e-ISSN No.: 2582-4228

Journal of Indian Association for Environmental Management

Journal homepage: www.http://op.niscair.res.in/index/php/JIAEM/index

Advancement in Green and Eco-friendly Technologies for Industrial waste Remediation

Aditya S. Jadhav[a], Shivam Jagtap[a], Jotiram G. Gujar[*], Sonali P. Kadam[b], Somnath Nandi[c] Shriram S. Sonawane[*]

[a] Department of Chemical Engineering, Sinhgad College of Engineering, Vadgaon, Pune 411041, India

[b]Department of Computer Engineering, Bharati Vidyapeeth's College of Engineering for Women, Pune, Maharashtra, India

[c] Department of Technology, Savitribai Phule Pune University, Pune 411007, India

[d]Visvesvaraya National Institute of Technology, Nagpur, MS, 440010, India.

[*] Corresponding Author: shriramsonawane@gmail.com; jotiramgujar@gmail.com

Submitted:04April 2024 Revised:06April 2024 Accepted: 08April 2024

***Abstract*: Industrial waste generation poses significant environmental challenges worldwide, demanding innovative and sustainable solutions for effective remediation. Green innovative technologies (GIT) comprise any innovations that contribute to the development of major products, services, or processes that reduce environmental harm, impact, and degradation while increasing natural resource usage. The overview of the importance and scope of industrial waste management, highlighting the need for sustainable practices was reviewed in this manuscript. Traditional waste remediation methods were discussed, emphasizing their limitations and adverse environmental impacts. In contrast, the principles of green and eco-friendly technologies are introduced, emphasizing their potential to minimize environmental harm and achieve a circular economy.**

It focuses on various green technologies for industrial waste remediation, such as biofilters, bioreactors, physio-chemical methods, etc. Additionally, it explores the use of blockchain and IoT (Internet of Things) in waste remediation. This review underscores the need to transition towards green and eco-friendly technologies for industrial waste remediation. Integrating these sustainable practices into industries will require collaborative efforts and partnerships among stakeholders. By implementing and accelerating the adoption of green technologies, industries can contribute significantly to environmental preservation, resource conservation, and a sustainable future.

***Keywords*: Remediation, Sustainable practices, Bioreactors, Blockchain, IoT, Green Technologies.**

I. INTRODUCTION

According to the present rate of garbage generated, there will be a 70% increase in waste output. The quantity of waste generated globally, which came to 2.01 billion tons annually (World Bank, U.S., 2019), is predicted to rise within the subsequent 30 years, to 3.4 billion tons. Each day, additional waste is generated around the world. In recent years the metropolitan region's individuals produced 2.01 billion tons of solid trash. Every day, every individual contributed roughly 0.74 kilos of solid trash. Urbanization will cause an annual increase in waste generation (Nizami S et. al, 2017; Bethi B et. al, 2021; Bethi B et. al, 2017; Ahmad K et. al, 2019) of 70% between 2016 and 2050 (Zhang M et. al, 2016). More waste is expected to be created, attaining 3.04 billion tons in 2050 from 2.01 billion metric tons in recent years. Without a doubt, the expanding water crisis poses an imminent risk to the lives of individuals. Contrarily, water toxicity has become a dangerous problem, especially in developing countries (Gadhe A et. al, 2015; Gujar J G and Sawant A, 2019; Gujar J et. al, 2010; Thakur P et. al, 2022).On the contrary, water contamination is an alarming problem, especially in developing nations (Sabiha-Javied F H et. al, 2015). The associated demographic growth brought on by the Industrial Revolution increased the need for freshwater resources. Even if there are several therapeutic choices, including biological, pharmacological, and physical techniques (Gujar J G et. al, 2023; Mungray A K et. al, 2022; Katole A A et. al, 2016; Pagliano G et. al, 2017), the truth is very different. According to the 2019 Our World in Data research, just two million tons of plastic were created globally in 1950. As of 2015, there were a total of 381 million tons of plastic manufactured yearly, nearly 200 times more than there had been in the 1950s (Gadhe A et. al, 2015). The development of waste-to-energy technologies is a result of the necessity to lessen the dangerous emissions created during the disposal of organic waste. The consumption of petroleum and coal as a source of energy and materials will shortly be supplanted by this approach (Sheth Y et. al, 2021; Uppalwar et. al, 2022; Gujar J et. al, 2022). Waste that can be recycled after being appropriately used is referred to as recyclable waste and is

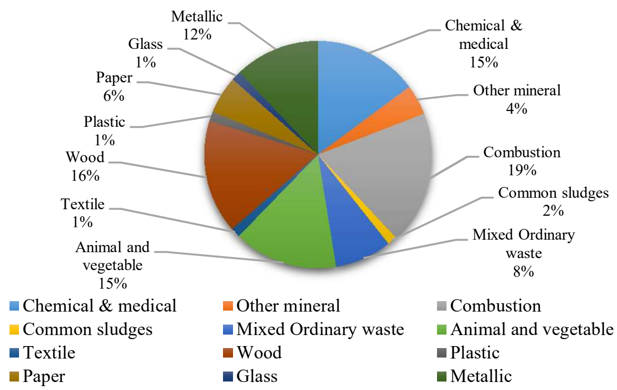

Fig 1. Common Sources of Industrial Waste(Sonawane S S et. al, 2022)

created by both industrial and domestic sources. They are made up of debris such as old glass, plastic, electronics, metal, paper, and appliances that have been utilized but are not up to par (Abhijit G et. al, 2016). Hazardous waste is an unfavourable outcome for several businesses, including garages, healthcare facilities, water treatment facilities, automatic garages, labs, and industry. Pathogens, radiation, heavy metals, chemicals, or solid, liquid, or sludge might all be present in this waste. However, household waste containing pesticides, leftover paint, computers, and batteries might be dangerous (Gadhe A et. al, 2014; Gadhe A et. al, 2013; Gadhe A et. al 2014; Thakur P P et. al, 2023) Industrial pollution can be caused by a variety of things, including sewage leaks, industrial spills, agricultural runoff, and biological contamination. Occasional overgrowth in plants is possible because of the increased nutrients in the water. However, the pH of the soil is impacted by these additional nutrients, which kills plants (Mossali E et. al, 2020). An efficient waste management system might reduce environmental damage and tackle the world's energy crisis. Reducing municipal solid garbage production at the source is the simplest and most effective strategy to address the present ecological problems faced by the world (Korpe S A et. al, 2022). Garbage management, as well as disposal, involves the utilization of solid municipal waste in waste-to-energy pathways (Malkapuram S T et. al, 2021; Sheth Y et. al, 2021; Sonawane S et. al, 2021; Sonawane S S et. al, 2022; Sonawane S S et. al, 2021).

Among these, the most noteworthy sources of industrial heavy metals are the plating, galvanizing, and iron and steel industries, which contribute to the generation of zinc, nickel, and copper pollutants. Additionally, the battery manufacturing sector stands out as a major source of lead contamination. In terms of heavy metals generated as waste, lead and cadmium tend to be the most prominent due to their extensive use in batteries, electroplating, and various industrial processes. However, advancements in waste management and stricter regulations have been working towards minimizing these pollutants and their adverse environmental impacts.

Figure 1. Illustrates common sources of industrial waste, with a significant portion, totalling 29 %, attributed to minerals. Combustion processes account for approximately 14 % of the generated waste, while 11% corresponds to chemical and medical by products as metallic waste constitutes 9 % of the overall waste distribution.

The review focuses on different categories of green and eco-friendly technologies for industrial waste remediation, including biological, physical, chemical, advanced oxidation processes, and membrane technologies. Furthermore, it addresses the challenges and barriers in implementing green technologies for industrial waste management and identifies future research directions and opportunities for improvement such as integrating blockchain and use of green IoT techniques. Overall, this review highlights the significance of green and eco-friendly technologies in industrial waste management and emphasizes the need for their widespread adoption to achieve sustainable and environmentally friendly practices.

Effect on Health

Concern is expressed over the agro ecosystem's rising metal concentration (Sonawane S S; Sharma P). The pollution of metals in settings has been assessed using several tools, including the factor of enrichment (EF), accumulation index, potential risk index, and the urbanization-related load of pollutants index (PLI). Inhalation, ingesting, and skin contact are the three main ways that heavy metal-contaminated urine can enter the body (Sharma P. et. al, 2020).

As a result, children who live in industrial regions have a higher chance of being exposed to contaminated urban soils, endangering their health. Approving the allowable absorption limits for each of these metals in natural waters set by the World Health Organization (WHO) (Nizam S et. al, 2013; Vishal R et. al, 2018; Gujar J. G et. al, 2010). Waste from industries, municipalities, and cement plants can include hazardous metals that harm biotic and human life. Because it results in a rise in trace metal levels, particularly heavy metals, increased industry associated with urbanization is a curse for rivers (Ghanshyam B et. al, 2016; Engwa G A et. al, 2019). Children who live in industrialized regions are therefore more likely to come into contact with contaminated city soils, endangering their health.

Table 1 shows the toxicity of various heavy metals poses significant risks to both humans and plants. Cobalt (Co) adversely affects pulmonary functions and the eyes in humans, while reducing essential nutrients in plants. Arsenic (As) leads to cancer and skin problems in humans and diminishes plant vitality. Chromium (Cr) causes cancers and renal issues in humans and affects plant nutrition. Copper (Cu) damages the liver, kidneys, and causes discomfort in humans, and restricts root growth in plants. Cadmium (Cd) harms human kidneys and bones while slowing germination and kidney function in plants. Mercury (Hg) induces neurological problems in humans and impedes growth in plants. Nickel (Ni) affects human respiratory function and enzyme activity in plants. Manganese (Mn) relates to Parkinsonian syndromes in humans and reduces chlorophyll in plants, impacting health. Such detrimental effects underline the importance of addressing heavy metal pollution for the well-being of both humans and plants.

According to research, heavy metals are harmful (Kumar N et. al, 2018; Ghanshyam B et. al, 2017; Xiong X et. al, 2022; Frutos F G et. al, 2012). Numerous serious human diseases, such as cancer, neurological problems, respiratory problems, and renal pathology, can be brought on by heavy metal exposure (Smith E et. al, 2015) by (WHO) the authority to set the maximum levels of metals in natural waters that can be absorbed (Frutos F. J. et. al, 2010; Hong S U and Xingang L I, 2011). Municipal, commercial, and concrete waste can contain toxic metals that harm biotic and human beings. The urbanization-related increased industry is bad for streams as it raises trace metal levels, especially heavy metals (Kumar N et. al, 2018; Sonawane S H et. al, 2020). Several dangerous substances that have been introduced into the environment build up in both water and soil body sediments. According to the research, 17 of the more than 50 heavy metals released into the water are toxic and may affect the health of people. Cadmium is a particularly hazardous element that may bio-accumulate in ecosystems and animals even in trace concentrations. Long-term exposure to cadmium may potentially harm the kidneys. Most nations and international organizations see cadmium as a pollutant (Malika M et. al, 2021; Charde S J and Sonawane S, 2021). The presence of lead, one of the most dangerous heavy metals, in drinking water is a serious problem. Lead can change the calcium in bones, opening the door for future replacement sites. Copper and other heavy metals may be harmful if consumed in excess. If the amount of metal ions in drinking water is decreased or maintained below tolerable values, this type of poisoning can be prevented (Abhijit G et. al, 2013).

TABLE 1
Heavy Metal Pollutant Effect on Humans and Plant

Heavy Metal	Toxicity on Humans	Effect on Plants	Reference
Co	Pulmonary functions, Effect on eye	Decreased the amount of sugar, carbohydrate, protein, and amino acids	(Kumar A et. al, 2023)
As	Skin disorders, birth defects, and cancer.	Declining leaf and plant health	(Hadiani M R et. al, 2018)
Cr	Acute tubular necrosis, acute renal failure, necrosis, hyperemia, cancers, and lymphocytic	Deteriorate the state of nutrition	(Mohsenpour S F et. al, 2021)
Cu	Nausea, vomiting, stomach cramps, liver and kidney damage, vertigo, headaches, and nausea.	Impact root development	(Chaturvedi P et. al, 2021)
Cd	Damage to the kidneys and bones	Influence how quickly seeds germinate.	(Vikrant K et. al, 2018)
Hg	Abnormalities of behaviour and neurological conditions such as tremors, sleeplessness, and memory loss.	Chlorosis, decreased the germination of seeds, plant height	(Ojuederie O B et. al)
Ni	Adult respiratory distress syndrome, decreased lung function, and lung and nasal sinus cancer	Reduced enzyme activity that had an impact on the CO_2 fixation and Calvin cycle	(Wagh S J et. al, 2012)
Mn	Parkinsonian syndromes hurt death rates.	Reduction in the level of chlorophyll	(Kumar N et. al, 2018)

Green and Eco-Friendly Technologies for Industrial Waste Remediation

Industrial waste can pose a serious threat to the environment. Fortunately, there's a growing toolbox of green technologies for remediation. Some of these eco-friendly approaches are as follows.

Biological Treatment Method

The use of biological treatment techniques is one potential strategy for environmentally acceptable waste remediation. This category includes a range of methods that take advantage of living things' ability to degrade or absorb pollutants. It includes techniques like bioremediation, which uses bacteria to break down toxic compounds, and phytoremediation, in which plants absorb contaminants. Below is a thorough description of the procedure.

Bioremediation

The process of bioremediation is a cost-effective, ecologically friendly, and sustainable way to deal with hazardous waste (Mangesh W et. al, 2013; Thakur P P et. al, 2022; Jadhav A et. al, 2023; Khudur L S et. al, 2015). Part of the procedure involves using bacteria and other microorganisms to eliminate or degrade organic and inorganic contaminants. Some microbe species are capable of releasing enzymes that can clear contaminated regions of harmful pollutants. Bioremediation can be carried out in situ or ex-situ, depending on factors such as cost, site features, types and concentrations of contaminants, etc. Site characterization, which determines the optimal in situ or situ biological remediation strategies, is the most important phase in the bioremediation process (Mulbry W. et. al, 2008).

When selecting a bioremediation approach, factors such as the kind of pollutant, the level and extent of the contamination, the type of environment, the site, the expense, and regulatory requirements are all taken into account (Thakur P P et. al, 2023;

Juwar V and Sonawane, 2014; Khedkar R S et. al, 2012). Before beginning a bioremediation project, performance requirements, such as oxygen and nutrient levels, pH, temperature, and other abiotic factors parameters that affect the effectiveness of the biological remediation processes, are carefully evaluated.

Additionally, other remediation techniques (Singh A and Olsen S I ,2011) may be considered for cleaning up areas that have been polluted with chemicals other than hydrocarbons. These techniques may also be more beneficial to apply during remediation. Furthermore, it is probably conceivable to simply prevent and control environmental contamination with pollutants other than hydrocarbons given the nature of the operations that result in crude oil pollution. Additionally, it appears that our reliance on petroleum and other similar products as significant energy sources is the cause of the rising pollution from this class of pollutants (Pangestuti R and Kim S K, 2011; Cepoi L et. al, 2016).

Phytoremediation

Utilizing macroalgae, microalgae, and cyanobacteria to eliminate xenobiotics, nutrients, and carbon dioxide from wastewater is known as phytoremediation (Brar A et. al, 2017). As long as the generated biomass is recycled, using photoautotrophic bacteria is an environmentally favourable method with no secondary contamination (Chen Q et. al, 2009; Khedkar R S et. al, 2013; Hakke V et. al, 2021; Shimpi N G et. al, 2021; Kodape S M et. al, 2012). Additionally, photoautotrophic bacteria belong to the most important bio-resources that are now gaining a lot of attention because of their capability for rapid development, the ability to be grown on inhospitable terrain, and the need for less water and space. Photoautotrophic metabolism uses light as a source of energy through photosynthetic activities, which subsequently converts it into chemical energy. Converting a considerable amount of CO_2 into biomass and eating it, results in the release of O_2 into the atmosphere (Bazrafshan E et. al, 2015). The resulting biomass can then be used in a variety of processes, such as the anaerobic digestion of the material to generate biogas, the fermentation of the material to make bioethanol, and the high-temperature conversion of the material to produce bio-crude oil (Dronkar et. al, 2018). Chlorella, Scenedesmus, Phormidium, Botryococcus, Chlamydomonas, Spirulina, Oscillatoria, Desmodesmus, Arthrospira, Nodularia, Nostoc, and other species are used for phytoremediation (Akinterinw A and Adibayo I, 2018; Tawila Z M A et. al, 2019). The cleaning potential has been studied for macroalgae like *Ulva lactuca* and *Kappaphycusalvarezii*. The microalgae-based products can also be used to create fertilizers, food additives, and cosmetics. *Haematococcuspluvialis*, *Emilianiahuxleyi*, and *Dunaliellatertiolecta* are a few marine algae species that are present in seas that have undergone modifications to create an abundance of pigments, omega-3 fatty acids, astaxanthin, and other chemicals (Verma A K et. al, 2012).

Physical and chemical treatment

A chemical reaction known as an electrochemical process occurs when an electric current is sent through a water-based metal solution and either initiates or catalyzes the reaction. A cathode plate and an insoluble anode are connected by an electric current to do this. In a minimally acidic or neutralized electrolyte, heavy metals precipitate as hydroxides throughout the process (Chollom M N et. al, 2014). The quality of the treated wastewater would be affected by the quantity of produced ions or charge loading, together with the outcomes of current and time (Chollom M N, 2014; Chandane V S et. al, 2017). Two examples of the electrolytes used in the approach are copper and nickel sulphates.

Electroflotation and electrocoagulation

Using an electrical current, the electrochemical process of the electrocoagulation process removes metals from liquids. Use electrocoagulation equipment to remove tannins, pigments, dissolved metals, and particles in suspension. Contaminants in wastewater are kept in solution by an electrical charge. These ions and other charged particles become destabilized and precipitate when they are neutralized by the ions created during the electrocoagulation process. By electrically dissolving aluminium or iron ions from aluminium or iron electrodes, electrocoagulation is a technique for producing coagulants locally. In this process, the cathode produces hydrogen gas, whilst the anode produces metal ions. Hydrogen gas bubbles carry contaminants to the solution's surface, where they may easily be collected, concentrated, and eliminated. Several reactions happen when aluminium is employed as the electrode during the electrocoagulation process (Sonawane S S et. al, 2009).

Figure 2. depicts a comprehensive array of conventional strategies employed for the disposal of industrial waste. These methodologies encompass diverse approaches, beginning with biological treatments such as Bioremediation, Phytoremediation, and composting. Bioremediation exploits the metabolic activities of microorganisms to neutralize pollutants, while Phytoremediation leverages plants to absorb and mitigate contaminants, thereby facilitating environmental cleanup. Composting, an organic decomposition process, aids in converting waste into nutrient-rich soil amendments. In addition to biological methods, various physical and chemical treatments constitute integral components of waste management. Electro-flotation, involving the use of electrodes to facilitate the separation of suspended particles, demonstrates enhanced efficiency in waste removal. Electrocoagulation, which promotes the aggregation of contaminants through electrical charge interactions, further contributes to efficient waste elimination. Precipitation, a chemical process, precipitates pollutants for subsequent removal. Modern advancements in waste management have seen the integration of membrane separation processes, including Nanofiltration (NF), Ultrafiltration(UF), and Microfiltration(MF). Nanofiltration exhibits remarkable proficiency in selectively removing ions and small molecules, thereby enhancing water quality. Ultrafiltration (UF) addresses larger particles and macromolecules, ensuring a refined effluent. Microfiltration, meanwhile, focuses on the separation of suspended solids and microorganisms, culminating in clarified waste streams. As technology continues to evolve, novel methods and refinements

in existing techniques continue to emerge, striving for ever-greater efficiency and sustainability in the realm of industrial waste removal.

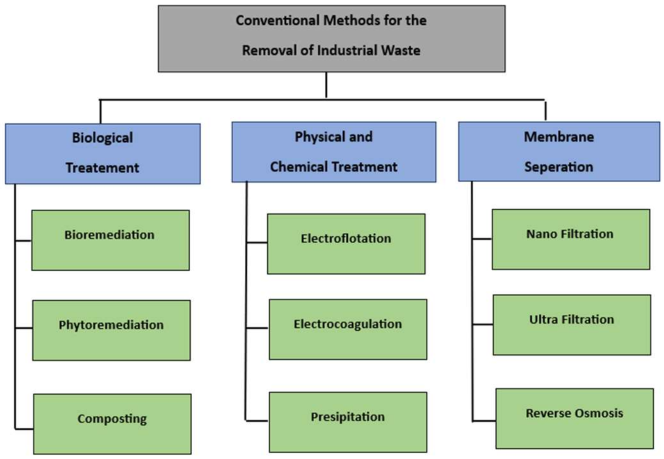

Fig 2: Conventional Method for the Removal of Industrial Waste

Precipitation

Chemical precipitation is a common method for removing inorganic metal ions from solutions (Muro C et. al, 2012; Klavarioti M et. al, 2009; Sonawane S S et. al, 2023). An insoluble substance is produced and allowed to precipitate by the process of chemical precipitation. Waste materials are combined with a precipitation reagent as part of the process, which triggers chemical reactions that produce insoluble compounds. The insoluble substance separates into particles that are chemically clumped together and removed using filtration or sedimentation (Sonawane S S et. al, 2022). One treatment technique that may remove heavy metals from wastewater is chemical precipitation.

Coagulation and fluctuation of the limits of wastewater treatment technology are being pushed by many sectors due to rising environmental consciousness and stricter restrictions. Because it is simple and effective, coagulation is one of the most frequently used techniques for treating wastewater (Comninellis Christos et. al, 2018). Coagulation is the process of removing a particle's charge. This method may be used to extract heavy metal particulates from a solution (Pablos C et. al, 2018). Whether or not water treatment equipment is utilized, this way of treating heavy metal contamination is quite effective. This method destabilizes charges on particulates by adding highly charged, tiny molecules to wastewater. The process of flocculation, in which colloidal particles separate from a solution to produce flocs and sediments, frequently uses this approach. Some of the coagulants and flocculants used are magnesium chloride ($MgCl_2$), aluminium sulfate (alum), aluminium hydroxide, and poly aluminium chloride (pAlCl) (Dewil R et. al, 2017). To remove lead from wastewater when other heavy elements such as zinc and iron are present (Endale S A et. al, 2022). The polyelectrolyte is Korat PA3230, and the substance that coagulates is magnesium chloride, poly aluminium chloride, or aluminium sulphate (alum).

Membrane separation

From pre-treatment to post-treatment, pressure-driven membrane technologies are by far the most often employed throughout the whole wastewater treatment process. To accomplish separation, these methods rely on hydraulic system pressure. These operations may be categorized into four main groups. These include reverse osmosis (RO), nanofiltration, ultrafiltration, and microfiltration. Apart from the amount of pressure required, the main distinction between these methods is the size of the membrane perforations (Swain M R et. al, 2019). RO has long been at the forefront of water reclamation through the treatment of wastewater and desalination of saltwater. The natural osmotic pressure in the feed can be balanced using the hydrostatic pressure created during reverse osmosis. Osmosis does not occur in nature in this manner. Each water molecule adheres to the membrane's surface when pressure is applied. The membrane's structure allows these molecules to pass through, and they gradually desorb on the permeate side, where they are finally collected. Each water molecule adheres to the membrane's surface when pressure is applied. After diffusing across the membrane material, the molecules finally desorb at the permeate side of the membrane for collection (Ehrlich H et. al, 2021).

(AOP) Advance Oxidation Process

The referred Advanced Oxidation Processes (AOPs) are a group of related but dissimilar technologies that, among other things, focus primarily (but not only) on the generation of highly reactive hydroxyl radicals(Al-Salem S M et. al, 2009). AOPs include electrochemical procedures, wet oxidization processes, heterogeneous as well as homogeneous photocatalysis, Fenton and Fenton-like processes, and photocatalysis. They also involve the utilization of ozonation, ultrasonography, microwaves, and g-irradiation. They successfully break down refractory components without producing an additional waste stream, unlike, for example, membrane processes, which is one of their key benefits over traditional treatments. The development of harmful microbes in the effluent is typically limited, too. This has a significant advantage over rival methods such as the chlorination of organics, which produces several organo-chlorinated compounds(Al-Salem S M et. al, 2010).

Table 2. describes the utilization of various methods for the treatment of industrial waste and exhibits a range of advantages and disadvantages. Biological treatment, although feasible for removing certain metals, is hindered by the absence of fully developed and marketed technologies. Photochemical processes demonstrate the advantage of not generating sludge, yet they give rise to the formation of potentially problematic by-products. Ozonation, although effective when applied in the gaseous state and possessing a short half-life, may lead to alterations in volume. Oxidation proves rapid in removing toxic pollutants, but this efficacy is counterbalanced by high energy consumption and the generation of undesirable by-products.

TABLE 2

Common Industrial Waste Remediation Techniques(Ragaert K et. al, 2014; Ranade V V and Bhandari V M, 2014)

Methods	Advantages	Disadvantages
Biological treatment	Removing some metal is doable.	Technology that has not yet been created and sold
Photochemical	No sludge is created.	Emergence of a by-product
Ozonation	Applied in a gaseous condition; volume change	Short half-life
Oxidation	Quick method of removing harmful contaminants	The generation of waste and high energy costs
Ion exchange	Effective heavy metal removal from several sources	Adsorbents need to be recycled or thrown away.
Coagulation/flocculation	Reasonably priced	High production of sludge and the creation of large particles.
Irradiation	Effective in a lab	Need a lot of dissolved oxygen
Electrokinetic coagulation	Reasonably priced	High generation of sludge
Electrochemical treatment	Fast and effective for certain metal ions	High energy costs and the creation of large particles
Adsorption	Simple and flexible design, usability, and sensitivity to dangerous pollutants	Adsorbents need to be renewed.
Membrane-based filtering methods	Good removal of heavy metal	Costly and concentrated sludge manufacturing

Ion exchange serves as an effective means for eliminating various heavy metals, though the requirement for adsorbent regeneration or disposal poses a challenge. Coagulation/flocculation stands as an economically viable option, but it produces substantial sludge and large particles. Irradiation showcases effectiveness at a laboratory scale, yet its demand for a significant dissolved oxygen supply can be a limitation. Electrokinetic coagulation demonstrates economic feasibility, but it results in notable sludge production. Electrochemical treatment stands out for its swift and efficient removal of certain metal ions; however, it is hampered by high energy costs and the production of significant particle sizes.

Adsorption methods offer design simplicity, flexibility, ease of use, and resilience to harmful contaminants, though the requirement for adsorbent regeneration presents a consideration. Membrane filtration technologies excel in removing heavy metals, yet they lead to the concentrated production of sludge, coupled with high costs. Considering the most relevant treatments, ion exchange, coagulation/flocculation, and electrochemical treatment hold promise due to their effective heavy metal removal capabilities. It's important to carefully assess the advantages and disadvantages of each method in the context of specific waste types and treatment goals to determine the optimal approach for industrial waste management.

Future prospects

Sustainability refers to an organization's efforts to address safety, health, and environmental (HSE) issues that might negatively affect stakeholders, contractors, and the surrounding community. The Brundtland Commission originally defined sustainable development in 1987. Since the term has to do with the future, they defined it (Ranade V V and Bhandari V M, 2014). Therefore, sustainable development is defined as growth that satisfies present desires without jeopardizing the capacity of generations to come to satisfy their requirements. We can establish a sustainable environment if we keep working to protect the social framework and environmental circumstances necessary for sustainability while not overusing the natural resources that support it. The triple bottom line, often known as the three criteria, ought to be followed as a consequence. They are a successful business or organization that continues to work toward maintaining a robust ecosystem and provides the environment with the necessary upkeep (Khattak S I and Ahmad M, 2021). Two main factors might endanger sustainability: When the rate of technology usage outpaces the rate of resource production by the environment, it has an impact on the demands of future generations.

We can establish a sustainable environment if we keep working to protect the social framework and environmental circumstances necessary for sustainability while not overusing the natural resources that support it. The triple bottom line, often known as the three criteria, ought to be followed as a consequence. They are a successful business or organization that continues to work toward maintaining a robust ecosystem and provides the environment with the necessary upkeep (McNeely J A et. al, 2019). Two main factors might endanger sustainability: When the rate of technology usage outpaces the rate of resource production by the environment, it has an impact on the demands of future generations. The impact of the waste produced by the techno sphere on the natural world should also be considered. A healthy ecosystem is in danger because resource output is falling (Kumar A et. al, 2022).

The 4th industrial revolution, or 4.0 Industry, predicts a fast shift in technology, businesses, cultural norms, and procedures due to growing interconnection and intelligent technologies. Klaus Schwab, the executive chairman of the World Economic Forum, founded it to draw focus on the fact that the current advances represent more than merely efficiency gains but also an important shift of industrial capitalism. There have become two important problems that humanity must solve. The SDGs are one of them, and responding to the changes IR 4.0 has brought about is the other. At the 2011 "Hannover Fair" event, Industry 4.0 was first introduced in Germany as a proposal to create a fresh model of German economic planning based on advanced technology projects. This was carried out to promote the start of IR 4.0. Technology has become able to accurately assess how it affects the economy and society as a result of its quick advancement. The principles of manufacturing, economic expression, & environmental sustainability have occasionally clashed. The extraction of raw minerals and soil exploration has produced significant amounts of waste in addition to the use of water and energy. High production, efficient processes, and sustainable development define the Industry-4.0 engineering paradigm. This emerging industry is viewed as an illustration of sustainable manufacturing. One of the elements that most firmly supports this understanding is the enormous range of fundamentally novel technologies featured in Industry 4.0 (Jotiram G et. al, 2024).

Blockchain and Green IoT

A substantial rise in the use of energy from fossil fuel resources has been caused by the massive growth of worldwide industrial activity during the last several decades, and the increasing carbon footprint caused by technological improvement has also played a role in the global warming phenomenon. We also need to focus on creating an IoT ecosystem that is more ecologically friendly due to the considerable increase in energy usage brought on by IoT technology (Rathod A P et. al, 2014). Researchers and companies are interested in the Green Internet of Things (GIoT), which offers power-efficient services and makes it easier to produce and consume clean energy. Blockchain technology has gained popularity as an IoT technology and has drawn significant attention from governments, energy companies, start-ups, financial organizations, and researchers. Understanding the essential components that must be taken into account while developing a GIoT ecosystem is crucial, as is how the use of blockchain makes the Internet of Things (IoT) system more ecologically friendly. The term "GIoT" refers to a new wave of IoT design concepts. An essential component of the GIoT for conserving energy is the green intelligent device (GSD) (Buthale R et. al, 2018). Energy conservation may assist in reducing emissions, damage to the environment, pollution, and harmful impacts on human health. Because there are so many distinct bottom-layer GSDs available in the GIoT, it has become more difficult for users to get to and regulate GSDs. There is no one GSD administration solution, therefore users are forced to use a range of GIoT applications and access various GIoT cloud platforms to access and handle these diverse GSDs. The capacity of GSD applications is constrained by this splintered GSD management model, and user control and access for various GSDs are made more difficult.

Renewable Energy Perspectives

Green energy comes from a non-depleting renewable resource and is sometimes referred to as alternative energy. Recently, this energy source has become more well-liked. The ability of the environment to support itself is unaffected. Pollution is largely caused by scientific and technological advancements unrelated to effective pollution management techniques. Science-based development for industrial growth has sparked controversies and concerns, especially at the forefront of green legislation, while ignoring the preservation of the natural world and having a significant negative impact. Eco-industrial growth, which is closely related to environmental long-term viability set out to find alternative solutions to the complex problems of managing and utilizing sources of clean energy and the effects of climate change. The greatest and most cheap alternative energy source is renewable energy. Particularly in India, renewable energy has huge promise. It may be possible to reduce the effects of warming temperatures on a global scale by boosting the usage of renewable energy sources. biomass, geothermal energy, tidal, solar, and seemingly limitless quantities of wind, sunlight, and solar energy are the major sources of clean renewable energy. Consequently, expanding the use of sources of clean energy may both halt global warming and ensure that food is produced sustainably in the future (Haddadi E. et. al, 2023; Guo Yet. Al, 2020).

Table 3 shows that industries generate a diverse range of effluents containing pollutants that demand efficient treatment for environmental protection. Recent advancements have led to innovative methods across industries, some of which stand out for their effectiveness and sustainability. In electric power plants, microbial fuel cells have emerged as a promising biological treatment. These cells utilize biocatalysts to simultaneously produce power and eliminate pollutants like carbon dioxide, ammonia, and hydrogen sulfide. This approach offers enhanced resistance to environmental stress, making it a sustainable choice for treating organic waste, phosphorus, and nitrogen in effluents. In the battery manufacturing sector, the use of pyro, hydro, and bio hydrometallurgy for metal recovery from effluents is notable. This mechano-chemical approach focuses on efficiently separating valuable metals like cobalt, nickel, and lithium. This method aligns with sustainability by economically recovering precious metals while minimizing environmental impact.

For nuclear power plants, solidification with obstacles halts the movement of radioactive substances, ensuring they're harmless to both humans and the environment. This chemical technique addresses the challenge of treating radioactive waste, showcasing a sustainable solution that prevents radio-nuclide migration.

In mining and quarrying industries, the use of bacteria for bioremediation and phytoremediation stands out. This biological approach efficiently breaks down organic pollutants like pyrite (FeS2) and pyrrhotite (FeS). By harnessing natural processes, this method offers a less expensive and environmentally friendly way to treat wastewater effluents containing polymetallic sulfides.

In the food industry, innovative physicochemical techniques involving neoteric extractants, such as eutectic solvents and ionic liquids, offer effective separation of valuable phenolic compounds from effluents. This approach aids in treating organic substances like flavonoids and non-flavonoids, making it a sustainable way to recover valuable chemicals from food effluents.

In agriculture, the utilization of microalgae for intensified biological N and P removal is a sustainable alternative. This biological method enhances nutrient removal through autotrophic nitrification and heterotrophic denitrification. By incorporating microorganisms, this approach efficiently treats organic waste, phosphorus, and nitrogen in agricultural wastewater.

Among these advancements, the most advanced, effective, and sustainable method appears to be the microbial fuel cell technology used in electric power plants. This method not only addresses pollution concerns but also generates power, showcasing a holistic approach to effluent treatment. Its ability to tackle organic waste and nutrient removal while producing usable energy makes it a promising solution for sustainable wastewater treatment.

In conclusion, industries are embracing innovative approaches to effluent treatment, aiming for both effectiveness and sustainability. Each sector's unique challenges are being met with advanced methods that hold promise for a cleaner environment. The microbial fuel cell technology, with its dual benefits of power production and pollution elimination, exemplifies the evolving landscape of wastewater treatment.

II. Conclusion

The management of industrial waste is a global concern due to its detrimental effects on the environment and human health. In response to these challenges, there has been a significant focus on the development and implementation of green and eco-friendly technologies for industrial waste remediation. This review paper has provided an overview of the advancements in these technologies and their potential applications in addressing the complexities of industrial waste management.

The review highlighted various categories of green technologies for industrial waste remediation, including biological, physical, chemical, advanced oxidation processes, and membrane technologies. In addition to this, advanced methods such as biofilters, bioreactors, and physicochemical methods were also discussed. These technologies offer promising solutions for the efficient and sustainable treatment of industrial waste, with each approach having its advantages and limitations.

However, it is important to acknowledge that the implementation of green technologies may face challenges related to cost, scalability, and regulatory frameworks. Overcoming these barriers will require collaborative efforts from industry, government, and research institutions. Looking ahead, future research should focus on optimizing existing green technologies, exploring innovative approaches, and integrating digital technologies to enhance the efficiency and effectiveness of industrial waste management. Additionally, efforts should be made to raise awareness and promote the adoption of green technologies among industries, policymakers, and the public.

In conclusion, the adoption of green and eco-friendly technologies is crucial for achieving sustainable and environmentally friendly industrial waste management. By implementing these technologies, we can minimize the environmental and health impacts of industrial waste, conserve resources, and move towards a circular economy. Stakeholders from various sectors must collaborate to drive the widespread adoption of green technologies and ensure a cleaner and more sustainable future.

TABLE 3

Industries generate a diverse range of effluents containing pollutants that demand efficient treatment for environmental protection.

Industry type	Composition of effluent	Advances in wastewater treatment recently	Category of treatment	Targetofeffluent removal	Advantages	Reference
Electricitypowerplants	CO_2, ammonia, hydrogen sulphide, siloxanes, methane, and suspended solids	Development of microbial fuel cells using biocatalysts for simultaneous power generation and waste pollution eradication	Biological	Other organic waste, phosphorus, and nitrogen	Provides enhanced resistance to environmental stress	(Malika M et. al, 2023)
Battery manufacture	Aluminium, cobalt, copper, lead, iron, hydrogen fluoride, lithium, manganese, and nickel are a few of the metals mentioned.	Utilizing pyro, hydro, and biohydrometallurgy to recover metal from effluent.	Mechanical and chemical	Cobalt, Nickel, and lithium	Separation of economically feasible and valuable metals	(Canadas R et. al, 2020)
Nuclear power generation plants	Radioactive materials that are liquid (tritium) and gaseous (inert gas, halogen, aerosol)	Moving water radionuclides and droning in isolation from the biosphere are halted by solidifying with barriers.	Chemical	Radioactive substances	Harmless to both humans and the environment	(Gavali A A et. al, 2023)

Mines and quarries	Minerals that include sulphur, such as pyrite (FeS_2) and pyrrhotite (FeS)	Utilizing bacteria to break down the organic pollutants in wastewater effluent, bioremediation and phytoremediation.	Biological	Polymetallic Sul-hides	Less expensive and disruptive to the environment	(Pathak U et. al, 2022)
Food	Organic compounds include things like nutrition, sugar, lipids, colourants, preservatives, and suspended particles.	Hydrophobic neoteric extractants, such as eutectic solvents, ionic liquids, bio-based solvents, etc., are used for phenolic compounds.- liquid-	Physiochemical	Flavonoids and non-flavonoids are phenolic chemicals.	Helps to separate very valuable chemicals such as phenolic anti-oxidants	(Jun K C et. al, 2020)
Agriculture	Synthetic chemicals, organic substances, suspended particles, nitrogen, and phosphorus, as well as antibiotics	Utilizing microalgae in wastewater effluent to intensify biological N and P removal through autotrophic nitrification and heterotrophic denitrification	Biological	Other organic waste, phosphorus, and nitrogen	Alternatives to traditional biological treatment that are sustainable and favourable to the environment	(Kuyukina M. S. et. al, 2020)
Dairy	Whey proteins, lactose, sulphate, chlorides, soluble organics, suspended and dissolved particles, lipids, and BOD and COD	Using unmodified rice husk, a byproduct of the rice milling process, as a biosorbent that gets protonated at low pH and traps organic molecules to the binding sites	Physical and Chemical Adsorption	Natural substances	Simple availability of basic supplies and economical	(Awaleh M O and Soubaneh Y D, 2014)
Oil-extracting mills and plants	BOD, COD, suspended particles, organic carbon, nitrogen, methane, carbon dioxide, hydrogen sulphide.	Utilization of palm kernel shell to create a biomass adsorbent for the adsorption of organic contaminants from wastewater by combining zeolite with iron oxide	Physio-chemical(adsorption)	Pollutants that are weakly organic or inorganic, heavy metals	Pollutants that are weakly organic or inorganic, heavy metals	(Patil P P et. al, 2022)
Petroleum and petrochemical	Oil, hydrocarbons, gases like CO_2 and H_2S, and dissolved organic acid	Moving bed biofilm reactor powered by continuous flow intermittent cleaning biofilm technology and a continuous stirred tank bioreactor powered by integrated native microbial association	Biological	Total petroleum hydrocarbons and COD	Enhanced mass transfer between the hydrocarbon and the biocatalyst, strong resilience to harmful effects, and extreme precision	(Ram C et. al, 2020)
Organicchemicals	Heavy metals such as chromium, lead, and copper; organic chemicals such as benzene, toluene, and phenol; hydrocarbons; BOD; resins; pesticides; and synthetic fibres; as well as crude oil and grease	An integrated treatment approach combining a fixed biofilm bioreactor, a two-phase partitioning bioreactor, and a batch reactor with sequencing is used to get rid of the dangerous contaminants.	Physical, chemical,and biological	Inorganic substances and other metals.	Possible from an economic and technological perspective	(Branca T A et. al, 2020)
Leather	Heavy metals, chromium, H_2S, dissolved solids, volatile organic compounds, sulphides, calcium/ammonium salts, and COD and BOD	Discarded tea leaves from homes and tea shops are utilized to filter out heavy metals from tannery effluent because of their high biosorption potential.	Physico-chemical(adsorption)	Lead, chromium, iron, nickel, and other heavy metals	Effective, affordable, and widely accessible inexpensive	(Kadam S et. al, 2020)

Paper and pulp	Examples of organic matter include lignin, cellulose, tannins, diterpene alcohols, suspended particles, chlorinated resin acids, COD, and BOD	Includes a bacterial consortium (*Actinomycetes sp.*) That produces laccase enzyme to break down cellulose and lignin in an alkaline environment, as well as a fungal consortium (Nigrospora sp., curvularialunata sp.) That removes BOD, COD, and lignin.	Biological	BOD, COD, lignin, cellulose, and hemicellulose	Cheap and environmentally friendly	(Kale P et. al, 2023)
Iron and steel	Benzene, cyanides, mineral particles, sulphur compounds, metal ions, and oil and grease	Iron oxide-containing steel slags are used to remove metallic iron, while induction furnaces based on steel slags are used to extract chromium.	Physical and chemical methods for (adsorption)	Heavy metals	Reusing steel waste is an economically viable option.	(Dogaru L, 2020)
Pharmaceutics	COD, organic substances such as alcohol, aromatic compounds, acetone, antibiotics, and chlorinated hydrocarbons are some of the dissolved and suspended solids.	Metallic iron is removed using steel slags containing iron oxide, while chromium is extracted using induction furnaces based on steel slags.	Physio-chemical method (membrane filtration) Physio-chemical method (membrane filtration)	Antibiotic-tetracycline	Heightened operational effectiveness	(Sivakumar P et. al, 2013)
Textile	Heavy metals (copper, chromium, cadmium, zinc, etc.), reactive, volatile, azonic dyes and fibres, as well as hazardous compounds (acids, alkalis, surfactant-dispersion agents).	TiO_2 nanoparticle-based photocatalytic degradation, carbon-based nanomaterials Nano sorbents include carbon nanotubes, zeolites	(Photocatalysis) Chemical Physical-chemical (pollutant adsorption) Physical-chemical (pollutant adsorption) Physical-chemical (pollutant adsorption)	Dyes Inorganic and organic contaminants Metal oxides Heavy metals	Utilizing nanotechnology to treat textile wastewater is effective at removing and recovering contaminants.	(Sonawane S S et. al, 2008)

III. REFERENCES

Abhijit G, Shriram S and Mahesh V (2013). Kinetic modeling of biohydrogen production from complex wastewater by anaerobic cultures. Res J Chem Environ, 1,7 (12), 129.

Abhijit, G, Sonawane Shriram S and Mahesh V (2016). Ultrasonication as a pre-treatment strategy for enhancement of biohydrogen production from dairy wastewater. Res J Chem Environ, 20 (4), 10.

Ahmad K, Wajid K, Khan Z I, Ugulu I, Memoona H, Sana M, Nawaz K, Malik I S, Bashir H and Sher M (2019). Evaluation of potential toxic metals accumulation in wheat irrigated with wastewater. Bull Environ ContamToxicol, 102, 822.

Ahmaruzzaman M (2011). Industrial wastes as low-cost potential adsorbents for the treatment of wastewater laden with heavy metals. Adv Colloid Interface Sci, 166 (1-2), 36.

Akinterinw A and Adibayo I (2018). Cross-linked-substituted (esterified/etherified) starch derivatives as aqueous heavy metal ion adsorbent: a review. Int J Chem, 1 (2), 167.

Al-Salem S M, Lettieri P and Baeyens J (2009). Kinetics of polyethylene terephthalate (PET) and polystyrene (PS) dynamic pyrolysis. Int Proc Chem Biol Environ Eng, Montreal (Quebec), 1.

Al-Salem SM, Lettieri P and Baeyens J (2010). The valorization of plastic solid waste (PSW) by primary to quaternary routes: From re-use to energy and chemicals. Prog Energy Combust Sci, 36 (1), 103.

Awaleh M O and Soubaneh Y D (2014). Wastewater treatment in chemical industries: the concept and current technologies. Hydrol Curr Res, 5 (1), 1.

Bazrafshan E, Mohammadi L, Ansari-Moghaddam A and MahviA H (2015). Heavy metals removal from aqueous environments by electrocoagulation process–a systematic review. J Environ Health Sci Eng, 13, 1.

Bethi B, Sonawane S H, Potoroko I, Bhanvase B A and Sonawane S S (2017). A novel hybrid system based on hydrodynamic cavitation for treatment of dye wastewater: A first report on bench scale study. J Environ Chem Eng, 5 (2), 1874.

Bethi B., Sonawane S. H., Bhanvase B. A. and Sonawane S. S. (2021). Textile industry wastewater treatment by cavitation combined with fenton and ceramic nanofiltration membrane. Chem Eng Process, 168, 108-140.

Branca T A, Colla, V, Algermissen D, Granbom H, Martini U, Morillon A, Pietruck R and Rosendahl S (2020). Reuse and recycling of by-products in the steel sector: Recent achievements paving the way to circular economy and industrial symbiosis in Europe. J Met, 10 (3), 345.

Brar A, Kumar M, Vivekanand V and Pareek N (2017). Bioconversion of chitin to bioactive chitooligosaccharides: amelioration and coastal pollution reduction by microbial resources. Biotechnol J, 7, 1.

Buthale R and Gujar J G (2018). Application of Nanofiltration for the Rejection of Chromium Ions From Synthetic Wastewater. Int J Eng, 5, 54.

Cañadas R, Gonzalez-Miquel M, González E J, Díaz I and Rodriguez M (2020). Overview of neoteric solvents as extractants in food industry: A focus on phenolic compounds separation from liquid streams. Int Food Res J, 136, 109558.

Cepoi L, Donţu N, Şalaru V and Şalaru V (2016). Removal of organic pollutants from wastewater by cyanobacteria. Int BiodeteriorBiodegradation , 27.

Chandane V S, Rathod A P, Wasewar K L and Sonawane S S (2017). Response surface optimization and kinetics of isopropyl palmitate synthesis using homogeneous acid catalyst. Int J Chem React Eng, 15 (3) 2016-0111.

Charde S J and Sonawane S S (2016). Thermo mechanical properties of polycarbonate-OMMT clay nanocomposites using artificial neural network. IEEE Trans Nanotechnol, 1.

Chaturvedi P, Giri B S, Shukla P and Gupta P (2021). Recent advancement in remediation of synthetic organic antibiotics from environmental matrices: Challenges and perspective. Bioresour Technol, 319, 124-161.

Chen Q, Luo Z, Hills C, Xue G and Tyrer M (2009). Precipitation of heavy metals from wastewater using simulated flue gas: sequent additions of fly ash, lime and carbon dioxide. Water Res, 43 (10), 2605.

Chollom M N (2014). Treatment and reuse of reactive dye effluent from textile industry using membrane technology. PhD diss.

Comninellis Christos (2008). Advanced oxidation processes for water treatment: advances and trends for R&D. Clean Technol Environ Policy, 83, 769.

Dewil R, Mantzavinos D, Poulios I and Rodrigo M A (2017). Electrochemical oxidation of key pharmaceuticals using a boron doped diamond electrode. J Environ Manage, 195, 93.

Dogaru L (2020). The main goals of the fourth industrial revolution. renewable energy perspectives. Procedia Manuf, 46, 397.

Dronkar, M., & Gujar, J. G. (2018). Study of Purification & Separation of Natural Polyphenols (Gallic Acid) from Pomegranate Peel, International Journal of Science Technology & Engineering, 5 (6), 45-49.

Ehrlich H, Bailey E, Wysokowski M and Jesionowski T (2021). Forced biomineralization: A review. Biomimetics, 6 (3), 46.

Endale S A, Taffese W Z, Vo D H and Yehualaw M D (2022). Rice husk ash in concrete. J Environ Sustain, 15 (1), 137.

Engwa G A, Ferdinand P U, Nwalo F N and Unachukwu M N (2019). Ameliorative effect of Nigella sativa conjugated silver nanoparticles against chromium-induced hepatotoxicity and renal toxicity in mice. Phytother Res, 10, 70.

Frutos F G, Pérez R, Escolano O, Rubio A, Gimeno A, Fernandez M D, Carbonell G, Perucha C and Laguna J (2012). Remediation trials for hydrocarbon-contaminated sludge from a soil washing process: evaluation of bioremediation technologies. J Hazard Mater, 199, 262.

Frutos F J G, Escolano O, García S, Babín M and Fernández M D (2010). Bioventing remediation and ecotoxicity evaluation of phenanthrene-contaminated soil. J Hazard Mater, 183 (1-3), 806.

Gadhe A, Sonawane S and Varma M (2014). Ultrasonic pretreatment to enhance biohydrogen production from food waste. Bioenergy Res, 242.

Gadhe A, Sonawane S S and Varma M N (2013). Optimization of conditions for hydrogen production from complex dairy wastewater by anaerobic sludge using desirability function approach. Int J Hydrog Energy, 38 (16), 6607.

Gadhe A, Sonawane S S and Varma M N (2014). Kinetic analysis of biohydrogen production from complex dairy wastewater under optimized condition. Int J Hydrog Energy, 39 (3), 1306.

Gadhe A, Sonawane S S and Varma M N (2015). Enhanced biohydrogen production from dark fermentation of complex dairy wastewater by sonolysis. Int J Hydrog Energy, 40 (32) 9942.

Gadhe A, Sonawane S S and Varma M N (2015). Enhancement effect of hematite and nickel nanoparticles on biohydrogen production from dairy wastewater. Int J Hydrog Energy, 40 (13), 4502.

Gadhe, A, Sonawane S S and Varma M N (2014). Ultrasonic pretreatment for an enhancement of biohydrogen production from complex food waste. Int J Hydrog Energy, 39 (15), 7721.

Gavali A A, Baviskar J A, Gujar J G and Sonawane S S (2023). A comprehensive review of the development of nano-bio adsorbents for the separation of heavy metals from wastewater. J Indian Assoc Environ Manag, 42 (4), 24.

Ghanshyam B, Shriram S S and Kailas W L (2016). Effect of Octadecyl Amine modified MMT on Thermal Stability, Visco-elastic Properties and Crystallization Behaviour of

Polyamide 6 Nanocomposites. Res J Chem Environ, 20 (11), 1.

Ghanshyam B, Sonawane Shriram S, Wasewar K L, Rathod A P and Parate V R (2017). Synthesis and characterization of $CaCO_3$-SiO_2 core-shell nanoparticles with PA6 nanocomposites. Res J Chem Environ, 21, 5.

Gujar J G and Sawant A (2019). A Study of Extraction of Ferulic Acid from Bamboo Plant. Int J Res Eng Sci Manag, 2 (8), 103.

Gujar J G, Chattopadhyay S, Wagh S J and Gaikar V G (2010). Experimental and modeling studies on extraction of catechin hydrate and epicatechin from Indian green tea leaves. Can J Chem Eng, 88(2), 232.

Gujar J G, Patil S S and Sonawane S S (2023). A Review on Nanofluids: Synthesis, Stability, and Uses in the Manufacturing Industry. Curr Nanomater, 8 (4), 303.

Gujar, J G, Kadam S and Patil U D (2022). Recent Advances of Artificial Intelligence (AI) for Nanobiomedical Applications. Disruptive Developments in Biomedical Applications Biomed J, 3.

Gujar, J. G., Wagh, S. J., &Gaikar, V. G. (2010). Experimental and modeling studies on microwave-assisted extraction of thymol from seeds of Trachyspermumammi (TA). *Separation and Purification Technology*, *70*(3), 257-264.

Guo Y, Wang J, Shinde S, Wang X, Li Y, Dai Y, Ren J, Zhang P and Liu X (2020). Simultaneous wastewater treatment and energy harvesting in microbial fuel cells: an update on the biocatalysts. RSC Adv, 10 (43), 25874.

Haddadi E, Gujar J G and Sonawane S S (2023). Kinetics and isotherm studies for the adsorption of boron from water using titanium dioxide. Can J Chem Eng, 101 (3), 1335.

Hadiani M R, Darani K K, Rahimifard N and Younesi H (2018). Biosorption of low concentration levels of Lead (II) and Cadmium (II) from aqueous solution by Saccharomyces cerevisiae: Response surface methodology. Biocatal Agric Biotechnol, 15, 25.

Hakke V, Sonawane S, Anandan S, Sonawane S and Ashokkumar M (2021). Process intensification approach using microreactors for synthesizing nanomaterials—A critical review. J Nanomater, 11(1), 98.

Hong S U I and Xingang L I (2011). Modeling for volatilization and bioremediation of toluene-contaminated soil by bioventing. Chin J Chem Eng, 19 (2), 340.

Jotiram G, Patil S, and Sonawane S (2024). Review on the Encapsulation, Microencapsulation, and Nano-Encapsulation: Synthesis and studys in the Process Industry for Corrosion Inhibition. Current Nano 20 (3), 314-327.

Jun K C, Raman A AA and Buthiyappan A (2020). Treatment of oil refinery effluent using bio-adsorbent developed from activated palm kernel shell and zeolite. RSC Adv, 10 (40), 24079.

Juwar V and Sonawane S (2014).Development of nano based thermic fluid: rheological aspects of new energy system. Recent advances in bioenergy research. Bioenergy res, 487.

Kadam S, Shinde, A S, Bari A M and Gujar J G (2020). Applied Computer Vision and Soft Computing with Interpretable AI (Chapman and Hall/CRC), 135.

Kale P, Pujari S, Gujar J G, Sontakke R, Haddadi E I and Sonawane S S (2023). Batch distillation for separating the acetone and n-heptane binary azeotrope mixture: Optimization and simulation. J Indian Chem Soc, 100 (1), 100795.

Katole A A, Gujar J G and Chavan S M (2016). Experimental and Modeling Studies on Extraction of Eugenol from Cinnamomum Zeylanicum (*Dalchini*). IJSTE, 2, 831.

Khattak S I and Ahmad M (2021). The cyclical impact of green and sustainable technology research on carbon dioxide emissions in BRICS economies. Environ Sci Pollut Res, 1.

Khedkar R S, Sonawane S S and Wasewar K L (2012). Dispersions of CuO nanoparticles in paraffin prepared by ultrasonication: a potential coolant.NtCommun Heat Mass Transf, 39(5), 665.

Khedkar R S, Sonawane S S and Wasewar K L (2013). Water to Nanofluids heat transfer in concentric tube heat exchanger: Experimental study. Procedia Eng, 51, 318.

Khudur L S, Shahsavari E, Miranda A F, Morrison P D, Nugegoda D and Ball A S (2015). Evaluating the efficacy of bioremediating a diesel-contaminated soil using ecotoxicological and bacterial community indices. Environ Sci Pollut Res, 22, 809.

Klavarioti M, Mantzavinos D and Kassinos D (2009). Removal of residual pharmaceuticals from aqueous systems by advanced oxidation processes. Environ Int, 35 (2), 402.

Kodape S M, Rathod A P and Sonawane S S (2012).Study on Synthesis and Characterization of $CoFe_2O_4$ Nanoparticles. Biol Environ, 46.

Korpe S A, Landge V, Hakke V S, Rao P V, Sonawane S H and Sonawane S S (2022). Advanced oxidation processes for tannery industry wastewater treatment. Water Res, 253.

Kumar A, Singh P, Raizada P and Hussain C M (2022). Impact of COVID-19 on greenhouse gases emissions: A critical review. Sci Total Environ, 806, 150349.

Kumar A, Thakur P P, Manjakuppam M and Sonawane S S (2023). Promising nanoparticles for water reuse and recovery. Water Environ Res, 129.

Kumar N, Sonawane S S and Sonawane S (2018). Experimental study of thermal conductivity, heat transfer and friction factor of Al_2O_3 based nanofluid.Int Commun Heat Mass Transf, 90, 1.

Kumar N, Urkude N, Sonawane S S and Sonawane S H (2018). Experimental study on pool boiling and Critical Heat Flux enhancement of metal oxides based nanofluid. Int Commun Heat Mass Transf, 96, 37.

Kuyukina M S, Krivoruchko A V and Ivshina I B (2020). Advanced bioreactor treatments of hydrocarbon-containing wastewater. Appl Sci, 10 (3), 831.

Malika M and Sonawane S S (2021). he sono-photocatalytic performance of a novel water based Ti^{+4} coated Al(OH) 3-MWCNT's hybrid nanofluid for dye fragmentation. Int J Chem React Eng , 19 (9) 901.

Malika M and Sonawane S S (2022). The sono-photocatalytic performance of a Fe_2O_3 coated TiO_2 based hybrid nanofluid under visible light via RSM. Colloids and Surfaces A J Environ Manage, 641, 128545.

Malika M, Jhadav P G, Parate V R and Sonawane S S (2023). Synthesis of magnetite nanoparticle from potato peel extract: its nanofluid applications and life cycle analysis. Chem Pap, 77 (2), 1081.

Malika M, Pargaonkar A and Sonawane S S (2023). Performance of an Emulsion Nanofluid Membrane for the Extraction of Antimony Heavy Metal: Experimental and Numerical Investigation. Chem Pap, 1.

Malkapuram S T, Sharma V, Gumfekar S P, Sonawane S, Sonawane S, Boczkaj G and Seepana M M (2021). Advanced oxidation processes for tannery industry wastewater treatment. Sustain Energy Technol Assess, 48, 101-576.

Mangesh W, Kailas W and Shriram S (2013). Reactive extraction of picolinic and nicotinic acid by natural non-toxic solvent. Res J Chem Environ, 17 (2).

McNeely J A (2021). Nature and COVID-19: The pandemic, the environment, and the way ahead. Ambio, 50 (4), 767.

Mohsenpour S F, Hennige S, Willoughby N, Adeloye A and Gutierrez T (2021). Integrating micro-algae into wastewater treatment: A review. Sci Total Environ, 75 (2), 142-168.

Mossali E, Picone N, Gentilini L, Rodrìguez O, Pérez J M and Colledani M (2020). Lithium-ion batteries towards circular economy: A literature review of opportunities and issues of recycling treatments. J Environ Manage J Environ Manage, 264, 110-500.

Mulbry W, Kondrad S, Pizarro C and Kebede-Westhead E (2008). Treatment of dairy manure effluent using freshwater algae: algal productivity and recovery of manure nutrients using pilot-scale algal turf scrubbers. Bioresour Technol, 99 (17) 8137.

Mungray A K, Mungray A A, Sonawane S S and Sonawane S (2022). Novel Approaches Towards Wastewater Treatment and Resource Recovery Technologies. Elsevier sci.

Muro C, Riera F and del Carmen Díaz M (2012). Membrane separation process in wastewater treatment of food industry. J Food Process Eng, 253.

Nizam, S, Kato M, Yatsuya H, Khalequzzaman M, Ohnuma S, Naito H and Nakajima T (2013). Differences in urinary arsenic metabolites between diabetic and non-diabetic subjects in Bangladesh. Int J Environ Res Public Health Int J Env Res Pub He, 10 (3), 1006.

Nizami A. S., Rehan M., Waqas M., Naqvi M., Ouda O. K., Shahzad K., Miandad R., Khan M. Z., Syamsiro M., Ismail I. and Pant D. (2017). Waste biorefineries: Enabling circular economies in developing countries. Bioresour Technol, 241, 1101.

Ojuederie O B and Babalola O O (2017). Microbial and plant-assisted bioremediation of heavy metal polluted environments: a review. Int J Environ Res Public Health Int J Env Res Pub He, 14 (12), 1504.

Pablos C, MarugánJ ,VanGrieken R and Serrano E (2013). Emerging Micropollutant Oxidation During Disinfection Processes Using UV-C, UV-C/H_2O_2, UV-A/TiO_2 and UV-A/TiO_2/H_2O_2. Water Res, 47 (3), 1237.

Pagliano G, Ventorino V, Panico A and Pepe O (2017). Integrated systems for biopolymers and bioenergy production from organic waste and by-products: a review of microbial processes Biotechnol Biofuels, 10 (1), 1.

Pangestuti R and Kim S K (2011). Biological activities and health benefit effects of natural pigments derived from marine algae. J Funct Foods, 3 (4), 255.

Pathak U, Das P, Banerjee P and Datta S (2016). Treatment of wastewater from a dairy industry using rice husk as adsorbent: treatment efficiency, isotherm, thermodynamics, and kinetics modelling. J Thermodyn.

Patil P P, Gujar J G and Chavan S M (2022). Rejection Behaviour of Manganese Ions from Synthetic Wastewater by Nanofiltration Membrane. J Environ Manage, 42 (2), 1.

Ragaert K, Delva L and Van Geem K (2017). Mechanical and chemical recycling of solid plastic waste. J Waste Manag, 69, 24.

Ram C, Rani P, Gebru K A and Mariam Abrha M G (2020). Pulp and paper industry wastewater treatment: use of microbes and their enzymes. Phys Sci Rev, 5 (10), 201.

Ranade V V and Bhandari V M (2014). Industrial wastewater treatment, recycling and reuse. Butterworth-Heinemann int med rev, Neurol.

Rathod A P, Wasewar K L and Yoo C K (2014). Enhancement of esterification of propionic acid with isopropyl alcohol by pervaporation reactor. J Chem.

Sabiha-Javied F H, Munawar S, Qasim M, Anees M M, Ghani M U, Azad A, Khalid M, Ullah I and Ansar A (2015). Management of municipal solid waste generated in eight cities of Pakistan. J Sci Eng Res, 1186.

Sharma P, Singh S P, Pandey S, Thanki A and Singh N K (2020). Role of potential native weeds and grasses for phytoremediation of endocrine-disrupting pollutants discharged from pulp paper industry waste. Bioremediat J, 17.

Sharma P, Tripathi S and Chandra R (2020). Phytoremediation potential of heavy metal accumulator plants for waste management in the pulp and paper industry. Heliyon, 6 (7).

Sheth Y, Dharaskar S, Khalid M and Sonawane S (2021). An environment friendly approach for heavy metal removal from industrial wastewater using chitosan based biosorbent: A review. Sustain Energy Technol Assess, 43, 100951.

Sheth Y, Dharaskar S, Khalid M and Sonawane S (2021). An environment friendly approach for heavy metal removal from industrial wastewater using chitosan based biosorbent: A review. Sustain Energy Technol Assess, 43, 100951.

Shimpi N G, Kakade R U, Sonawane S S, Mali A D and Mishra S (2011). Influence of nano-inorganic particles on properties of epoxy nanocomposites. PolymPlast Technol Eng, 50 (8), 758.

Singh A and Olsen S I (2011). A critical review of biochemical conversion, sustainability and life cycle assessment of algal biofuels. Appl Energy, 88 (10), 3548.

Sivakumar P, Sindhanaiselvan S, Gandhi N N, Devi S S and Renganathan S (2013). Optimization and kinetic studies on biodiesel production from underutilized Ceiba Pentandra oil. J Fuels, 103, 693.

Smith E, Thavamani P, Ramadass K, Naidu R, Srivastava P and Megharaj M (2015). Remediation trials for hydrocarbon-contaminated soils in arid environments: evaluation of bioslurry and biopiling techniques. Int BiodeterBiodegr, 101, 56.

Sonawane S H, Bhanvase B A, Sivakumar M and Potdar S B (2020). Current overview of encapsulation. J Microencapsul, 1.

Sonawane S S, Gadhe A and Thakur P (2021). Nano-biotechnology for bacterial modification for wastewater treatment and resource recovery. J Environ Manage, 41 (4), 45.

Sonawane S S, Gadhe A, Thakur P P, Sonawane S H and Mohammed H A (2022). Nano-biotechnology for bacterial modification for wastewater treatment and resource recovery.Water Res, 295.

Sonawane S S, Malika M, Thakur P P and Sonawane S H (2022). Carbon nano tubes (CNT) based hybrid nano fluids for the wastewater treatment plants in the industry. Water Res, 313.

Sonawane S S, Mishra S and Shimpi N G (2009). Polyamide nanocomposites: investigation of mechanical, thermal and morphological characteristics. PolymPlast Technol Eng, 48 (10), 1055.

Sonawane S S, Patil V S, Usmani G A, Wani K S and Parate V R (2008). Study the kinetics of catalytic esterification reaction between n-butanol and acetic acid. Mater Sci Res India, 5 (1), 135.

Sonawane S S, Thakur P P, Malika M and Ali H M (2023). Recent advances in the applications of green synthesized nanoparticle based nanofluids for the environmental remediation. Curr Pharm Biotechnol, 24 (1), 188.

Sonawane S S, Thakur P, Bhaisare S and Jadhav P (2022). Energy recovery from industrial wastewaters. Curr Pharm Biotechnol, 163.

Sonawane S, Thakur P, Sonawane S H and Bhanvase B A (2021). Nanomaterials for membrane synthesis: Introduction, mechanism, and challenges for wastewater treatment. Nanomaterials, 537.

Sonawane, S. S., Jadhav, A. S., Holkar, A. D., Gujar, J. G., and Kadam, S. P (2023). Assessing Emission and Reduction Strategies For Volatile Organic Compounds (VOCs) In Refinery. J Environ Manage, (JIAEM), 43(3), 9-18.

Swain M R, Singh A, Sharma A K and Tuli D K (2019). Bioethanol production from rice-and wheat straw: an overview. Bioenergy Res, 213.

Tawila Z M A, Ismail S, Amr S S A and Abou Elkhair E K (2019). A novel efficient bio flocculant QZ-7 for the removal of heavy metals from industrial wastewater. RSC Adv, 9 (48), 27825.

Thakur P P, Malika M and Sonawane S S (2023). Energy recovery from industrial wastewaters. Water Resour, 3, 319.

Thakur P P, Sonawane S S and Mohammed H A (2023). Recent Trends in Applications of Nanofluids for Effective Utilization of Solar Energy. Curr Nanosci, 19 (2), 170.

Thakur P P, Sonawane S S and Sonawane S H (2022). Nano-particle-enhanced ionic liquids (NEIL) for the wastewater treatment. Water Res, 325.

Thakur P, Uslu H and Sonawane S S (2022). Experimental investigation of CO_2 absorption process using nanofluids. J Nanofluids, 227.

Uppalwar, C. S., Thakur, A. N., Gujar, J. G., Sonawane, S. S. (2022). Low-Cost Adsorbents and Nanomaterials for Removal of Heavy Metals from Contaminated Water. *J. Indian Assoc. Environ. Manag*, 42 (4), 1-9.

Verma A K, Dash R R and Bhunia P (2012). A review on chemical coagulation/flocculation technologies for removal of colour from textile wastewaters. J Environ Manage, 93 (1), 154.

Vikrant K, Giri B S, Raza N, Roy K, Kim K H, Rai B N and Singh R S (2018). Bioresour Technol, 253, 355.

Vishal R, Shriram S and Shyam S (2018). Food fortification of soy protein isolate for human health. Res J Chem Environ, 22, 108.

Wagh S J, Gujar J G and Gaikar V G (2012). Experimental and modeling studies on extraction of amyrins from latex of mandar (*Calotropis gigantea*). Indian J Agric Chem, 19, 247.

World Bank, U.S. (2019). World Development Report, Population Growth.

Xiong X, Zhang Y, Wang L and Tsang D C (2022). Overview of hazardous waste treatment and stabilization/solidification technology. Waste Manag Res, 1.

Zhang M, Xie L, Yin Z, Khanal S K and Zhou Q (2016). Biorefinery approach for cassava-based industrial wastes: Current status and opportunities. Bioresour Technol, 215, 50.