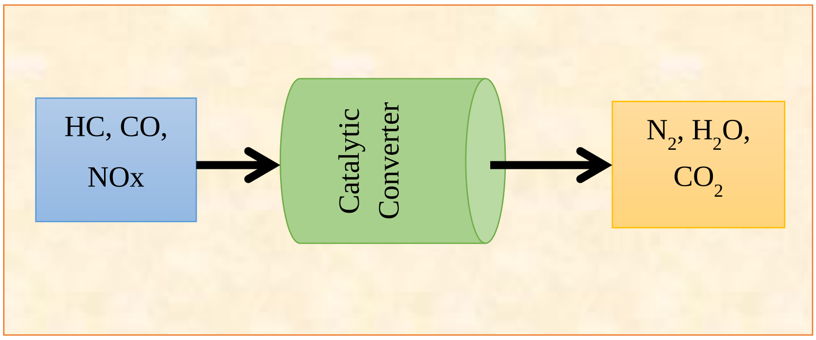

Figure 4: A general representation of a catalytic converter

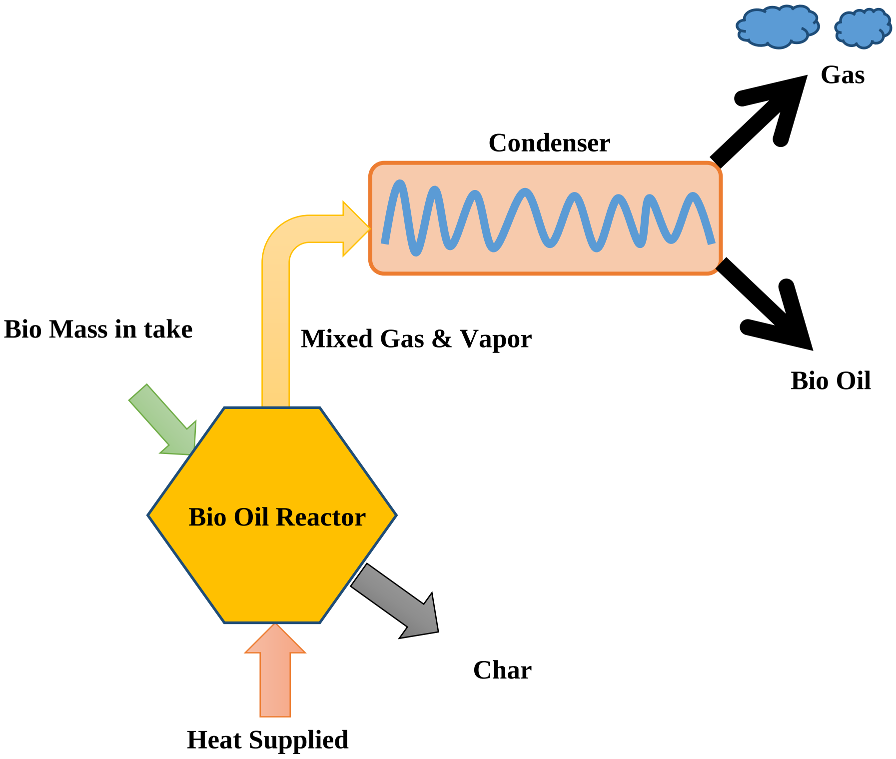

Figure 5: The pyrolysis process of bio-oil

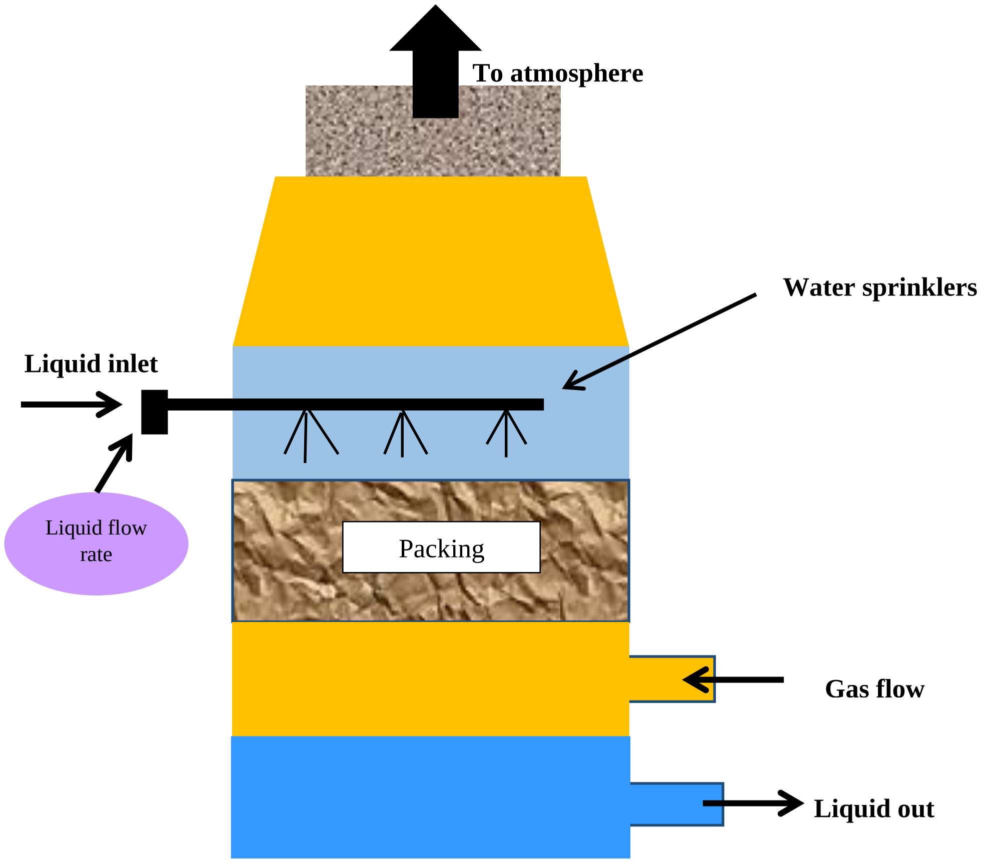

Figure 6: A packed wet scrubber

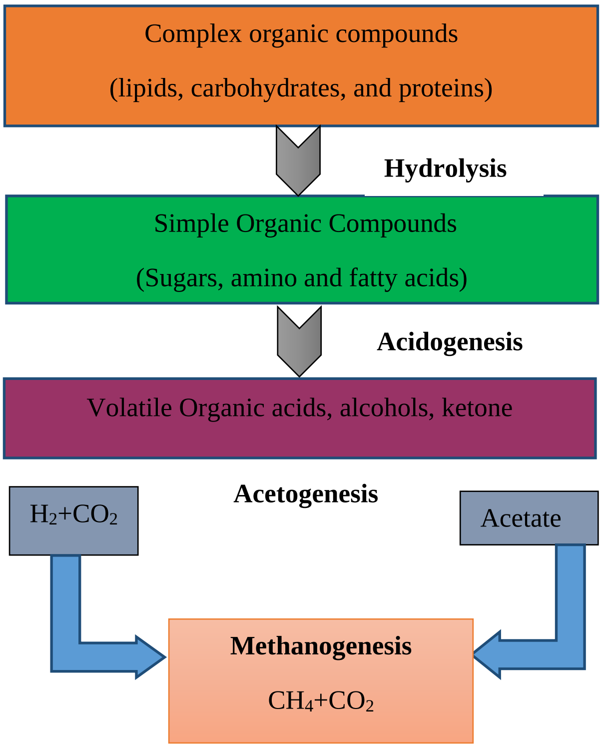

Figure 7: Process of anaerobic digestion

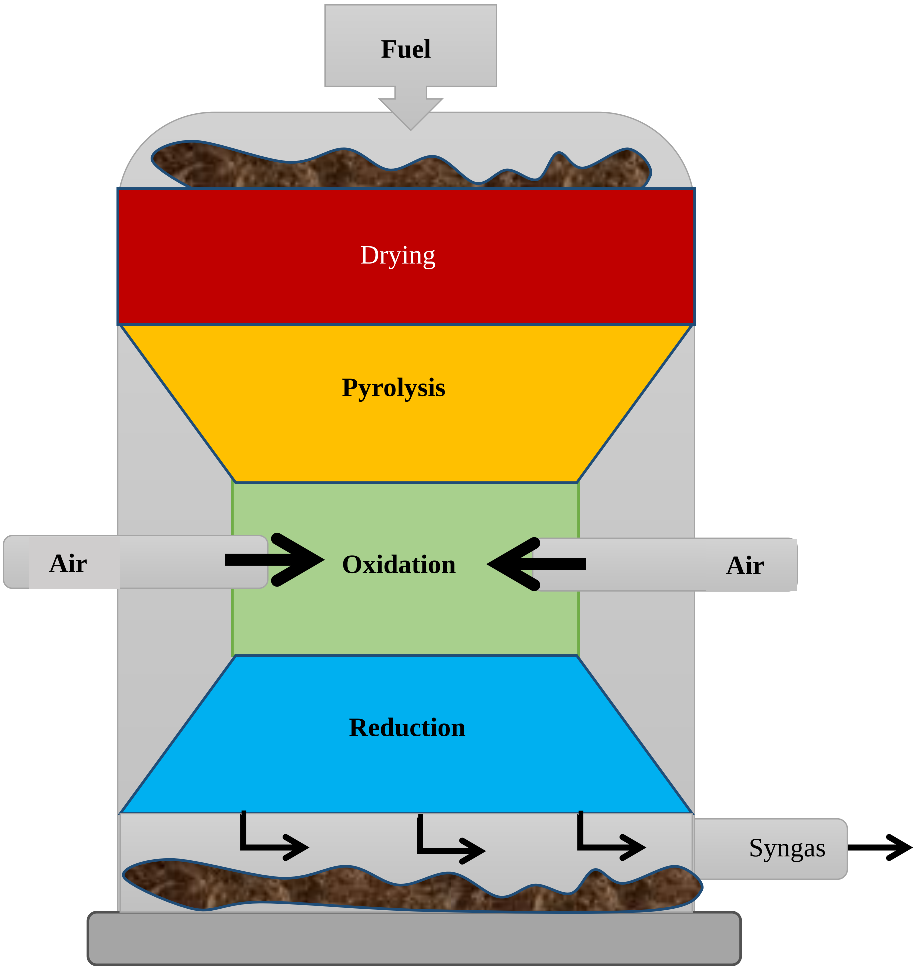

Figure 8: Fixed bed downdraft reactor

4.2.1. Benefits of Bio-pesticides

Bio-pesticides work as growth regulators, gastrointestinal disruptors, neuromuscular toxins, metabolic poisons, and multi-site inhibitors, among other mechanisms, to restrict pest growth and avoid the development of resistance that chemical pesticides are known to cause. The historical over-reliance on conventional pesticides, especially during the Green Revolution, has negative effects on biodiversity, pollution, and the comeback of secondary pests. Bio-pesticides, on the other hand, provide a safer and greener substitute by reducing these problems. Because of its superiority over synthetic pesticides in terms of resistance management, low toxicity, environmental friendliness, specificity, biodegradability, and stability against environmental stress, bio-pesticides are becoming more and more in demand as traditional pesticides are becoming less and less effective[55].

4.3. Bio-fertilizers

Living microorganisms known as "bio-fertilizers" improve plant nutrition by preparing and increasing the accessibility of supplements in soil. Currently used as bio-fertilizers contain many microbial taxa, such as helpful microscopic organisms and parasites. They successfully colonize the rhizosphere, rhizoplane, or internal root. Hydrolysate has multiple uses, including bioactive peptides, protein supplements, and the production of domesticated animal feed. It enhances the water retention capacity, C/N ratio, and soil nutrients. The hydrolysate's plant growth expanding workouts enhance its potential for use in natural cultivation and advance the development of the soil environment and micro biota. Microalgae are a viable and sustainable substitute for treating wastewater while producing useful items. One practical method of utilizing renewable resources to manufacture biomass from wastewater nutrients is the use of microalgae, which have a short lifespan, a rapid growth rate, and an efficient CO_2 usage rate[56].

4.4. Bio-catalysis

Bio-catalysis is a green and sustainable technology, based on the concepts and measurements of sustainable development and green chemistry. The tremendous progress made in molecular biology and biotechnology over the last 20 years is mostly to blame for this. The field of protein engineering has facilitated the refinement of already available enzymes as well as the development of novel bio-catalytic processes that were not previously seen in nature. Enzymatic transformations that meet predetermined parameters may now be developed with great ease, leading to inherently sustainable processes. For instance, this method has been effectively used in the commercial production of active medicinal compounds. Apart from protein engineering, several other components of bio-catalysis engineering may be employed to enhance the productivity, economy, and durability of bio-catalytic processes, including substrate, medium, and reactor engineering [57]. Moreover, an enzyme's stability can be increased by immobilization, allowing for repeated usage and improved performance as well as economic viability. As a result, bio-catalysis is used extensively in the manufacturing of some commodity chemicals and medications. The developing bio-based economy will also encourage its wider adoption in the future. Sustainable chemical practices are promoted by the twelve principles of green chemistry. To produce safer goods, they place a higher priority on atom efficiency, waste prevention, and the use of less hazardous ingredients. Environmental effect is decreased by emphasizing renewable resources and energy efficiency. Waste production is reduced by shortening synthesis pathways and promoting catalytic reactions. Product design for deterioration makes disposal more ecologically friendly. Pollution hazards are proactively identified and reduced through the application of analytical methods. During the whole chemical production process, intrinsically safer procedures put safety first. When taken as a whole, these ideas direct chemists toward reducing environmental damage and promoting a greener future [58].

5. Waste to Energy Technology

Global researchers now view climate change as a serious issue that requires rapid attention. As a result, certain recent measures have been implemented. Two major environmental issues—landfill overflow and rising energy demand—can be resolved by the waste-to-energy (WTE) supply chain. Waste management and greenhouse gas emissions are addressed concurrently by WTE through the conversion of various municipal solid wastes into electricity. This strategy is in line with the circular economy system (CES), which seeks to achieve a mutually beneficial link between environmental health and economic growth. In the WTE supply chain, bio-heating, incineration, and co-digestion are often used techniques that convert bio-based waste into energy forms that may be used, such as bio-gas and biofuel. With the right methods, a variety of biomass sources may be effectively transformed into bioenergy products, assisting communities in having access to environmentally friendly electricity and thermal sources [59].

5.1. Incineration and Gasification

Traditionally, land disposal, incineration, and application on land were the methods used to handle bio-solids, such as sludge from pulp and paper mills and municipal sewage sludge (MSS). The organic portion of the sludge is entirely burned during the incineration process, which produces ashes, wastewater, flue gases, and energy (in the form of heat). On the other hand, by adding heat and a mixture of steam, oxygen, and/or nitrogen in a reaction vessel, the MSS may be used in the gasification process to produce H_2 and CO (i.e., syngas) and CH_4. After being cleaned and purified, the syngas can be further processed via a catalytic Fischere-Tropsch process to create a liquid fuel [60]. Two key methods for gasifying mixed-solid waste (MSW) are fluidized beds and fixed beds. Gasification in a fixed-bed reactor is a novel technology that offers an intriguing way to dispose of MSW among other MSW treatment techniques. Before entering the reactor, fuels undergo pretreatment. Subsequently, they enter the reactor and generate syngas. In fixed-bed reactors, the feedstock is transformed into usable energy while the fuel flows either concurrently or counter currently to a supply of syngas. Fuel and syngas flow in the same direction in the downdraft reactor. Even if the arrangement is somewhat different, the same region as in the updraft gasifier may be identified. Fuels with a lot of moisture and ash are not suited for this kind of reactor. Though they're good for small-scale uses, fixed-bed reactors often have poor scale-up capabilities. Before storage, pollutants are removed from MSW. Figure 8 shows that in a downdraft gasifier, the flow of syngas and fuel occurs simultaneously [61]. This fuel can then be used in fuel cell applications, burned for heat recovery, fed towards an internal combustion engine generator to produce electricity, or produced in a variety of other ways. Appropriate pretreatments were necessary to apply the gasification process. For instance, sludge should normally have a moisture concentration of 10–20%, which is far less than the 40–99% moisture content seen in raw sludge. The most developed Waste-to-Power (electricity) technique in use today is considered to be incineration. To create crude syngas, the municipal solid waste is fed into a fluidized bed gasifier together with oxygen and steam at a high temperature. The purified syngas are utilized to produce electricity, H_2, or SNG after impurities are removed, heat is recovered, and acid gas is removed[62].

5.2. Pyrolysis

Using renewable energy sources is becoming a crucial component of sustainable development. If municipal solid waste (MSW) is integrated with contemporary technologies like pyrolysis, it has enormous promise for usage as a renewable energy source. Pyrolysis technology is thought to be a unique and simple energy production method for turning municipal solid waste (MSW) into biofuel. Because it offers enough heat transmission at a relatively cheap energy cost, the rotary pyrolysis technique is found to be the most popular method for pyrolysis of municipal solid waste. In MSW pyrolysis, temperature is the primary factor that is extensively researched. Maximum bio-oil yields during pyrolysis are often achieved at intermediate temperatures. Moreover, the way different factors interact might have an impact on the pyrolysis process. In figure 5 a pyrolysis process of bio oil has been discussed [63]. Emission control systems such as catalytic converters, scrubbers and filters etc. should be installed in pyrolysis plants in order to make the processing of municipal solid waste (MSW) more ecologically friendly. In all, around 43% of the MSW that is pyrolyzed provides bio-oil, 27% biochar, and 25% syngas. With modernization and industrialization on the rise, the global demand for energy is increasing rapidly. Energy is essential to human activity and the development of technology, which directly affects our quality of life. However, because of population increase, growing energy demands, and depleting fossil fuel supplies, this need is a factor in the global energy dilemma. Concerns about the environment and climate change are raised by the usage of fossil fuels, which has led to a quest for alternative energy sources like renewable energy [64].

5.3. Anaerobic Digestion

Recent research has demonstrated that temperature affects the microbial populations and metabolic processes involved in anaerobic digestion. As the temperature rises, their metabolic activity increases dramatically. Temperature affects the metabolic processes involved in anaerobic digestion, making it a crucial element for the formation of biogas. Therefore, to preserve temperature stability and prevent temperature variations, insulation and external heating are required. Furthermore, producing biogas through anaerobic digestion is a feasible alternative that may both augment and decrease the consumption of non-renewable energy sources like fossil fuels [65]. Anaerobic digestion breaks down organic matter through a sequence of biochemical events in the absence of oxygen, allowing the utilization of biodegradable waste for energy production. Fuels are produced and trash is managed using this technique. There are various important steps and technical considerations in the process of constructing and evaluating anaerobic digestion facilities economically. In the first step, large complex molecules are broken down into smaller constituent parts, such as sugars amino and fatty acids etc. and make them accessible to other bacteria. In the next step fermentative bacteria undergo the process of acidogenesis and break down the remaining components and produce volatile fatty acids (VFA), alcohols and ketones, then these simple molecules go through the process of acetogenesis and primarily produce CH_3COOH, CO_2, and H_2. The last step is methanogenesis, which involves the conversion of primary products of acetogenesis into CH_4 and CO_2. Figure 7 explains the process of anaerobic digestion [66]. The adaptable process can treat a variety of organic waste streams of anaerobic digestion. These include manure from big confined and concentrated animal feeding operations, agricultural and food wastes, wastewater from cities and animals, and crops impacted by pests or disease. They also include plant waste from agriculture, such as energy crops. Several types of reactors may be used for the process, each has unique properties. Continuous reactors constantly feed organic matter and remove end products, while batch reactors introduce biomass to the reactor at the beginning and seal it for the life of the operation [67].

6. Renewable Energy Technologies

Development requires energy, and sustainable energy systems are necessary for development to be sustainable. While the use of renewable energy has advanced significantly worldwide, with some nations attaining double-digit percentages in the provision of power, others—particularly in transportation—lag. Using locally accessible energy sources and site-specific strategies are frequently needed to fully utilize renewable energy. To efficiently satisfy energy demands, a shift to renewable energy requires resource evaluations, appropriate technologies, and integrated systems. In addition to discussing sustainability and wider system consequences, this review article examines a variety of renewable energy potentials and technologies, such as wind, wave, geothermal, sun, and salinity gradients. It offers a thorough overview of the area by combining research from the Sustainable Development of Energy, Water, and Environmental Systems (SDEWES) conference series [68].

6.1. Efficient CO_2 Conversion

One of the biggest scientific issues of our day is greenhouse gas mitigation. A possible solution to reduce these emissions is to catalytically transform waste CO_2 into compounds that are useful to industry. With this strategy, the carbon footprint of fossil fuels would be lessened, new feed stocks for petrochemical manufacturing would be available, and income would be generated to cover the expenses of CO_2 collection and storage. Ultimately, the conversion of CO_2 emissions into fuels and other valuable products can contribute to the establishment of a closed-loop, carbon-neutral energy system. Because electrochemical CO_2 conversion can function with high reaction rates and good efficiency under ambient settings, it is a viable option for large-scale carbon management applications. Two electrically biased electrodes are essential components of a typical electrochemical system: the positively charged anode oxidizes H_2O into O_2 and protons, while the negatively charged cathode enables the conversion of CO_2 and protons into products. This dynamic interaction allows CO_2 to be converted into a wide range of useful compounds [69].

6.2. Wind Energy

Out of all the sources of renewable energy, wind energy is becoming more and more common and competitive with traditional energy sources. For thousands of years, people have used wind energy to propel ships across oceans, pump water, and grind grain. Beginning in 1887, an automated wind turbine fitted with a 12-kW DC generator was used to convert wind energy into electrical energy. Much advancement has been achieved in the mechanical and electrical component design of wind turbines to increase the efficiency and reliability of energy generated by these machines and to make them competitive with fossil fuel-based power plants. By the 1980s, wind turbine technology had advanced to a point where utility-scale wind turbines with a capacity of 50 kW could be put into service. Compared to the group of tiny turbines, huge turbines can collect more wind power at cheaper installation and maintenance costs. The turbines of the turbine mill turn as the wind blows. With the aid of an electrical generator, the wind energy is transformed into mechanical energy, which is then transformed into electrical energy [70].

6.3. Solar and Hydra Energy

Using sunlight and water, photo-electrochemical (PEC) solar energy conversion offers the possibility of producing sustainable fuels at a reasonable cost. Solar energy makes up more than 99 percent of all renewable energy on Earth and is plentiful and carbon-free. Solar water splitting, which is modeled after photosynthesis, uses light energy to extract electrons from water, creating oxygen and hydrogen fuel. Direct use of hydrogen is possible, as is its conversion into carbon-based fuels. Although carbon-neutral fuels may be produced by combining solar hydrogen with atmospheric CO_2, recovering CO_2 from coal-fired power plants is less efficient than using solar energy directly. Future chemical and energy sectors will depend on renewable hydrogen to replace hydrogen obtained from fossil fuels in a variety of processes. Now, the most efficient solar energy conversion technology is photo-voltaic (PV). Semiconductor based water splitting for solar hydrogen production is possible via integrated photo-electrochemistry or PV-coupled electrolysis. The goal is to ascertain the best economical process for producing hydrogen using solar energy [71].

Water splitting may produce hydrogen and other sustainable forms of thermal, electrical, photonic, and biological energy from renewable sources such as biomass, wind, water, and solar. Most of the hydrogen produced today is obtained by steam reforming of fossil fuels; however, electrolysis using renewable power is gaining popularity. The quest for renewable alternatives is being driven by the pollution and limited nature of fossil fuels. Research demonstrates that renewable energy sources can provide power, which makes the creation of hydrogen through procedures like water electrolysis promising. Hydrogen generation is another possible benefit of biological processes such as microbial fermentation [72].

7. Barriers for Cleaner Production

The successful implementation of sustainable practices and business models is hindered by several obstacles, which can even reverse the progress made in environmental improvement and innovation. These obstacles include, but are not limited to, those about the economy, motivation, technology, education, lobbying, and many other areas. Drivers gaining traction and becoming hard to ignore are pushing back against these obstacles. Government regulations, consumer trends and demands, opportunities in overseas markets, enhancing local and global market perceptions, opportunities to collaborate with well-established larger companies, etc. are some of the factors that are forcing businesses and even entire industries to modify their current practices to improve their overall ecological footprint while, frequently concurrently, generating cost savings through the global optimization of their entire supply chain [73]. There are two types of barriers to cleaner production: internal and external. The following are examples of internal barriers: insufficient knowledge and experience; lack of understanding of environmental concerns; conflicting corporate agendas; limited rationality in decision-making; lack of communication; inertia in middle management; and labour force barriers. The adoption of cleaner manufacturing processes inside businesses may be hindered by these internal challenges. The inadequacy of current regulatory strategies, the challenge of obtaining cleaner technology, the difficulty of obtaining outside funding, the presence of unfavourable economic incentives, the lack of markets for recycled goods, and economic cycles are examples of external barriers. To overcome these obstacles and advance cleaner production, comprehensive methods must be developed. These external hurdles may also obstruct the adoption of cleaner manufacturing processes[74].

Conclusions and Recommendations

This review has emphasized the life-threatening environmental challenges resulting from the massive amounts of waste generated globally each year, which contribute to serious environmental issues and the depletion of resource reserves. To address these challenges, advanced waste management techniques have emerged as essential tools for achieving cleaner production, surpassing the limitations of conventional solid waste management methods that often lead to harmful chemical leaching. Advanced technologies, such as catalytic converters, filters, and scrubbers, have demonstrated superior efficiency and adaptability in transmuting toxic emissions into less harmful substances. Additionally, the use of biological methods; including bio-pesticides, bio-catalysis, and bioremediation, has proven highly effective in promoting cleaner production.

Processes like gasification, pyrolysis, and anaerobic digestion also play a crucial role by converting waste materials into energy, thus contributing to a closed-loop system of energy and economy. While these methods are cost-effective, they do present certain limitations that need to be addressed. The integration of renewable energy sources, such as solar, wind, and hydro, is pivotal to cleaner production, providing sustainable and environmentally friendly alternatives to traditional fuels. Cleaner production is indispensable for maintaining environmental quality, conserving dwindling resources, and ensuring their efficient use, while also meeting market demands and enhancing health and safety. The adoption of advanced waste management technologies and the integration of renewable energy sources are imperative for sustainable development. Future research should focus on overcoming the current limitations of these methods, improving their scalability, and enhancing their economic viability to fully harness the potential of cleaner production practices. In future, CP requires more consideration and the government should pay attention to the new methods and techniques that can lead the production processes towards a sustainable and cleaner environment. Use of plastic and the non-biodegradable things should be minimized. Adaptation of 4R technique and closed loop system is required. Future research should focus on overcoming the identified limitations, exploring the scalability and long-term impacts of these strategies, and addressing the practical implementation challenges to fully realize the potential of sustainable industrial practices.

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