Open Access

Advances in Environmental and Engineering Research

LIDSEN Publishing Inc.

Review

Valorization of Plastic Wastes for the Development of Adsorbent Designed for the Removal of Emerging Contaminants in Wastewater

Matthew Adah Onu [1,*], Olusola Olaitan Ayeleru [1], Helen Uchenna Modekwe [2], Peter Apata Olubambi [1]

1. Centre for Nanoengineering and Advanced Material, University of Johannesburg, Doornfontein Campus, Johannesburg, 2028, South Africa; E-Mails: meetchiefonu@gmail.com; olusolaolt@gmail.com; polubambi@uj.ac.za
2. Renewable Energy and Biomass Research Department of Chemical Engineering, University of Johannesburg, 2028, Johannesburg, South Africa; E-Mail: uche_lyne2@yahoo.com

* **Correspondence:** Matthew Adah Onu; E-Mail: meetchiefonu@gmail.com

Academic Editor: Andrea Capodaglio

Special Issue: Opportunities and Challenges in Governing Plastics Waste

Adv Environ Eng Res
2023, volume 4, issue 4
doi:10.21926/aeer.2304055

Received: August 28, 2023
Accepted: December 20, 2023
Published: December 29, 2023

Abstract

Plastic waste accrual in the environment has been identified as the topmost significant global issue related to modern civilization. Traditional waste disposal methods, such as open burning, landfilling, and incineration, have increased greenhouse gas emissions in economic and material losses. Unless immediate action is made to curtail demand, prolong product lifespans, enhance waste management, and encourage recyclability, plastic pollution will increase due to an almost threefold increase in plastic use spurred by growing populations and affluence. Plastic production primarily is from crude oil or gas despite more than a fourfold growth from ~6.8 million tonnes in 2000 to ~30 million tonnes in 2019; only ~6% of the world's total plastics production is made from recycled plastics. The competitiveness and profitability of secondary markets may increase with the establishment of recycled content objectives and advancements in recycling technology. In this review, emerging approaches and the creation of value-added materials from waste plastics such as carbon nanotubes and other carbonaceous nanomaterials production, the environmental impacts of plastic waste, African status concerning plastic waste, the importance of modern techniques in plastic waste management, and the circular economy impact on plastic waste utilization are the high points of this study.

Keywords
Plastic waste; carbon nanotubes; circular economy; adsorption; environmental management

1. Introduction

Plastics are suitable for usage with multiple successes when considering stability and flexibility. As a result, plastics rank third among industrial materials used today after concrete and steel [1]. Plastic production could keep increasing due to the flexible uses of plastic materials across many sectors of human endeavor globally [2]. Globally, since 1950, there has been a noticeable growth in the manufacturing and use of plastic [1]. The non-degradable nature of plastics results in a significant plastic waste (PW) buildup in landfills and seas since most produced plastics are created for performance and persistence rather than recycling and decomposability [3]. Plastics contribute significantly to global waste due to their single use in sterile packaging, storage, transportation, and disposable medical components [4]. ~20% of global PW is routinely recycled, and the remaining contributes to worldwide waste and environmental degradation. Recycling is usually tricky since post-consumer PW frequently contains diverse contaminants, including organic and inorganic ones, and typically consists of mixed polymers of unknown composition. This waste is either burned at power plants, disposed of in landfills, or washed into the ocean, where its latent values are lost [3]. Plastic is currently the primary focus of the global waste management agenda. Subsequently, conferences of the Basel and Stockholm Convention parties have voiced worries about the dangers of PW, marine plastic accumulation, and microplastics and have underlined the significance of lowering consumption and guaranteeing the ecologically sound treatment of waste plastics [5]. Workable solutions and persuasive approaches to address the growing amount of PW have not been developed, which leads to the accumulation of this waste and its destructive effects on the environment. An innovative method of waste plastics management is of utmost urgency. Creating higher-value materials such as hydrogen, synthetic oil, and carbon nanotubes (CNTs) from PW has recently drawn much attention in the research arena [6, 7]. Belbessai et al. highlighted the advantages of utilizing PW as a carbon source in synthesizing carbon nanomaterials (CNMs) over carbon-based light molecules, such as methane, ethylene, and acetylene [8]. The application of CNTs in wastewater treatment (WWT) through various modifications for emerging contaminants removal makes the usage of waste plastics as a source of feedstocks for CNTs production more promising [9]. Plastic materials, such as PS, PET, PU, PVC, etc., have been valorized into valuable functional materials for CO_2 capture and utilization [10]. PET-derived activated carbon has been utilized as adsorbent material in temperature swing CO_2 adsorption (capture) [11]. PET has been chemically transformed into terephthalic acid, an essential organic building block for metal-organic frameworks (MOFs) [12]. Song and coworkers produced MOFs (Ni-MOF nanocrystals) from PET and electroplating sludge, and it was reported that the produced Ni-MOF nanocrystals showed superior activity in the photoreduction of CO_2 [13].

In wastewater, fluorescent carbon nanoparticles produced from sulfonated PS wastes were applied in sensing hazardous transition metal cations (such as Cu, Ni, and Mn) [14]. Fluorescent carbon dots (CDs) produced from plastic wastes are utilized as sensor material in detecting histamine, Hg, Cu, and Fe [15]. Similarly, Chaudhary and coworkers studied the antibacterial and antifungal activities of carbon dots (CDs) prepared from upcycling different single-use plastic wastes [16]. The produced CDs were also employed in detecting Cu ions in aqueous media. Plastic waste-derived activated carbon has been used to remove polycyclic aromatic hydrocarbons (PAHs) from polluted water [17]. Wankasi and Dikio also developed adsorbents from PVC, which effectively remove Pb ions from an aqueous environment [18].

Plastic waste materials are valorized as additives and raw materials for brick production and road pavements in the construction sector [19]. There is also recent development in the large-scale waste plastics valorization route (waste refinery), where plastic wastes have been valorized into fuels, energy, chemicals, and monomers [20].

Mishra and Sundaram, in their study, reported the main advantages of CNTs as possessing the potential to adsorb a broad spectrum of inorganic and organic compounds, microorganisms, and heavy metals [21]. Carbon materials generated from PW exhibit notable characteristics such as elevated porosity levels, high specific surface areas (SSAs), diverse surface chemistries (including dopants or functional groups), excellent conductivity, and robust stability. As a result, PW-derived carbon materials (PWCMs) are commonly utilized in applications about sustainable environmental practices (pollutant adsorption/degradation, solar evaporation, and CO_2 capture) or green energy (batteries, supercapacitors, and water-splitting systems). PWCMs can save expenses and help manage PW while offering significant environmental and economic advantages [22]. Besides the carbonization of PW for WWT, various novel techniques are emerging for PW utilization. For instance, Hernández-Del Castillo et al. developed a novel polypropylene-TiO_2: Bi spherical floater for efficient photocatalytic degradation of the recalcitrant 2,4,6-TCP herbicide and reported >90% performance in the degradation of 2, 4, 6-TCP herbicide [23]. Clean water is essential to civilization, and since traditional water and WW remediation methods typically cannot effectively eradicate all growing pollutants (such as pharmaceuticals and flame retardants), new and creative treatment methods are being explored [24]. Although different investigations have tried to address the problem of the continuous proliferation of PW, little research has been done on the development of adsorbents from PW for application in emerging contaminants removal from WW, leaving much room for enhancement. As a result, there is little or no information on PW conversion into value-added materials in Africa, particularly in the sub-Saharan African (SSA) region. This review study aims to present the paradigm shift in the use of plastic materials from a linear economy (LE) mode to a circular economy (CE), the development of value-added adsorbent from waste plastic, its application in emerging pollutant removal in wastewater (WW), environmental impacts of PW, and significance of contemporary PW management strategies are the focus of this paper. Previous works on the creation of adsorbents made from PW and their applications in the removal of emerging antibiotic contaminants (tetracycline (TC)), which, when detected in aqueous environments (even at a minimal amount) causes antibiotic resistance (AR) in organisms were also reviewed. PW volarization is pivotal to the circular economy and sustainable development that would usher in both environmental wellness and economic benefits in SSA and ultimately lead to a clean and green environment.

1.1 Historical Background of Plastic Development

Humanity has worked to create materials with advantages that have not been present in naturally occurring materials from the beginning of time. Natural substances with inherent plastic characteristics, such as chewing gum and shellac, were first used to produce plastics [25]. The next stage in the development of plastics entailed chemically altering natural substances, including galalite, rubber, nitrocellulose, and collagen. Ultimately, over a century ago, a wide variety of wholly synthetic products that we would identify as modern plastics started to be made ([25]. Leo Baekeland created “Bakelite” (today known as phenol-formaldehyde), the first synthetic plastic substance (meaning it included no molecules occurring in nature), in 1909 [26]. To fulfill the demands of the rapidly electrified United States, Baekeland had been researching a synthetic equivalent for shellac, a natural electrical insulator created in 1856. In addition to being a superior insulator, bakelite distinguished itself from the rival product “celluloid” by being strong, heat resistant, and ideally suited for mechanical mass manufacturing. Bakelite, which possessed “a thousand applications,” could be shaped or molded into almost anything, providing a wide range of options. Although these characteristics provide a robust and long-lasting product, they also result in lengthy degradation times. This means the effects may last many years in the environment [26, 27]. During the two World Wars, many plastics-related inventions occurred; cellophane was invented in 1913, followed by polyvinyl chloride in 1927, polystyrene and nylon in 1938, and polyethylene in 1942. These breakthroughs changed the way that plastics are used today. Roland Barthes, a philosopher, stated a few years later that plastic is the product of alchemy despite having names of Greek shepherds [27]. Figure 1 depicts the progress of global plastics production annually and global primary plastic production of various industrial sectors in millions of tonnes per annum. It took up to the 1950s to witness a substantial increase in plastic production globally. Over the past 70 years, plastics production has risen 230 times, reaching 460 million tonnes in 2019 [28], and by 2050, plastics production has been projected to reach 1 billion tonnes.

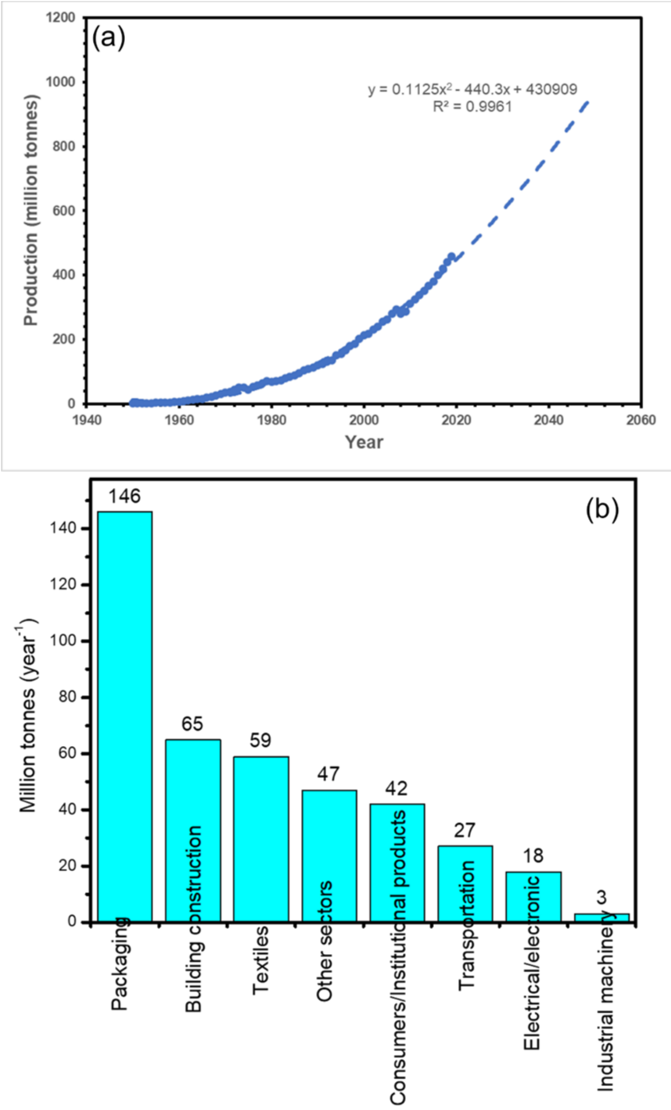

Figure 1 (a) Global plastics (polymer resin and fibers) production in millions of tonnes per annual basis and (b) Global primary plastic production, industrial allocation by sector 2015, measured in tonnes per annum [28]. This work is shared under the CCBY 4.0 license. Accessible online: 'https://ourworldindata.org/plastic-pollution.' Retrieved 20 March 2023.

Given the kind and quantity of plastics used and their limited valuable lives compared to their high levels of durability and persistence in nature, plastics have significantly burdened our world [1]. Zhang et al. stated that in 2017, there were 348 million tons of plastic produced globally, with five primary varieties dominating the market: polyethylene terephthalate (PET) 7.4%, polypropylene (PP) 19.3%, polyethylene (PE) 17.5% polyvinyl chloride (PVC) 10%, and polystyrene (PS) 6.7% [24]. Plastics play an essential role in our lives. Thus, some experts are attempting to improve plastics' safety and environmental friendliness. Researchers are working to create bioplastics, materials synthesized from plants that are alternative to fossil fuels and more ecologically friendly than traditional plastics [29, 30].

2. Plastic Types

Thermosets and thermoplastics are the two primary types of plastic. Thermoplastics can be melted or softened at high heat or pressure and can return to their solid state under cold circumstances [31]. It is possible to chill and harden thermoplastics repeatedly. On the other hand, after being heated once, thermosetting polymers harden indefinitely. The fundamental difference between the two is that once a thermoset has been created, it cannot be remolded since it sets permanently when heated. On the other hand, thermoplastics may be heated again, reshaped, and cooled as necessary without undergoing any chemical changes [32]. These physical and chemical properties enable thermosets to withstand elevated temperatures without compromising their structural integrity, unlike thermoplastic materials with low melting points. Two commonly used polymers for single-use plastics, for instance, are polyethylene terephthalate (PET) and polyethylene (PE) [31].

2.1 Thermoplastics

The thermoplastics consist of straight or slightly branched molecules that do not form chemical bonds with one another when heated. Instead, weak van der Waal forces (weak interactions between the molecules) hold thermoplastic strands together, causing the lengthy chemical chains to group together like tangled spaghetti. Like candle wax, thermoplastics may be heated and cooled repeatedly, softening and hardening [33]. Because of this, thermoplastics can be molded and used practically endlessly. As individual molecules make up thermoplastic polymers, molecular weight significantly impacts the characteristics of these materials. For instance, a thermoplastic material's tensile, impact, and fatigue strength increase with increasing molecular weight. Polypropylene (PP), polystyrene (PS), polyvinyl chloride (PVC), polyethylene (PE), polyethylene terephthalate (PET), polyamides (PA), polycarbonate (PC), expanded polystyrene (EPS), polymethyl methacrylate (PMMA), thermoplastic elastomers (TPE), polyarylsulfone (PSU), fluoropolymers, and others are examples of thermoplastics [34].

2.2 Thermosets

When heated, the chain molecules that make up thermosetting polymers bind chemically or crosslink. When the molecules in thermosetting polymers crosslink, they form a robust, three-dimensional network that resembles a single enormous molecule. Like cured concrete, thermosetting plastics cannot be remelted once hardened [34]. As a result, thermosetting polymers are frequently utilized to create heat-resistant items since they can withstand temperatures exceeding 260°C without melting [35]. In contrast to thermoplastics, thermosetting plastics are made of a single molecular network, and their molecular weight does not significantly influence their characteristics. Instead, different types and quantities of reinforcements, such as glass fibers, are added to thermosetting polymers to alter various features. It is possible to preserve thermosetting polymers in liquid form. Thermosetting plastics include, among others, polyurethane (PUR), unsaturated polyesters, epoxy resins, melamine resins, vinyl esters, silicone, phenol-formaldehyde resins, urea-formaldehyde resins, phenolic resins, and acrylic resins [34].

3. Environmental Impacts of Plastic Waste

Polymers have long been a catalyst for growth, but their increasing prevalence in the environment has become a development issue. Due to their distinctive qualities, plastics have become a pervasive part of modern life. The adverse effects of society's use of plastic have emerged recently due to the enormous costs that plastic waste has imposed on the environment, biodiversity, livelihoods, and public health [36]. Plastic offers several advantages to society and is not fundamentally harmful. However, the existing "take-make-waste" linear economic paradigm is the main factor contributing to plastic pollution [37]. With barely 20% of plastics entering the value chain again and massive volumes of plastic waste entering terrestrial and marine habitats each year, the plastic value chain continues to be archetypically linear, endangering both the environment and marine life [38]. The amount of throwaway plastic items on the market and the poor recycling rate have seriously harmed marine and terrestrial habitats. PW is becoming a global environmental disaster. "Limiting plastic" has gained worldwide acceptance, and several nations and regions have started initiatives to restrict and outlaw plastic [39]. Three major environmental problems that PW contributes to and whose effects may be mitigated by suitable waste management (WM) programs are as follows: (i) the exhaustion of fossil fuels and other natural resources to produce virgin plastic, which eventually becomes PW; (ii) the harm to ecosystems brought on by human action; and (iii) global warming, which is brought on by the emission of greenhouse gases (GHGs), part of which is created from PW and municipal solid waste (MSW) [40]. The global polymer production and total percentage demand of different polymer types are shown in Figure 2.

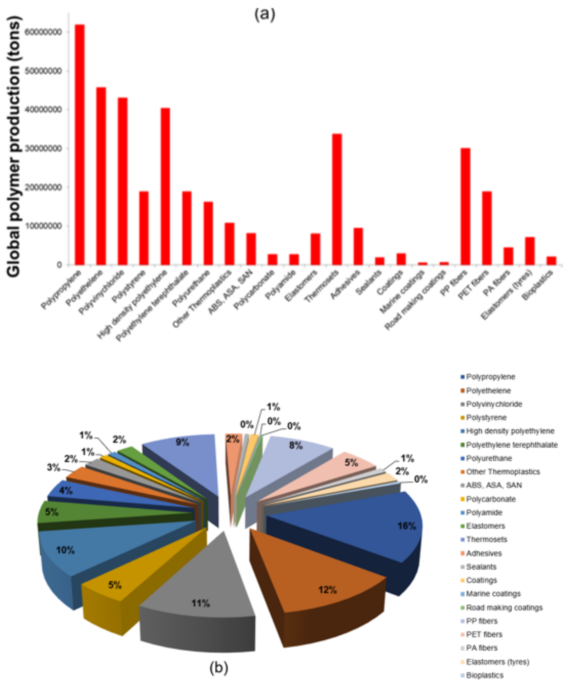

Figure 2 (a) Global polymer production of different polymer types, (b) percentage share total demand of different polymer types. Data source [41]. This work is shared under the CCBY.40 license. Available online: https://wedocs.unep.org/handle/20.500.11822/26745;jsessionid=F65A543A91D4AEAF3C00AAC03B215C82. Retrieved 4 April 2023. Keys: ABS, Acrylonitrile butadiene styrene; ASA, Acrylonitrile styrene acrylate; SAN, Styrene-acrylonitrile.

3.1 Land Environment

Major international organizations, such as the United Nations (UN), the World Economic Forum (WEF), the World Health Organization (WHO), and the European Union (EU), have made environmental plastic pollution one of their top priorities. In the past, manufacturing processes for plastics were mostly linear and more concerned with obtaining raw materials and turning them into usable goods than with product recycling or reuse [30]. An analysis of the adverse effects caused by improper plastic waste management, including the intense use of non-renewable materials, the deterioration of ecosystems, and the production of greenhouse gases (GHGs), suggests that they may be 40 billion USD annually. Suppose the present consumption modes and techniques for handling plastic waste do not change. In that case, plastic waste in landfills and the environment will be around 12 billion tonnes by the year 2050, a figure that has been around since the commencement of large-scale production of plastics in 1950 [42]. We do not fully understand how single-use plastics and microplastics affect the terrestrial ecosystem. It is still unclear where these pollutants penetrate dry land and streams, where they end up, their impacts on ecosystems, and whether there are any second- or third-order effects on the food chain [43]. Wastes made of plastic pollute the land because of the chemical breakdown of their degradable components. Additionally, the environment quickly absorbs plastic waste microplastics through primary and secondary sources [44].

3.2 Marine Environment

The ecological effect of PW differs according to the size of their particles; the core impacts on the ocean include aesthetics and entanglement [24]. The accumulation of plastics in the marine environment is hazardous as sea animals could get entangled or mistake them for food, which could suffocate them [41]. It has been projected that from 140 Mt in 2019, the amount of plastics expected to accumulate in aquatic habitats, streams, rivers, lakes, seas, and oceans in 2060 is expected to be 493 Mt, which would be more than fourfold [45]. The anticipated increase in flows into aquatic ecosystems would further worsen an already major environmental issue. Regional variations in contributions to aquatic leakage are anticipated to continue to change. It was predicted that China, India, non-OECD Asia, and Sub-Saharan Africa would account for 79% of all aquatic leakage. While China is the country that releases the most plastic into freshwater ecosystems, growing economies in Asia have a substantial impact on the amount of plastic that leaks into marine ecosystems [45].

4. African Status concerning Plastic Wastes

There are no comprehensive reports or references on the situation and effects of plastic contamination in Africa, nor are there any details on the legislative and regulatory frameworks necessary to tackle this issue from an African perspective [37]. Egypt, Nigeria, and South Africa are the continent's three most economically developed nations and are the most significant contributors to plastic waste generation. Algeria and Morocco are reportedly among the nations contributing to polluting the oceans with plastic [37]. Africa's top goal is to address the need for appropriate waste management services for its residents, essential for addressing the public health imperative. The core of any integrated waste management system is controlled waste disposal and thorough, dependable, and frequent city cleaning. In African nations, plastic waste is anticipated to double by 2030, reaching 165 million tonnes. Egypt, Nigeria, South Africa, Algeria, Morocco, and Tunisia will be home to most of this. Most plastic that makes its way to African coastlines is created in industrialized, wealthy nations. In 2010, it was projected that every year, up to 4.4 million tonnes of improperly disposed plastic waste were present in the waters and seas off the coast of Africa [46]. A more recent analysis makes a far higher estimate and considers contributions from landlocked nations. In 2015, Africa produced 19 million tonnes of plastic waste, of which 17 million were inadequately managed [37].

5. Classification of Adsorbents

Adsorbents are derived from natural sources or through industrial manufacture and/or activation processes when used to treat water. Natural zeolites, clay minerals, oxides, and biopolymers are common natural adsorbents. Several engineered adsorbents include carbonaceous adsorbents, polymeric adsorbents, oxidic adsorbents, and zeolite molecular sieves [47, 48]. Degradation, recycling, and upcycling are some of the treatment methods established for PW transformation into goods with additional value. The conversion of plastic waste into carbon-based functional materials is particularly appealing due to the valuable uses of plastic waste-derived carbon materials (PWCMs) for environmentally friendly practices and the field of green energy [22]. Pawar et al. reported using waste Polyethylene terephthalate (PET) as a precursor for aerogel development as an oil absorbent in the chemical industry [49]. Basically, in this review, we focused our research on adsorbents. According to a study by Crini et al., classified adsorbents into the following: (1) Natural materials such as sawdust, wood, fuller's earth, or bauxite; (2) Natural materials that have been modified to improve their structures and properties, such as activated carbons, activated alumina, or silica gel; (3) Man-made materials such as polymeric resins, zeolites, or aluminosilicates; (4) Agricultural solid wastes and Industrial By-Products such as Date Pits, Fly Ash, or Red Mud; and (5) Biosorbents for example, chitosan, fungi or bacterial biomass [50].

5.1 Activated Carbon

The phrase "activated carbon" (AC) refers to highly carbonaceous materials with a high permeability and sorption capacity created from wood, coal, coconut shells, cones, biomass, and many other materials. AC is one of the commonly utilized adsorbents for removing different types of toxins from water and air [51]. These materials are understood to be principally amorphous carbonaceous ones that may be distinguished from elemental carbon by oxidizing the carbon atoms on their exterior and interior surfaces [52]. Their sizeable specific surface areas, good porosity, and changeable surface-containing functional groups that cause strong surface reactivity set them apart from other materials. Granular activated carbon (GAC) and powdered activated carbon (PAC) are the two main types of activated carbon [53].

5.2 Carbon Nanotubes

Carbon nanotubes (CNTs) have led nanotechnology since Iijima's groundbreaking paper in 1991. It is possible to imagine CNT as a continuous, one-nanometer-diameter-thick sheet of graphene, a kind of graphite with one atom of thickness. CNT may be divided into two groups: single-walled CNT

(SWCNT), which is made of a single graphitic sheet coiled into a tube, and multi-walled CNT (MWCNT), which is made of concentric sheets of graphite cylinders [54]. CNTs have been described as having a hollow tubular shape, great tensile qualities, excellent water resistance, a large surface area, and excellent electrical conductivity [55]. Figure 3 depicts different types of SWCNTs and MWCNTS. These advanced nanomaterials for high-performance water purification are being explored in adsorption strategy for removing contaminant species. Additionally, these materials have demonstrated potential as size-exclusion membrane filters, which let water flow while obstructing the passage of impurities [56]. When it comes to water filtration, nanotechnology-based methods are far more effective than conventional ones since they may be made with characteristics that improve the adsorption of materials from the water. For instance, excellent performance at a reasonable cost may be achieved in water treatment solutions by manipulating features like pore volume and reactivity and hydrophilic and hydrophobic interactions at the nanoscale. Babaei et al., in their work, oxidized MWCNT for TC removal from aqueous media and reported a precise tubular shape with an external diameter of 18 nm [57]. The morphology obtained using FESEM at different magnifications is shown in Figure 4.

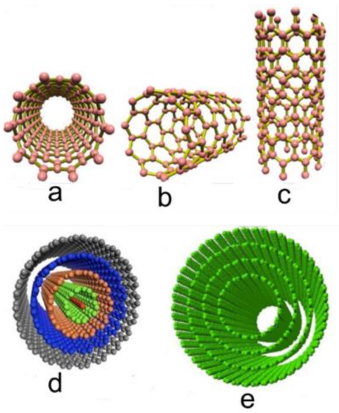

Figure 3 Different structures of SWCNTs (a-c) and different structures of MWCNTs (d-e). Source: [58]. Open access, available at https://austinpublishinggroup.com/ebooks.html. Retrieved 4 April 2023.

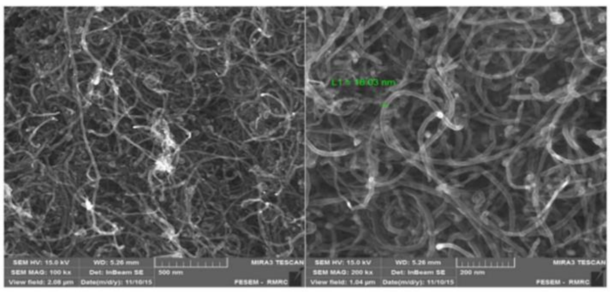

Figure 4 SEM images of oxidized MWCNT at different magnifications [57]. This work is shared under the CCBY.40 license.

6. A Novel Approach for Value-Added Product Development from Plastic Wastes

Plastic waste accumulation globally poses a serious concern when it degrades into smaller fragments in the environment, and the ecosystems are entirely endangered. Plastics are durable because of their inborn qualities. They have found countless uses in industries including construction, electronics, adhesives, home goods, paints, automotive, coatings, energy storage, and various medical disciplines [59]. There are currently no workable solutions or persuasive strategies for dealing with the growing plastic waste, which has led to the aggregation of this waste, causing havoc. Waste plastic is now reused mostly by physical recycling, which can only reuse thermoplastics. Because of the unintended damage throughout the recycling process, the quality of recovered plastics eventually declines. Given this context, catalytic upcycling has gained attention recently as a viable method to handle plastic waste because it can transform a variety of plastic wastes into new products under benign circumstances [60].

6.1 Use of Waste Plastics as Feedstock for Carbon Nanotubes/Hydrogen Production

Since most plastics, including PE, PP, PS, and PET, are made of carbon and hydrogen, they might be exploited as feedstocks to create new materials such as carbon compounds and hydrogen gas. In recent years, there have been research efforts on converting waste plastics into various carbon compounds, mainly carbon nanotubes, carbon nanofiber, graphene, and many more [60]. Despite the massive carbon deposition, adjusted experimental settings, and creation of appropriate reactors, the production of CNTs from polymers heavily depends on the design of highly active catalysts with prolonged catalytic life [61]. On the possibilities of synthesizing CNTs from various types and mixtures of plastics, several reviewed studies in the literature have been conducted, with systematic research on catalysts and substrates, parametric conditions, methods of synthesis, reactor design and types, and conversion procedures [24, 62-64]. Table 1 summarizes selected studies that used waste plastics to synthesize new materials such as CNTs and hydrogen as clean energy.

Table 1 Plastic waste utilization in the production of carbon nanotubes.

Recycled PW	Catalyst	Process	Main results	Temperature	Gas flowrate (mL/min)	Reference
PE	CoMo/MgO 0.5 g	Two-step CVD	MWCNTs	700°C	N_2/H_2 = 30/60	[65]
MWP	Ni/Fe/zeolite 0.5 g	Two-stage CVD	MWCNTs 12-25 nm	800°C	100	[66]
PP	Ni-Foam	Two-stage CVD	Oil and CNTs	600-800°C	60	[67]
PP	NiMo/corn cob char 1.0 g	One step CVD	CNTs	700°C	120	[64]
PE	FeNi	CVD	CNTs 20-30 nm	773-1073 K	-	[68]
PP	Biochar	Two-step CVD	Hydrogen, Bamboo-type CNTs	500-900°C	-	[69]

PE	Ni	One-step catalytic-pyrolysis	CNTs 30-50 nm	973 K	-	[70]
PP & LDPE	NiMnAl 424 & NiMnAl 444 (3 g)	two-stage reaction system	CNTs and clean hydrogen	800°C	80.0	[71]
PE	$NiCo_2O_4/\alpha$-Al_2O_3 (1 g)	modified two-stage reactor	MWCNTs composite	800-1000°C	-	[72]

Keys: PE, polyethylene; PP, polypropylene; MWP, mixed waste plastic. DPE, low-density polyethylene

6.2 Selected Techniques for Carbon Nanotubes Synthesis

The production of nanostructures is as wide as the materials themselves [73]. For instance, fullerene, which stands as an allotrope form of carbon, occurs as hollow spheres, ellipsoids, and nanotubes (single-walled carbon nanotubes (SWCNTs) and multi-walled carbon nanotubes (MWCNTs)) arise naturally as combustion products [73]. A simple hydrocarbon is burned in fuel-rich flames, and geodesic polyarenes are exposed to ultraviolet (UV) laser energy, forming fullerenes [74]. Numerous synthetic techniques have been developed for the making of nanostructures. CNTs were initially prepared in 1991 through the arc evaporation of graphite [75]. After this discovery, carbon nanotubes were obtained as the product of ethylene and acetylene pyrolysis over iron (Fe), cobalt (Co), and so on [76, 77]. The presence of metals influenced the size profile of the carbon nanotubes significantly. The synthesis of nanostructures/nanomaterials for this study is discussed under the following headings: arc discharge, laser ablation, chemical vapor deposition, and solvothermal/hydrothermal techniques.

6.2.1 Arc Discharge Method

The arc discharge technique produces various nanostructured materials, mostly carbon-based ones, such as fullerenes, carbon nanohorns, carbon nanotubes, few-layer graphene, and amorphous spherical carbon nanoparticles [78]. The arc discharge process is the first and oldest technique for CNT development. The vacuum chamber is where CNT growth operations take place. Two carbon electrodes are employed in the vacuum chamber as the carbon supply. An inert gas, such as helium or argon, speeds up carbon deposition. Both electrodes get an intense DC voltage. Typically, a 20-25 v potential is delivered across electrodes 1 mm apart and 5-20 µm in diameter. Helium is maintained at a flow rate of 50-600 torr [79]. Compared to other methods, it grows CNTs with the fewest structural defects because it evaporates carbon atoms from plasma at higher temperatures (over 1700°C) [80]. Figure 5 shows the diagram of the arc discharge technique for CNTs synthesis.

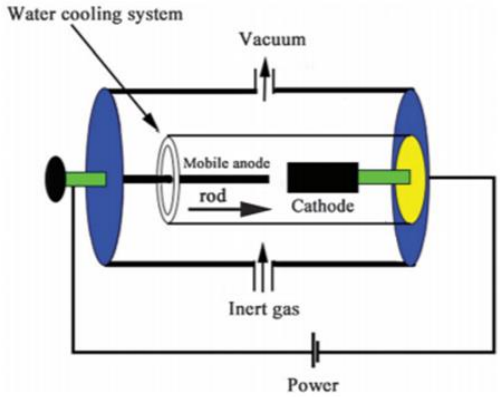

Figure 5 Simple diagram of arc discharge set for the synthesis of carbon nanotubes. Source: [58]. Open access is available at https://austinpublishinggroup.com/ebooks.html. Retrieved 4 April 2023.

6.2.2 Laser Ablation

Laser ablation and the arc discharge process have a similar fundamental idea. A carbon target is heated up using a laser source to produce CNTs and other carbonaceous byproducts, the sublimed carbon is quickly cooled down in an inert gas stream such as helium or argon [79]. One of the best processes for making SWCNTs is laser ablation. However, due to its high cost, this process is not very attractive for making MWCNTs. The benefit of creating high-purity, high-yield SWCNTs using laser ablation is that it takes only a brief amount of time: delivering up to ~90% pure 500 mg of SWCNTs in 5 min [80]. However, a modest yield of ablated nanoparticles, significant particle aggregations, and accumulation are drawbacks of pulsed laser ablation in the liquid approach. The laser parameters, including laser fluence, pulse width, repetition rate, and wavelength, significantly impact the properties of nanomaterials produced by pulsed laser ablation in liquid [81]. Figure 6 shows the diagrammatic description of the laser ablation process for CNTs synthesis.

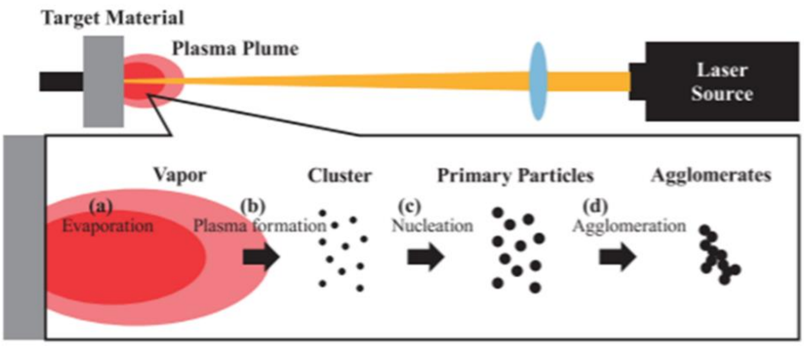

Figure 6 Laser ablation process for carbon nanotube synthesis [82]. This work is shared under the CC BY license (http://creativecommons.org/licenses/by/4.0/).

6.2.3 Chemical Vapor Deposition (CVD)

Chemical vapor deposition (CVD) makes mass production of quality carbon nanotubes possible. Several synthesis process variables affect the nature and form of the finished product [83]. Various CVD methods exist, including the plasma enhanced (PECVD), microwave plasma (MPECVD), radiofrequency CVD (RF-CVD), hot-filament (HFCVD), oxygen-assisted (OA), water-assisted (WA), and floating catalyst (FCCVD) techniques [80]. Looking at arc discharge and laser ablation, CVD is considered a simple and adaptable technology employed in synthesizing CNTs. The primary benefits of CVD include simple reaction control, high yield, minimal impurity generation, low cost, and relatively low working temperatures [84]. A furnace chamber is frequently used in the CVD procedure. All gases inside the chamber are first evacuated to prevent oxidation that could be triggered by oxygen-containing gases in the ambient air. Then, inert gas, such as helium or argon, is channeled into the reaction chamber together with the carbon precursor gases (especially hydrocarbon) [85]. Following the vaporization and decomposition of the gases in the furnace, an interaction between the reactive species produced by the gases and the catalyst results in carbon deposition on the substrate. The diagrammatic process of CVD is shown in Figures 7a and 7b. The synthesis temperature range between 600 and 1200°C would establish vapor decomposition. The vaporized hydrocarbons will interact with metal catalysts until they disintegrate into hydrogen and carbon. While hydrogen vaporizes, carbon will dissolve into the metal to develop into carbon nanomaterials [85, 86]. Many researchers have employed this method to produce carbon nanotubes from PW.

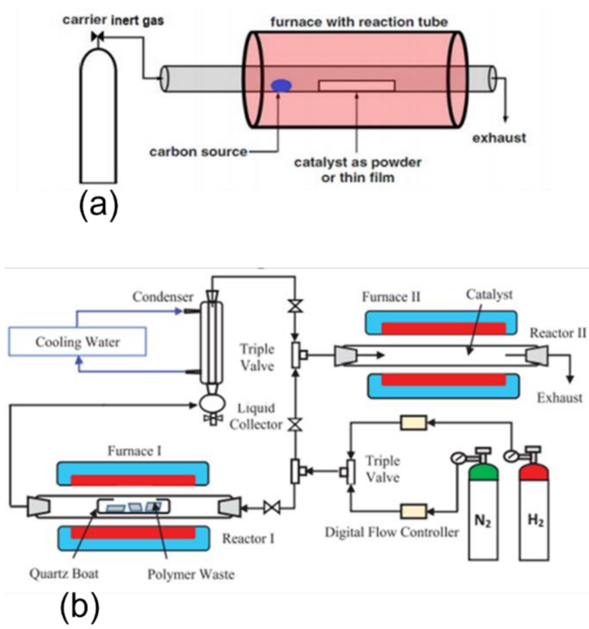

Figure 7 (a) and (b) single-stage and double-stage chemical vapor deposition techniques (sources: [87, 88]. They are shared under the Creative Commons Attribution 3.0 license (http://creativecommons.org/licenses/by/3.0).

6.2.4 Solvothermal and Hydrothermal Methods

These procedures and techniques for creating nanostructured materials are well-known and widely used methods for nanostructure synthesis. The reactions occur in a sealed reactor known as an autoclave, pressure vessel, or high-pressure bomb [78]. The hydrothermal technique, which includes adding a carbon precursor to compressed water heated to a high temperature, allows for the quick synthesis of crystalline materials while adjusting the particle diameter and morphology with varying pressure, temperature, and time. As a result, the hydrothermal approach has gained prominence as a means of manufacturing carbon products [89]. For the preparation of nanomaterials with adjustable size and shape, the solvothermal approach has also been given many benefits. In this process, an organic capping agent is heated with the solvent and carbon precursor. There are three steps: the first involves heating the solution, which causes the carbon precursor to dissociate; the second consists of aging the solution, which determines the size of the materials that are produced; and the third step entails separating the nanomaterials from the solvent [89].

6.3 Conditions for the Synthesis of Carbon Nanotubes from Waste Plastics

6.3.1 Catalysts

Catalyst design is crucial to regulate the creation of CNTs [90]. The composition, pretreatment conditions, preparation procedures, interactions with support, and shape of catalysts all significantly impact their stability, activity, and selectivity [91, 92]. The synthesis of high yields of CNTs that are of excellent quality, a very stable and active catalyst, is a prerequisite [93]. The capacity of a catalyst for CNT development to last a longer lifetime despite high carbon production is a gauge of its general effectiveness. It has proven effective in employing many nanoscale transition metal particles in CVD, whether in metallic or oxide form or as blends. Due to their high solubility and rapid rate of carbon atom diffusion at high temperatures, Fe, Ni, and Co are the catalysts that are commonly employed [94]. The catalyst used during the plastic's breakdown and carbon deposition process is crucial to determining the shape and structure of CNTs [95].

6.3.2 Temperature

Plastics' thermal deterioration is a complicated process that calls for mass and heat transmission. The temperature significantly influences how plastic materials decompose since various polymers have varying ideal breakdown temperatures [33]. Because of the increasing frequency of collisions between the hydrocarbon molecules during plastic degradation, the van der Waals interactions between the molecules' walls collapse, breaking individual carbon chains and vaporizing surface particles. The feeding gas directly impacts the ideal synthesis temperature. The CVD process typically operates between 600 and 1200°C [85], growth factors may control CNT diameter, and the growth temperature has the most impact. Liu et al. investigated the effects of temperature variations on the production and shape of carbon nanotubes using plastic waste as a carbon source [96].

6.3.3 Carrier Gases

Another critical factor in the formation of CNTs is the carrier gas and the flow rate; to promote the development of fine nanotubes, a low catalyst concentration, and a high carrier gas flow rate could be necessary. The formation of CNTs has been seen to be influenced by a variety of carrier gases, including nitrogen (N_2), argon (Ar), ammonia (NH_3), helium (He), and hydrogen (H_2) [97]. A study by Panahi et al. on the effects of different carrier gases observed that diatomic nitrogen (N_2) performed better when evaluated as a carrier gas for CNT formation of CNTs, outperforming the other three (N_2, Ar, He, and CO_2). It encouraged CNT length and yield as a whole. Since these carriers or protective gases (at least the first three) were considered inert and unreactive in the formation of CNTs, this was not previously anticipated [97]. In a similar study by Quinson et al. on the effect of carrier gas flow rate, it was discovered that a flow rate of 2500 sccm is preferable to values of 1000 or 5000 sccm for producing homogeneous, vertically aligned MWCNTs [98].

6.4 Typical Use of Carbon Nanotubes as Adsorbent

Adsorption, one of the oldest methods, has been used to remove organic and inorganic contaminants from water and wastewater. This phenomenon occurs at the surface when pollutants from the liquid or gaseous phase are transported to the surface of solid materials, also known as adsorbents. In this phenomenon, the adsorbent is crucial to the adsorption of contaminants [99]. The chemical and physical interactions are intense, quick equilibrium, extraordinary sorbent capacity, and distinctive superficial chemistry of CNTs were considered to make them superior to conventional sorbents like clay, zeolite, and activated carbon for the treatment of a variety of organic and inorganic pollutants [100]. Table 2 shows a few works of literature on applying CNTs to eliminate various contaminants from WW via the adsorption technique.

Table 2 CNTs-derived adsorbents and application in wastewater treatment.

CNTs derived adsorbent	Wastewater type	Treatment method	Pollutants removal	Efficiency %	Reference
La-CNTs	Aquaculture	Batch adsorption	TC	88.15	[100]
CNTs	Simulated diuron herbicide WW	Batch adsorption	Diuron herbicide	-	[101]
$MnFe_2O_4$ - MMWCNTs	-	Batch adsorption	TC	99.16	[102]
MWCNTs	Simulated WW	Batch adsorption	paracetamol	-	[103]
Oxidized MWCNT	Contaminated water	Batch adsorption	TC	-	[104]
MWCNTS	Aqueous solution	Batch adsorption	TC	99.8	[105]

Keys: La-CNTs, lanthanum-modified carbon nanotubes; TC, tetracycline; MMWCNTs, magnetic multi-walled carbon nanotubes.

6.4.1 The Use of Other Adsorbents in Pollutant Removal

Other adsorbents (including activated carbon, chitosan, bentonites, metal-organic frameworks, etc.) have also been used to remove different types of pollutants, such as toxic heavy metals, dyes, oils, pharmaceuticals, and other emerging contaminants from the aqueous environment due to their excellent physicochemical properties (excellent mechanical strength, thermal stability, large surface area, etc.) [106].

Due to the well-defined textural properties of adsorbents, large specific surface area, controllable pore structure, good adsorption capacity, and distinct surface charges [107], contaminants are usually adsorbed onto the surfaces of adsorbents. The adsorption capacity of adsorbents can be readily enhanced via surface modification by attaching more surface functional groups (amino, hydroxyl, carboxyl, phenyl, lactone groups, etc.) through oxidation, sulfuration, nitrogenation methods, etc. [108]. The operating conditions control the adsorption mechanism during adsorption, the adsorbent's physicochemical properties, and the contaminant's nature [106].

The interaction between pollutants and the adsorbent surface can occur through different mechanisms, including electrostatic interaction, ion exchange, aggregation, surface complexation/coordination, microprecipitation, reduction or oxidation, physical adsorption, etc. [106]. In addition, contaminants of inorganic (toxic heavy metal cations such as potentially harmful elements (PTEs) and nutrients) and organic nature (oils, dyes, polyaromatic hydrocarbons, etc.) have been removed using adsorbent materials derived from plastic wastes such as cup-stacked CNTs, porous carbon materials, graphene-based materials, carbon nanofibers, etc. [109-111].

6.5 Circular Economy and Its Impacts on Plastic Waste Generation and Management

A rising number of people are becoming interested in the circular economy (CE) as a potential means of boosting wealth in our society while lowering the demand for limited raw materials and eliminating harmful externalities [112]. CE is another possibility to the present linear, manufacturing, using, and discarding economic paradigm. It aims to maximize resource utilization throughout usage, reclaim and restore materials at the end of their useful life, and keep resources in use for as long as is practical. It offers the chance to reduce the damaging consequences of plastics while increasing the value of plastic materials and bringing about favorable effects on the environment, the economy, and society [112]. CE has been recognized for three key contributions: first, it can upsurge output and economic development; second, it could advance the quality and quantity of labor; and third, it can reduce mortality by reducing the negative consequences of environmental damages, including climate alteration, water and air pollutions [113]. A systemic strategy is necessary for such a transformation, which means going beyond minor adjustments to the current paradigm and creating new platforms for collaboration [114]. The circular economy agenda addresses the issue of plastic waste pollution, particularly concerning packaging [115]. The plastics industry's growing volume and technological demands conflict with the need to minimize the sector’s greenhouse gas emissions and carbon footprint, in addition to the significant environmental costs of land and marine plastic pollution [116-118]. However, the leading cause of plastic pollution is the linear economic paradigm of “take-make-waste” [37]. The corrective action is strengthening circularity by consolidating the plastic value chain linkages. This can only be done with the help of a potent mix of regulatory policy improvements and improved capacity and innovation in the collecting, sorting, and recycling sectors [119, 120]. With the assistance of financial institutions, such as through offering specialized funding programs and public-private cooperation, such an enabling environment may be developed for the widespread adoption of CE [120, 121]. Figure 8 illustrates the influence of circularity on waste plastic production and management. Implementing a circular economy in PW management might significantly affect the economy and ecology, including reduced use of non-renewable resources, less greenhouse gas emissions, zero waste, advantages for consumers, and new business possibilities [122].

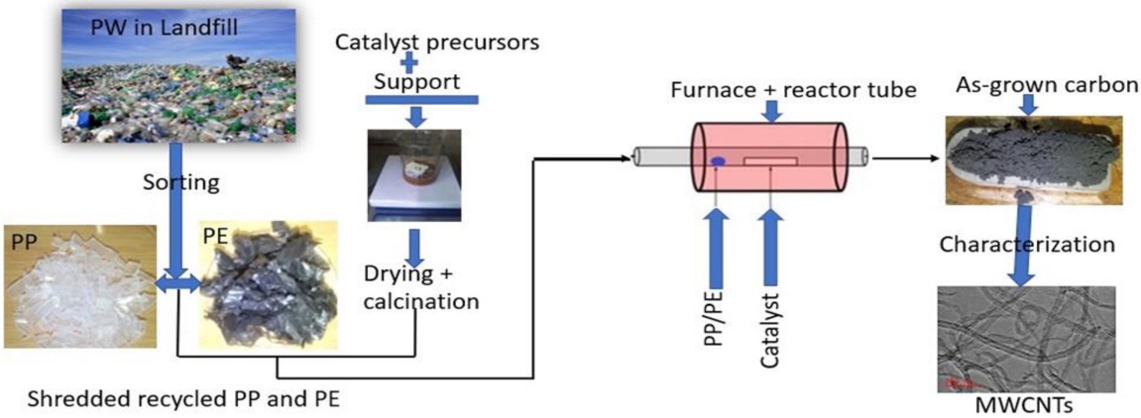

Figure 8 Plastic waste utilization for producing value-added materials: circular economy concept.

7. Conclusion

Plastic waste generation will undoubtedly continue to increase in the years to come, given the existing trend in producing and utilizing plastic materials globally. Given the above, the circular economy may address the challenges connected to acute global plastic waste generation. Using plastic waste as an alternative source of raw materials in producing value-added products for adsorbents and other varied applications would birth the beginning of sustainability in plastic waste management. Furthermore, jobs would be generated, living standards would improve, the unnecessary strain on the ecosystem and natural resources would be alleviated, the detrimental impacts of plastic waste on the ecosystem and public health would be reduced, and ultimately, a greener environment would be realized.

Acknowledgments

The University Research Committee (URC) of the University of Johannesburg (UJ) provided support for this work, which the first author would like to recognize.

Author Contributions

M. A. Onu: Conceptualization, Writing- Original draft preparation. O. O. Ayeleru: Supervised, Reviewed, and Corrected the Original draft. H. U. Modekwe: Manuscript Writing and Editing P. A. Olubambi: Supervised, Reviewed, Corrected the Original draft and provided the Funding for the Research.

Funding

The University Research Committee (URC) of the University of Johannesburg (UJ).

Competing Interests

The authors have declared that no competing interests exist.

References

1. Hossain MU, Ng ST, Dong Y, Amor B. Strategies for mitigating plastic wastes management problem: A lifecycle assessment study in Hong Kong. Waste Manag. 2021; 131: 412-422.
2. Maitlo G, Ali I, Maitlo HA, Ali S, Unar IN, Ahmad MB, et al. Plastic waste recycling, applications, and future prospects for a sustainable environment. Sustainability. 2022; 14: 11637.
3. Zhao X, Korey M, Li K, Copenhaver K, Tekinalp H, Celik S, et al. Plastic waste upcycling toward a circular economy. Chem Eng J. 2022; 428: 131928.
4. Celik G, Kennedy RM, Hackler RA, Ferrandon M, Tennakoon A, Patnaik S, et al. Upcycling single-use polyethylene into high-quality liquid products. ACS Cent Sci. 2019; 5: 1795-1803.
5. Babayemi JO, Nnorom IC, Osibanjo O, Weber R. Ensuring sustainability in plastics use in Africa: Consumption, waste generation, and projections. Environ Sci Eur. 2019; 31: 60.
6. Nistratov AV, Klushin VN, Makashova ES, Kim LV. Production and evaluation of properties of waste-based carbon adsorbent. Chem Eng Res Des. 2020; 160: 551-560.
7. Williams PT. Hydrogen and carbon nanotubes from pyrolysis-catalysis of waste plastics: A review. Waste Biomass Valoriz. 2021; 12: 1-28.
8. Belbessai S, Benyoussef EH, Gitzhofer F, Abatzoglou N. Carbon nanomaterial production using waste plastic pyrolysis over a new catalyst made from mining residues: Effect of plastic type. Chem Eng J Adv. 2022; 12: 100424.
9. Bin Dahman OA, Saleh TA. Synthesis of carbon nanotubes grafted with PEG and its efficiency for the removal of phenol from industrial wastewater. Environ Nanotechnol Monit Manag. 2020; 13: 100286.
10. Teo JYQ, Ong A, Tan TTY, Li X, Loh XJ, Lim JYC. Materials from waste plastics for CO_2 capture and utilisation. Green Chem. 2022; 24: 6086-6099.
11. Wang J, Yuan X, Deng S, Zeng X, Yu Z, Li S, et al. Waste polyethylene terephthalate (PET) plastics-derived activated carbon for CO_2 capture: A route to a closed carbon loop. Green Chem. 2020; 22: 6836-6845.
12. El Sayed ES, Yuan D. Waste to MOFs: Sustainable linker, metal, and solvent sources for value-added MOF synthesis and applications. Green Chem. 2020; 22: 4082-4104.
13. Song K, Qiu X, Han B, Liang S, Lin Z. Efficient upcycling electroplating sludge and waste PET into Ni-MOF nanocrystals for the effective photoreduction of CO_2. Environ Sci Nano. 2021; 8: 390-398.
14. Teo JYQ, Zheng XT, Seng DHL, Hui HK, Chee PL, Su X, et al. Waste polystyrene-derived sulfonated fluorescent carbon nanoparticles for cation sensing. ChemistrySelect. 2022; 7: e202202720.
15. Muro Hidalgo JM, Bazany Rodríguez IJ, Hernández JG, Pabello VM, Thangarasu P. Histamine recognition by carbon dots from plastic waste and development of cellular imaging: Experimental and theoretical studies. J Fluoresc. 2023; 33: 2041-2059.
16. Chaudhary S, Kumari M, Chauhan P, Chaudhary GR. Upcycling of plastic waste into fluorescent carbon dots: An environmentally viable transformation to biocompatible C-dots with potential prospective in analytical applications. Waste Manag. 2021; 120: 675-686.
17. Ilyas M, Ahmad W, Khan H. Utilization of activated carbon derived from waste plastic for decontamination of polycyclic aromatic hydrocarbons laden wastewater. Water Sci Technol. 2021; 84: 609-631.

18. Wankasi D, Dikio ED. Polyvinyl chloride waste as an adsorbent for the sorption of from aqueous solution. J Chem. 2014; 2014: 817527.
19. Tang KH. Valorization of plastic waste through incorporation into construction materials. Civ Sustain Urban Eng. 2022; 2: 96-109.
20. Palos R, Gutierrez A, Vela FJ, Olazar M, Arandes JM, Bilbao J. Waste refinery: The valorization of waste plastics and end-of-life tires in refinery units. A review. Energy Fuels. 2021; 35: 3529-3557.
21. Mishra S, Sundaram B. Efficacy and challenges of carbon nanotube in wastewater and water treatment. Environ Nanotechnol Monit Manage. 2023; 19: 100764.
22. Chen Z, Wei W, Ni BJ, Chen H. Plastic wastes derived carbon materials for green energy and sustainable environmental applications. Environ Funct Mater. 2022; 1: 34-48.
23. Hernández Del Castillo PC, Oliva J, Núñez Luna BP, Rodríguez González V. Novel polypropylene-TiO_2: Bi spherical floater for the efficient photocatalytic degradation of the recalcitrant 2,4,6-TCP herbicide. J Environ Manage. 2023; 329: 117057.
24. Zhang H, Pap S, Taggart MA, Boyd KG, James NA, Gibb SW. A review of the potential utilisation of plastic waste as adsorbent for removal of hazardous priority contaminants from aqueous environments. Environ Pollut. 2020; 258: 113698.
25. Plastic Europe. History of plastics [Internet]. Brussels, Belgium: Plastic Europe; 2023. Available from: https://plasticseurope.org/plastics-explained/history-of-plastics/.
26. Greenwood K. History of plastic production [Internet]. Brussels, Belgium: Plastic Europe; 2021. Available from: https://www.plasticcollective.co/history-of-plastic-production/.
27. Chalmin P. The history of plastics: From the Capitol to the Tarpeian Rock [Internet]. Paris, France: OpenEdition Journals; 2019. Available from: http://journals.openedition.org/factsreports/5071.
28. Ritchie H, Samborska V, Roser M. Plastic pollution [Internet]. Oxford, UK: Our World in Data; 2022. Available from: https://ourworldindata.org/plastic-pollution.
29. Chen GQ, Patel MK. Plastics derived from biological sources: Present and future: A technical and environmental review. Chem Rev. 2012; 112: 2082-2099.
30. Rosenboom JG, Langer R, Traverso G. Bioplastics for a circular economy. Nat Rev Mater. 2022; 7: 117-137.
31. World Economic Forum. Plastics, the circular economy and global trade [Internet]. Geneva, Switzerland: World Economic Forum; 2020. Available from: https://www3.weforum.org/docs/WEF_Plastics_the_Circular_Economy_and_Global_Trade_2020.pdf.
32. Bîrcă A, Gherasim O, Grumezescu V, Grumezescu AM. Introduction in thermoplastic and thermosetting polymers. Mater Biomed Eng. 2019; 1-28. doi: 10.1016/B978-0-12-816874-5.00001-3.
33. Yaqoob L, Noor T, Iqbal N. Conversion of plastic waste to carbon-based compounds and application in energy storage devices. ACS Omega. 2022; 7: 13403-13435.
34. Plastic Europe. Plastics - the facts 2020 [Internet]. Brussels, Belgium: Plastic Europe; 2020. Available from: https://plasticseurope.org/knowledge-hub/plastics-the-facts-2020/.
35. Dodiuk H. Handbook of thermoset plastics. Norwich, NY; US: William Andrew; 2021.
36. World Bank Group. Where is the value in the chain? Pathways out of plastic pollution [Internet]. Washington, DC, US: The World Bank; 2022. Available from:

https://thedocs.worldbank.org/en/doc/f52340e3963047eb5a92f0e47c082acf-0320072022/original/3P-ExecutiveSummary.pdf.

37. Sadan Z, de Kock L. Plastic pollution in Africa: Identifying policy gaps and opportunities [Internet]. Cape Town, South Africa: WWF South Africa; 2021. Available from: https://wwfafrica.awsassets.panda.org/downloads/wwf_plastic_pollution.pdf.
38. Wingfield S, Lim M. The United Nations Basel convention's global plastic waste partnership: History, evolution and progress. In: Microplastic in the environment: Pattern and process. Cham, Switzerland: Springer; 2021. pp. 323-331.
39. Jiang B, Yu J, Liu Y. The environmental impact of plastic waste. J Environ Earth Sci. 2020; 2: 26-35.
40. Ayeleru OO, Dlova S, Akinribide OJ, Ntuli F, Kupolati WK, Marina PF, et al. Challenges of plastic waste generation and management in sub-Saharan Africa: A review. Waste Manage. 2020; 110: 24-42.
41. Ryberg MW, Laurent A, Hauschild M. Mapping of global plastics value chain and plastics losses to the environment: With a particular focus on marine environment. United Nations Environment Programme Technical University of Denmark; 2018. Available from: https://wedocs.unep.org/20.500.11822/26745.
42. Meneses RA, Cabrera Papamija G, Machuca Martínez F, Rodríguez LA, Diosa JE, Mosquera Vargas E. Plastic recycling and their use as raw material for the synthesis of carbonaceous materials. Heliyon. 2022; 8: e09028.
43. Philip K. Impacts of Plastic and Microplastic waste on the Dry Land Environment. SolarImpulse Foundation; 2020. Available from: https://solarimpulse.com/news/impacts-of-plastic-and-microplastic-waste-on-the-dry-land-environment.
44. Evode N, Qamar SA, Bilal M, Barceló D, Iqbal HM. Plastic waste and its management strategies for environmental sustainability. Case Stud Chem Environ Eng. 2021; 4: 100142.
45. Organisation for Economic Co-operation and Development (OECD). Global plastics outlook policy scenarios to 2060 [Internet]. Paris, France: OECD; 2022. Available from: https://www.developmentaid.org/api/frontend/cms/file/2022/06/document.pdf.
46. Jambeck J, Hardesty BD, Brooks AL, Friend T, Teleki K, Fabres J, et al. Challenges and emerging solutions to the land-based plastic waste issue in Africa. Mar Policy. 2018; 96: 256-263.
47. Worch E. Adsorption technology in water treatment: Fundamentals, processes, and modeling. Berlin, Germany: Walter de Gruyter GmbH & Co KG; 2021.
48. El Baz AA, Hendy IA, Dohdoh AM, Srour MI. Adsorption technique for pollutants removal; current new trends and future challenges-A Review. Egypt Int J Eng Sci Technol. 2020; 32: 1-24.
49. Pawar AA, Kim A, Kim H. Synthesis and performance evaluation of plastic waste aerogel as sustainable and reusable oil absorbent. Environ Pollut. 2021; 288: 117717.
50. Crini G, Lichtfouse E, Wilson LD, Morin Crini N. Adsorption-oriented processes using conventional and non-conventional adsorbents for wastewater treatment. In: Green adsorbents for pollutant removal: Fundamentals and design. Cham, Switzerland: Springer; 2018. pp. 23-71.
51. Elewa AM, Amer AA, Attallah MF, Gad HA, Al Ahmed ZA, Ahmed IA. Chemically activated carbon based on biomass for adsorption of Fe (III) and Mn (II) Ions from aqueous solution. Materials. 2023; 16: 1251.

52. Bläker C, Muthmann J, Pasel C, Bathen D. Characterization of activated carbon adsorbents-state of the art and novel approaches. ChemBioEng Rev. 2019; 6: 119-138.
53. Muttil N, Jagadeesan S, Chanda A, Duke M, Singh SK. Production, types, and applications of activated carbon derived from waste tyres: An overview. Appl Sci. 2022; 13: 257.
54. Dalila AR, Abu Bakar S, Rosmi MS, Rosazley R, Rosli J, Rusop M. Carbon nanotubes: A brief outlook on history, synthesis methods and various bio-hydrocarbon sources. Adv Mater Res. 2014; 832: 792-797.
55. Gao X, Yang S, Hu L, Cai S, Wu L, Kawi S. Carbonaceous materials as adsorbents for CO_2 capture: Synthesis and modification. Carbon Capture Sci Technol. 2022; 3: 100039.
56. Sweetman MJ, May S, Mebberson N, Pendleton P, Vasilev K, Plush SE, et al. Activated carbon, carbon nanotubes and graphene: Materials and composites for advanced water purification. C. 2017; 3: 18. doi: 10.3390/c3020018.
57. Babaei AA, Lima EC, Takdastan A, Alavi N, Goudarzi G, Vosoughi M, et al. Removal of tetracycline antibiotic from contaminated water media by multi-walled carbon nanotubes: Operational variables, kinetics, and equilibrium studies. Water Sci Technol. 2016; 74: 1202-1216.
58. Lone Y. Nanotechnology, Carbon Nanotubes (CNTs) and Applications. In: Importance & Applications of Nanotechnology. Monroe Township, NJ, US: Austin Publishing Group; 2021. pp. 71-89.
59. Sharma B, Shekhar S, Sharma S, Jain P. The paradigm in conversion of plastic waste into value added materials. Clean Eng Technol. 2021; 4: 100254.
60. Tan T, Wang W, Zhang K, Zhan Z, Deng W, Zhang Q, et al. Upcycling plastic wastes into value-added products by heterogeneous catalysis. ChemSusChem. 2022; 15: e202200522.
61. Yao D, Zhang Y, Williams PT, Yang H, Chen H. Co-production of hydrogen and carbon nanotubes from real-world waste plastics: Influence of catalyst composition and operational parameters. Appl Catal B. 2018; 221: 584-597.
62. Alhanish A, Ali GA. Recycling the plastic wastes to carbon nanotubes. In: Waste recycling technologies for nanomaterials manufacturing. Cham, Switzerland: Springer; 2021. pp. 701-727.
63. Wang Y, Bailey J, Zhu Y, Zhang Y, Boetcher SK, Li Y, et al. Application of carbon nanotube prepared from waste plastic to phase change materials: The potential for battery thermal management. Waste Manag. 2022; 154: 96-104.
64. Modekwe HU, Moothi K, Daramola MO, Mamo MA. Corn cob char as catalyst support for developing carbon nanotubes from waste polypropylene plastics: Comparison of activation techniques. Polymers. 2022; 14: 2898.
65. Aboul Enein AA, Awadallah AE. Impact of Co/Mo ratio on the activity of Co Mo/MgO catalyst for production of high-quality multi-walled carbon nanotubes from polyethylene waste. Mater Chem Phys. 2019; 238: 121879.
66. Yao D, Yang H, Hu Q, Chen Y, Chen H, Williams PT. Carbon nanotubes from post-consumer waste plastics: Investigations into catalyst metal and support material characteristics. Appl Catal B. 2021; 280: 119413.
67. Eldahshory AI, Emara K, Abd Elhady MS, Ismail MA. High quality and maximizing the production of CNTs from the pyrolysis of waste polypropylene. Arab J Sci Eng. 2023; 48: 8655-8666.
68. Li K, Zhang H, Zheng Y, Yuan G, Jia Q, Zhang S. Catalytic preparation of carbon nanotubes from waste polyethylene using FeNi bimetallic nanocatalyst. Nanomaterials. 2020; 10: 1517.

69. Shah K, Patel S, Halder P, Kundu S, Marzbali MH, Hakeem IG, et al. Conversion of pyrolytic non-condensable gases from polypropylene co-polymer into bamboo-type carbon nanotubes and high-quality oil using biochar as catalyst. J Environ Manage. 2022; 301: 113791.
70. Zheng Y, Zhang H, Ge S, Song J, Wang J, Zhang S. Synthesis of carbon nanotube arrays with high aspect ratio via Ni-catalyzed pyrolysis of waste polyethylene. Nanomaterials. 2018; 8: 556.
71. Wu C, Nahil MA, Huang J, Williams PT. Production and application of carbon nanotubes, as a co-product of hydrogen from the pyrolysis-catalytic reforming of waste plastic. Process Saf Environ Prot. 2016; 103: 107-114.
72. Liu X, Xie W, Widenmeyer M, Ding H, Chen G, De Carolis DM, et al. Upcycling waste plastics into multi-walled carbon nanotube composites via $NiCo_2O_4$ catalytic pyrolysis. Catalysts. 2021; 11: 1353.
73. Al Mubaddel FS, Haider S, Al Masry WA, Al Zeghayer Y, Imran M, Haider A, et al. Engineered nanostructures: A review of their synthesis, characterization and toxic hazard considerations. Arab J Chem. 2017; 10: S376-S388.
74. Mojica M, Alonso JA, Méndez F. Synthesis of fullerenes. J Phys Org Chem. 2013; 26: 526-539.
75. Rasheed T, Adeel M, Nabeel F, Bilal M, Iqbal HM. TiO_2/SiO_2 decorated carbon nanostructured materials as a multifunctional platform for emerging pollutants removal. Sci Total Environ. 2019; 688: 299-311.
76. Gacem A, Modi S, Yadav VK, Islam S, Patel A, Dawane V, et al. Recent advances in methods for synthesis of carbon nanotubes and carbon nanocomposite and their emerging applications: A descriptive review. J Nanomater. 2022; 2022: 7238602.
77. Wang IW, Kutteri DA, Gao B, Tian H, Hu J. Methane pyrolysis for carbon nanotubes and CO_x-free H_2 over transition-metal catalysts. Energy Fuels. 2018; 33: 197-205.
78. Baig N, Kammakakam I, Falath W. Nanomaterials: A review of synthesis methods, properties, recent progress, and challenges. Mater Adv. 2021; 2: 1821-1871.
79. Yan Y, Miao J, Yang Z, Xiao FX, Yang HB, Liu B, et al. Carbon nanotube catalysts: Recent advances in synthesis, characterization and applications. Chem Soc Rev. 2015; 44: 3295-3346.
80. Salah LS, Ouslimani N, Bousba D, Huynen I, Danlée Y, Aksas H. Carbon nanotubes (CNTs) from synthesis to functionalized (CNTs) using conventional and new chemical approaches. J Nanomater. 2021; 2021: 4972770.
81. Ismail RA, Mohsin MH, Ali AK, Hassoon KI, Erten Ela S. Preparation and characterization of carbon nanotubes by pulsed laser ablation in water for optoelectronic application. Physica E Low Dimens Syst Nanostruct. 2020; 119: 113997.
82. Kim M, Osone S, Kim T, Higashi H, Seto T. Synthesis of nanoparticles by laser ablation: A review. Kona. 2017; 34: 80-90.
83. Dobrzańska Danikiewicz AD, Cichocki D, Pawlyta M, Łukowiec D, Wolany W. Synthesis conditions of carbon nanotubes with the chemical vapor deposition method. Phys Status Solidi B. 2014; 251: 2420-2425.
84. Abdulkareem AS, Kariim I, Bankole MT, Tijani JO, Abodunrin TF, Olu SC. Synthesis and characterization of Tri-metallic Fe-Co-Ni catalyst supported on $CaCO_3$ for multi-walled carbon nanotubes growth via chemical vapor deposition technique. Arab J Sci Eng 2017; 42: 4365-4381.
85. Saputri DD, Jan'ah AM, Saraswati TE. Synthesis of carbon nanotubes (CNT) by chemical vapor deposition (CVD) using a biogas-based carbon precursor: A review. IOP Conference Series: Materials Science and Engineering. Proceedings of the 15th Joint Conference on Chemistry (JCC

2020); 2020 September 9; Salatiga, Indonesia. Bristol, UK: IOP Publishing. doi: 10.1088/1757-899X/959/1/012019.
86. Aboul Enein AA, Awadallah AE. Production of nanostructure carbon materials via non-oxidative thermal degradation of real polypropylene waste plastic using La_2O_3 supported Ni and Ni-Cu catalysts. Polym Degrad Stab. 2019; 167: 157-169.
87. Aboul Enein AA, Adel Rahman H, Haggar AM, Awadallah AE. Simple method for synthesis of carbon nanotubes over Ni-Mo/Al_2O_3 catalyst via pyrolysis of polyethylene waste using a two-stage process. Fuller Nanotub Carbon Nanostruct. 2017; 25: 211-222.
88. Hatta MN, Hashim MS, Hussin R, Aida S, Kamdi Z, Ainuddin AR, et al. Synthesis of carbon nanostructures from high density polyethylene (HDPE) and polyethylene terephthalate (PET) waste by chemical vapour deposition. Journal of Physics: Conference Series. Proceedings of the International Conference on Materials Physics and Mechanics 2017; 2017 July 23; Langkawi, Malaysia. Bristol, UK: IOP Publishing. doi: 10.1088/1742-6596/914/1/012029.
89. Namitha R, Kannan K, Radhika D, Krishnamurthy G. Solvothermal/hydrothermal manufacturing of carbon nanotubes for hydrogen storage: A comparative study. Phys Chem Solid State. 2020; 21: 700-706.
90. Wang XD, Vinodgopal K, Dai GP. Synthesis of carbon nanotubes by catalytic chemical vapor deposition. In: Perspective of carbon nanotubes. Norderstedt, Germany: Books on Demand (BoD); 2019. pp. 13-31.
91. Paris CB, Howe AG, Lewis RJ, Hewes D, Morgan DJ, He Q, et al. Impact of the experimental parameters on catalytic activity when preparing polymer protected bimetallic nanoparticle catalysts on activated carbon. ACS Catal. 2022; 12: 4440-4454.
92. Shiba NC, Liu X, Hildebrandt D, Yao Y. Effect of pre-treatment conditions on the activity and selectivity of cobalt-based catalysts for CO hydrogenation. Reactions. 2021; 2: 258-274.
93. Modekwe HU, Mamo M, Moothi K, Daramola MO. Synthesis of bimetallic NiMo/MgO catalyst for catalytic conversion of waste plastics (polypropylene) to carbon nanotubes (CNTs) via chemical vapour deposition method. Mater Today Proc. 2021; 38: 549-552.
94. Ezz AA, Kamel MM, Saad GR. Synthesis and characterization of nanocarbon having different morphological structures by chemical vapor deposition over Fe-Ni-Co-Mo/MgO catalyst. J Saudi Chem Soc. 2019; 23: 666-677.
95. Liu X, Shen B, Wu Z, Parlett CM, Han Z, George A, et al. Producing carbon nanotubes from thermochemical conversion of waste plastics using Ni/ceramic based catalyst. Chem Eng Sci. 2018; 192: 882-891.
96. Panahi A, Sun X, Song G, Levendis YA. On the influences of carrier gas type and flow rate on CVD synthesis of CNTs from postconsumer polyethylene. Ind Eng Chem Res. 2020; 59: 14004-14014.
97. Quinson J, Bottein T, Dillon F, Meysami SS, Grobert N. Carbon nanotube columns for flow systems: Influence of synthesis parameters. Nanoscale Adv. 2020; 2: 5874-5882.
98. Pandey P, Dhiman M, Kansal A, Subudhi SP. Plastic waste management for sustainable environment: Techniques and approaches. Waste Dispos Sustain Energy. 2023; 5: 205-222.
99. Wang Y, Pan C, Chu W, Vipin AK, Sun L. Environmental remediation applications of carbon nanotubes and graphene oxide: Adsorption and catalysis. Nanomaterials. 2019; 9: 439.
100. Wu S, Yu X, Zhang Y, Liu Y, Yu R. Preparation, characterization, and adsorption properties of modified carbon nanotubes for highly effective removal of tetracycline from aquaculture wastewater. Environ Prog Sustain Energy. 2022; 41: e13896.

101. Deokar SK, Bajad GS, Bhonde P, Vijayakumar RP, Mandavgane SA. Adsorptive removal of diuron herbicide on carbon nanotubes synthesized from plastic waste. J Polym Environ. 2017; 25: 165-175.
102. Zhao W, Hao C, Guo Y, Guan C, Zhang H, Tian Y, et al. Modeling and optimization of adsorption conditions using response surface methodology for tetracycline removal by $MnFe_2O_4$/MWCNTs. 2022. doi: 10.21203/rs.3.rs-1470996/v1.
103. Aljeboree AM, Mahdi AB, Albahadly WK, Izzat SE, Kubaisy MM, Abid FM, et al. Enhancement of adsorption of paracetamol drug on carbon nanotubes concerning wastewater treatment. Eng Sci. 2022; 20: 321-329.
104. Yu F, Ma J, Han S. Adsorption of tetracycline from aqueous solutions onto multi-walled carbon nanotubes with different oxygen contents. Sci Rep. 2014; 4: 5326.
105. Zhang L, Song X, Liu X, Yang L, Pan F, Lv J. Studies on the removal of tetracycline by multi-walled carbon nanotubes. Chem Eng J. 2011; 178: 26-33.
106. Sajid M, Asif M, Baig N, Kabeer M, Ihsanullah I, Mohammad AW. Carbon nanotubes-based adsorbents: Properties, functionalization, interaction mechanisms, and applications in water purification. J Water Process Eng. 2022; 47: 102815.
107. Hussin F, Aroua MK, Kassim MA, Md Ali UF. Transforming plastic waste into porous carbon for capturing carbon dioxide: A review. Energies. 2021; 14: 8421.
108. Younas F, Mustafa A, Farooqi ZU, Wang X, Younas S, Mohy Ud Din W, et al. Current and emerging adsorbent technologies for wastewater treatment: Trends, limitations, and environmental implications. Water. 2021; 13: 215.
109. Alwaan IM, Jaleel MA. Preparation and Characterization of Activated Carbon with ($ZnCl_2$-Activated) from (PET) Bottle Waste for Removal of Metal ions (Cu^{+2}) in Aqueous Solution. IOP Conference Series: Materials Science and Engineering. Proceedings of the 1st International Conference on Sustainable Engineering and Technology (INTCSET 2020); 2020 December 15-16; Baghdad, Iraq. Bristol, UK: IOP Publishing. doi: 10.1088/1757-899X/1094/1/012131.
110. Gong J, Liu J, Chen X, Jiang Z, Wen X, Mijowska E, et al. Striking influence of NiO catalyst diameter on the carbonization of polypropylene into carbon nanomaterials and their high performance in the adsorption of oils. Rsc Adv. 2014; 4: 33806-33814.
111. Mensah K, Mahmoud H, Fujii M, Samy M, Shokry H. Dye removal using novel adsorbents synthesized from plastic waste and eggshell: Mechanism, isotherms, kinetics, thermodynamics, regeneration, and water matrices. Biomass Convers Biorefin. 2022. doi: 10.1007/s13399-022-03304-4.
112. Barra R, Leonard SA, Whaley C, Bierbaum R. Plastics and the circular economy: A Stap document [Internet]. Washington, DC, US: Scientific and Technical Advisory Panel to the Global Environment Facility; 2018. Available from: https://www.thegef.org/sites/default/files/publications/PLASTICS%20for%20posting.pdf.
113. Murti Z, Soedjati D, Barkah A, Rahardjo P. Review of the Circular Economy of Plastic Waste in Various Countries and Potential Applications in Indonesia. IOP Conference Series: Earth and Environmental Science. Proceedings of the 4th International Conference on Environment, Sustainability Issues, and Community Development (INCRID); 2022 September 1; Semarang, Indonesia. Bristol, UK: IOP Publishing. doi: 10.1088/1755-1315/1098/1/012014.
114. Agenda I. The new plastics economy rethinking the future of plastics [Internet]. Geneva, Switzerland: The World Economic Forum; 2016. Available from:

https://www.greenpeace.org/static/planet4-philippines-stateless-release/2019/05/b1e5a437-b1e5a437-wef_the_new_plastics_economy.pdf.
115. Diggle A, Walker TR. Environmental and economic impacts of mismanaged plastics and measures for mitigation. Environments. 2022; 9: 15.
116. Kumar R, Verma A, Shome A, Sinha R, Sinha S, Jha PK, et al. Impacts of plastic pollution on ecosystem services, sustainable development goals, and need to focus on circular economy and policy interventions. Sustainability. 2021; 13: 9963.
117. Kibria MG, Masuk NI, Safayet R, Nguyen HQ, Mourshed M. Plastic waste: Challenges and opportunities to mitigate pollution and effective management. Int J Environ Res. 2023; 17: 20.
118. Siltaloppi J, Jähi M. Toward a sustainable plastics value chain: Core conundrums and emerging solution mechanisms for a systemic transition. J Clean Prod. 2021; 315: 128113.
119. Babaremu KO, Okoya SA, Hughes E, Tijani B, Teidi D, Akpan A, et al. Sustainable plastic waste management in a circular economy. Heliyon. 2022; 8: e09984.
120. Bening CR, Pruess JT, Blum NU. Towards a circular plastics economy: Interacting barriers and contested solutions for flexible packaging recycling. J Clean Prod. 2021; 302: 126966.
121. Çevikarslan S, Gelhard C, Henseler J. Improving the material and financial circularity of the plastic packaging value chain in the Netherlands: Challenges, opportunities, and implications. Sustainability. 2022; 14: 7404.
122. World Health Organization. Economics of the health implications of waste management in the context of a circular economy [Internet]. Geneva, Switzerland: World Health Organization; 2023. Available from: https://www.who.int/europe/publications/i/item/WHO-EURO-2023-5536-45301-64839.