Sustainable re-utilization of waste materials as adsorbents for water and wastewater treatment in Africa: Recent studies, research gaps, and way forward for emerging economies

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Sustainable re-utilization of waste materials as adsorbents for water and wastewater treatment in Africa: Recent studies, research gaps, and way forward for emerging economies

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ABSTRACT

Access to clean water is a fundamental human right. However, due to the rapid urbanization and industrialization in many African countries, the emergence of a plethora of new classes of water contaminants coupled with aging wastewater treatment infrastructure and technologies, access to clean water has remained elusive especially to rural communities. Additionally, most countries in Africa cannot afford the capital investment associated with advanced and specialized treatment technologies. The solution seems to be the valorization of locally-sourced waste materials and their use as adsorbents, flocculants/coagulants, or photocatalysts, to be included in current and future wastewater treatment facilities. The present review presents a concise and comprehensive compilation, and critique of recent research water purification studies in Africa using waste-based adsorbents. While the abundance of industrial and agricultural wastes presents opportunity for sustainable exploitation for water treatment, several gaps warrant further research. Specifically, future research should include life cycle assessment (LCA) of the wastewater treatment plants (WWTPs) and proposed technologies, in-depth cost analysis, use of environmentally relevant concentrations in simulated studies or real wastewaters and examination of removal efficiencies for biological contaminants such as viruses, bacteria among others. Waste materials are shown to be suitable candidates for delivery of effective and techno-economic adsorbents for water purification in African countries.

1. Introduction

Advancement in technology, industrial processes, activities involving intensive energy use, use of chemicals in agricultural activities, rapid urbanization, population, and economic growth, among others, have all, individually and collectively, led to the enormous release of a myriad of organic and inorganic pollutants into the environment globally. Developed economies have put in measures to try to curb pollution. Unfortunately, environmental pollution has gone on unabated in most emerging economies, especially in Africa (Necibi et al.,

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2021), which in addition is a big consumer of most second-hand materials including banned products. Many pesticides, for example, that have been banned in developed countries still find their use in agricultural lands in Africa (Soko, 2018).

Environmental pollutants are mainly anthropogenic in nature and they include heavy metals, pesticides, pharmaceuticals, flame-retardants, dioxins and personal care products among others (Ali et al., 2012). Most emerging economies depend heavily on agriculture and as such, farmers are bound to rely on synthetic pesticides to increase production and preserve their products. Most health facilities in the developing nations lack proper disposal mechanisms such as incinerators and toxic medical wastes together with pharmaceutical drugs are therefore disposed with solid wastes resulting in environmental contamination (Chaukura et al., 2016). Ad-hoc and unscientific waste disposal approaches coupled with poor regulatory framework and enforcement leads to the presence of these toxic contaminants in water sources and eventual uptake by plants, animals and humans.

Many environmental pollutants are known to be persistent, non-biodegradable, bio-accumulative, toxic and hazardous to human health and the ecosystem in general (Kanamarlapudi et al., 2018; Omo-Okoro et al., 2018). For instance, pesticides and dioxins are carcinogenic, endocrine disruptors (Bornman et al., 2017), cause neurological disorders (Grova et al., 2019), give rise to congenital anomalies (Ouidir et al., 2020), result in immune dysfunction, and are harmful to the reproductive system (Matta et al., 2020). The undesirable synergistic effects caused by the simultaneous occurrence of all these pollutants in an organism is unfathomable.

These direct health effects make effective elimination of these contaminants from the environment and especially aquatic systems to be of monumental significance to researchers, regulatory authorities, and the public. In regard to this, the United Nations' Sustainable Development Goals (UN-SDGs) Target 6.3 demands countries "to improve water quality by reducing pollution, eliminating dumping and minimizing release of hazardous chemicals and materials, halving the proportion of raw wastewater and substantially increasing recycling and safe reuse globally". This is important because there are global challenges regarding access to clean water, especially in emerging economies. Access to clean water is a non-negotiable human right. For example, as of 2020, only 59% of Kenyans had access to safe drinking water with an estimated 9.9 million people drinking directly from contaminated surface water sources and an estimated five million people practicing open defecation (United Nations International Children Emergency Fund, 2020). Further, it is estimated that 70–80% of most illnesses in developing nations are waterborne (Bhatnagar and Sillanpää, 2010). Reversal of the declining water quality worldwide and enhancement of integrated water and wastewater management systems together with safe reuse are subjects of significant concern.

Unfortunately, conventional wastewater treatment methods such as use of lagoons, flocculation-coagulation, settling/sedimentation and screening processes are generally inefficient in the removal of most emerging pollutants due to the high chemical stability of the pollutants (Ncibi et al., 2017; Mashile et al., 2018). Further, technologies such as chemical-based flocculation/coagulation are time-consuming and costly, mainly due the use of expensive coagulants Moreover, disposal of the treatment byproducts such as the enormous amount of sludge generated is a challenge for developing economies (Nguyen et al., 2020). As such, the effluents are always released into streams, rivers or lakes, which inevitably exposes aquatic and terrestrial organisms to the pollutants. The sludge residue from the lagoons is also disposed of in landfills or used as manure in agricultural fields. The landfills directly contaminate groundwater through leaching, while run-offs from agricultural lands leads to contamination of surface waters.

Providing solutions to the aforementioned limitations has led to various technological advancements geared towards removing these pollutants from different aqueous environmental matrices. These include adsorption, membrane-based separation, electrochemical methods, reverse osmosis, ultrafiltration, chemical precipitation, ion exchange, photocatalysis, advanced oxidation methods among others (Sillanpää et al., 2018; Kanamarlapudi et al., 2018; Gurung et al., 2019; Nguyen et al., 2020).

However, most countries in Africa cannot afford the costs of advanced and specialized treatment technologies. In this context, the way forward in and for Africa requires a profound paradigm shift towards the establishment of innovative processes and technologies having the possibility to deal with the wastewater issue economically and effectively via locally-developed solutions for treatment and reuse. Of these, adsorption, flocculation/coagulation and photocatalytic degradation-based technologies have gained prominent positions in most wastewater treatment strategies primarily through the investigation of wastewater treatment solutions based on the valorization of waste materials to develop eco-friendly and techno-economic, single or integrated, processes to treat municipal wastewaters and industrial effluents.

Thus, the scope of this review project is to collect, showcase, analyze, critique and provide new research directions in relation with the recent research and development (R&D) efforts of African scientists in the field of waste materials re-utilization for an eco-friendly and low-cost water and wastewater treatment paradigm in the continent, and a sustainable management of wastes by reusing and valorizing wastes and byproducts from industrial, agricultural, and mining activities, to cite a few.

2. Waste-derived materials for wastewater treatment using adsorption: a global overview

In the search for eco-friendly and efficient materials and chemical compounds for wastewater treatment , several household, agro-industrial wastes and by-products have been investigated and proven to be viable alternatives to the conventional counterparts, including commercial activated carbons produced from non-renewable feedstocks such as lignite and coal.

Before focusing on related R&D in Africa, the present section highlights the global trend and great potentialities of this important research effort to develop sustainable wastewater treatment technologies using a wide selection of waste materials. It needs to be noted right from the start that in the African context, and for economic and availability reasons, the use of waste materials as adsorbents for wastewater treatment is clearly the main ongoing trend in this field, as it will be detailed in Section 3.

2.1. *Adsorption*

Adsorption is a physiochemical interface mass-transfer phenomenon applied for wastewater treatment and pollution removal, among other applications (Fig. 1). It is an established technology with proven advantageous features such as versatility, low-cost, high efficiency, prone for recycling, and relatively smoother implementation and operations (Fazal et al., 2019; Awad et al., 2020; Dotto and McKay, 2020). Overall, during an adsorption-based wastewater treatment process, organic and/or inorganic pollutants (adsorbates) are attracted to the outer and inner surfaces of the porous materials (adsorbents), through mass transfer and diffusion processes from the aqueous media to the active adsorbing sites of the adsorbents. The involved mechanism is either chemisorption (ionic interactions for instance) or physisorption or both (such as Van der Waals and π–π interactions) (Lashaki et al., 2016; Rasoulpoor et al, 2020).

2.2. *Waste-derived adsorbents for water treatment: selected worldwide R&D studies*

Numerous waste materials have been investigated as raw or modified adsorbents for the removal on various pollutants (dyes, surfactants, heavy metals, emerging contaminants, etc.) from domestic, municipal

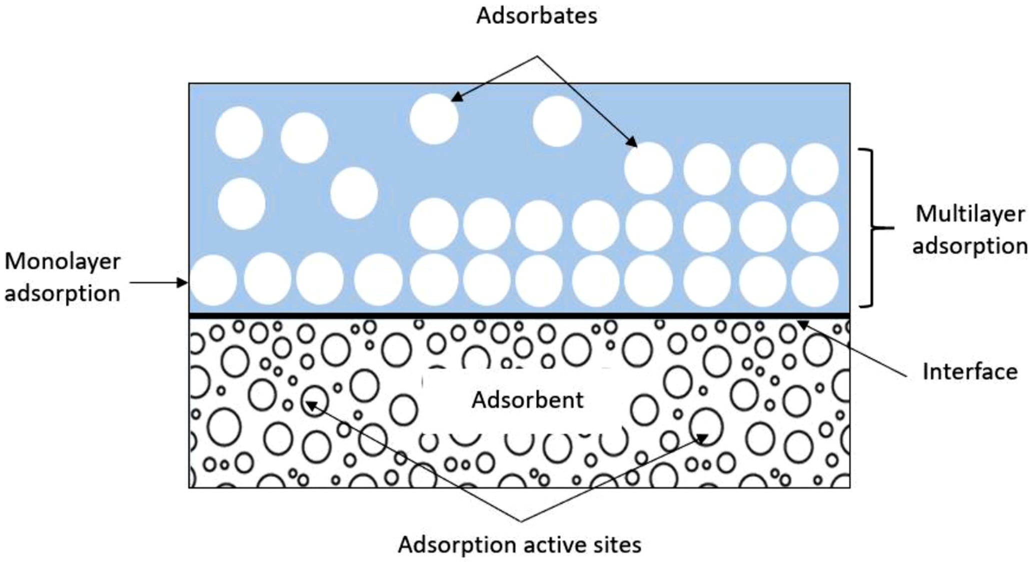

Fig. 1. Simple illustration of the adsorption process.

and industrial wastewaters. In Table 1, a selection of recent R&D investigations (2017–2022) related on the use of wastes as adsorbents of wastewater treatment is presented to showcase the versatility and abundance of such waste-derived materials, and their widespread utilization throughout the world (expect Africa, on which this review article is focusing).

Overall, among these various waste-derived adsorbents, carbonaceous porous materials including biochars, activated carbons (ACs) and

Table 1
Worldwide selection of waste-derived adsorbents of the removal of organic and inorganic pollutants from aqueous solutions.

Location	Pollutants	Adsorbents	Adsorbates	Max adsorption capacity	Key operating conditions			References
					Time (h)	pH	T (°C)	
USA	Dyes	Acivated carbon (AC) from Cashew nut shells	Methylene Blue (MB)	476 mg/g	24	7	25	Spagnoli, et al. (2017)
Pakistan		AC from used tea leaves	MB dye	321 mg/g	12	7	30	Mahmood et al. (2017)
Turkey		AC from active sludge	Crystal violet	62.1 mg/g	2.5	6	25	Sahbaz et al. (2019)
Malaysia		Modified coffee waste	Reactive Black 5 Congo Red	77.5 mg/g 34.4 mg/g	2	7	room temp.	Wong et al. (2020)
Brazil		AC from Palm Fibres	MB dye	110.8–162.5 mg/g	1	6	30	Maia et al. (2021)
USA/South Korea	Heavy metals	Biochar from loblolly pine	Cd^{2+}	167 mg/g	24	7.5	25	Park et al. (2017)
Viet Nam		AC from banana peel	■ Cu^{2+} ■ Ni^{2+} ■ Pb^{2+}	■ 14.3 mg/g ■ 27.4 mg/g ■ 34.5 mg/g	24	6.1–6.5	25	To et al. (2017)
Turkey		Brewed tea waste	■ Pb^{2+} ■ Zn^{2+} ■ Ni^{2+} ■ Cd^{2+}	■ 1.2 mg/g ■ 1.4 mg/g ■ 1.1 mg/g ■ 2.4 mg/g	0.5	4.0–5.0	25	Çelebi et al. (2020)
Brunei Darussalam		AC from sugarcane bagasse	Cr^{6+}	9.7 mg/g	2	6.5	26	Karri et al. (2020)
Japan	Fertilizers / Pesticides	Waste glass and shells' composite	Phosphate	73 mg/g	120	3–7	25	Jiang et al. (2017)
Hungary		Pomegranate peel powder	Ammonium	2.5 mg/g	2	6	25	Hodúr et al. (2020)
China		AC from tangerine seed	■ Metolcarb ■ Pirimicarb ■ Methiocarb	■ 9.11 mg/g ■ 39.37 mg/g ■ 93.4 mg/g	0.25	7	30	Wang et al. (2020)
Spain		AC from sludge	■ Acetamiprid ■ Thiamethoxam ■ Imidacloprid	■ 129 mg/g ■ 127 mg/g ■ 166 mg/g	24–144	7	25	Sanz-Santos et al. (2021)
China	Emerging pollutants	Waste tea-based AC	Oxytetracycline	286–345 mg/g	30	-	30	Kan et al. (2017)
Hong Kong		AC from palm kernel shell	■ Atenolol ■ Acebutolol ■ Carbamazepine	■ 0.69 mmol/g ■ 0.67 mmol/g ■ 0.72 mmol/g	24	7	25	To et al. (2017)
Brazil		AC from Macauba palm	■ Bisphenol A ■ Ethinylestradiol ■ Amoxicillin	■ 0.15 mmol/g ■ 0.10 mmol/g ■ 0.07 mmol/g	24	5.5	25	Moura et al. (2018)
USA		Biochar from agricultural wastes	■ Sulfapyridine ■ Docusate ■ Erythromycin	■ 1.22 mg/g ■ 19.68 mg/g ■ 17.12 mg/g	24	7–10	25	Ndoun et al. (2021)

carbon nanotubes (CNTs) are being subjected to a special focus from researchers all over the world using highly available and low cost agro-industrial wastes and household residues as feedstocks. These carbonaceous materials have been widely investigated and reported as efficient adsorbents for various pollutants mainly due to well-developed porous structure, variable pore size distribution, high surface area with functional groups that can be used as-prepared or after chemical modification to provide binding sites for adsorption of various contaminants in water, as illustrated in Fig. 2 for the case of CNTs.

3. Application of waste materials for water and wastewater treatment in Africa

The inefficiency of conventional wastewater treatment plants and the cost associated with advanced methods, has led to environmental chemists and material scientists looking into various cheaper alternatives of eliminating environmental contaminants (Omo-Okoro et al., 2018). Adsorption has been found to be a better alternative to all others because of its ease of use, availability, cost-effectiveness, no increase in the chemical oxygen demand of water, and the fact that it does not leave behind toxic by-products (Chaukura et al., 2016; Kanamarlapudi et al., 2018). Various adsorbents have been employed in the adsorption process, and Table 2 illustrates how they are classified.

Table 2
Classification of waste-derived adsorbent, and selected examples.

Classification	Examples
Household wastes	Scrap tires-derived activated carbons.
Agricultural by-products (used as such or after transformation onto biochars or activated carbons)	Pearl millet husk, peanut husk, rice, coconut and almond husks, silkworm pupa, hen feathers, tendu leaf, papaya wood, neem leaf, barks of trees, seeds of plants, silk cotton hull, sawdust, oak dust, potato peels, orange, citrus and banana peels, maize cobs, cocoa and coconut shells, carrot residues, barley straw, cassava wastes, eggshells.
Sea materials	Seaweed and algae, seafood processing wastes, peat moss, chitosan, fish scales, crab shells.
Industrial products	Fuel oil fly ash, bagasse fly ash, coal ash, petroleum wastes, sugar industry wastes, blast furnace slag, thermosensitive gel or polymer.
Soil and ore materials	Silica gel, natural and synthetic zeolites, ore minerals, modified red mud, clays, sediment and soil.
Metal compounds	Activated alumina, bauxite, activated and novel phosphate, synthetic iron sulphides.

It is evident from Table 2 that various biological materials especially agricultural-based waste products have been used to remove water contaminants by adsorption, a process being referred to as biosorption (Eletta and Ighalo, 2019). The biosorption activity entails the formation of a physical or chemical bond between a solid phase (sorbent) and a fluid phase comprising the sorbates-the chemical pollutants being abstracted (Al-Ghouti and Da'ana, 2020). The sorbate species have a higher affinity for the sorbent consequently being bound to the sorbent *via* diverse mechanisms (Adeniyi and Ighalo, 2019; Al-Ghouti and Da'ana, 2020).

For biosorption to be successful, the sorbate molecules and the surface of the sorbents should have approximately similar pore sizes since finer pore sizes take up smaller molecules and vice versa (Wang et al., 2017). Low molecular weight pollutants can also be displaced by high weight molecular species (Nguyen et al., 2020). It has also been observed that adsorbents show preferences to certain sorbates in a complex system due to other properties such as hydrophobicity, kinetic diameters, dissociation constants, chemical structure among others (Ali et al., 2012). Other parameters that affect the adsorption process are sorbate concentration, the textural characteristics of the adsorbent, temperature, presence of competing ions, and pH (Ngeno et al., 2016).

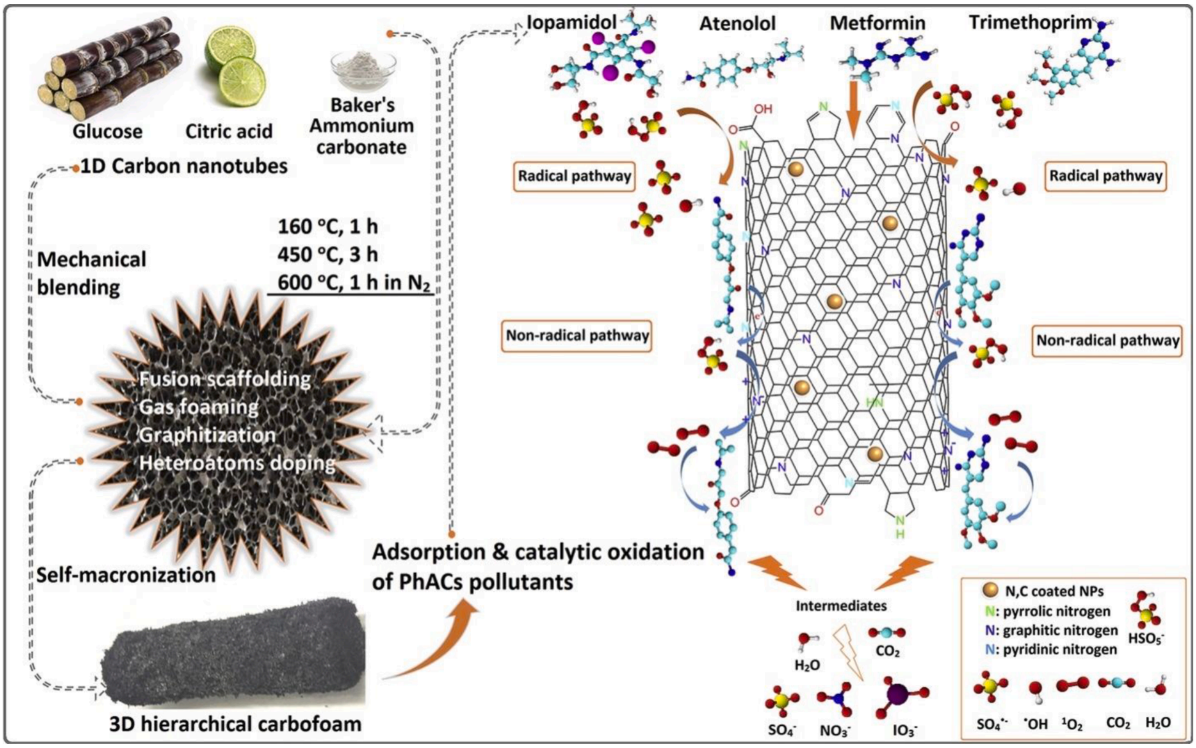

Fig. 2. 3D hierarchical porous carbofoams from macronized magnetic CNTs for the removal of pharmaceutically active xompounds (PhACs)from aqueous media (Do Minh et al., 2019). Reprinted with permission from Elsevier.

3.1. Desirable properties of sorbents

As alternatives to industrial adsorbents generally derived from finite resources such coal, lignite and peat, the precursors to sorbents should be easily accessible, cheap and non-toxic. The carbon or oxygen content should also be high to increase bonding possibilities between the sorbent and the sorbate. Other attributes include thermal resistance, resistance to wear, recyclability, and narrow pore diameters (Ali et al., 2012). This leads to increased exposed surface area and, hence, an elevated surface capacity and fast kinetics for adsorption. Further, the sorbents should also be easily desorbed thereafter thus enabling regeneration without releasing undesirable substances into the aqueous media (Kumar et al., 2019; Omo-Okoro et al., 2018).

Most waste biomaterials have been found to fulfil most, if not all, of those desired properties for the preparation of carbonaceous adsorbents. Additionally, they are a renewable resource. Usually, these waste materials, often bio-based ones, are used without thermal or chemical pretreatment or are pyrolyzed to obtain low-cost biochars that are alternatives to activated carbon. These carbonaceous chars can further be activated to improve their porosity and surface chemistry (Ali et al., 2012).

3.2. Processing, activation and characterization of carbonaceous sorbents

In general, sorbents are processed and/or activated using both physical and chemical methods. Some bio-based sorbents (biosorbents) are used directly as dried powdered biomass (Adeniyi and Ighalo, 2019). The majority, however, are transformed into carbonaceous materials through pyrolysis, a process of decomposing organic material through heating at elevated temperatures with neither oxygen nor halogen. This converts the material to carbon (Omo-Okoro et al., 2018). Heating rate and duration of carbonization and activation are the most significant variables during pyrolysis since they influence the ultimate pore structure, surface area and chemical properties of the resultant carbon (Ali et al., 2012). The resultant material constitutes an inflexible carbonaceous char containing pores packed with tarry pyrolysis deposits and necessitates activation to expand the internal surface area of the char thus increasing porosity. Activation may be achieved chemically or physically consequently obtaining activated carbons with diverse forms and dimensions given the varying pathways of activation (Adeniyi and Ighalo, 2019).

In chemical activation, chemical modifiers are infused into the biomass. Chemical activators in common use are zinc chloride ($ZnCl_2$) (Agarry et al., 2020), phosphoric acid (H_3PO_4), sulphuric acid (H_2SO_4), potassium hydroxide (KOH), sodium hydroxide (NaOH), potassium sulphide (K_2S) and potassium thiocyanate (KCNS) (Ali et al., 2012; Omo-Okoro et al., 2018). These chemically modifying groups in which most of them contain oxygen, sulphur and nitrogen are known to improve the adsorption and cation-exchange capacities. Once the biomass is saturated with the activators, it is then dehydrated to minimize tar formation and volatilization during pyrolysis. Chemical activation technique has some strengths including minimal temperatures of activation, shorter reaction time, reduced energy costs, and increased yield of material. The used material may however be environmentally hazardous (Omo-Okoro et al., 2018). Noteworthy, the cost of adsorbent development depends on the method of chemical activation, duration of pyrolysis and temperatures used.

Physical activation is the direct reaction between the carbonized char and an activator, which are mostly oxidizing agents like steam, carbon dioxide (CO_2), and air. Physical activators are clean, easy to handle and environmentally friendly but have a lower yield. Just like chemical activation, the main aim is to rid the structure of tarry amorphous carbon in the interstitial layers thus increasing the porosity and making the internal surface area accessible (Ali et al., 2012).

Nanotechnology has also been employed in producing nanocomposites from waste materials. Nanoscale structures are those whose atomic and molecular sizes are within 1–100 nm. Nanocomposites are materials synthesized from varied materials put together and structured into nanoscale size to increase their functionality and reactivity (Omo-Okoro et al., 2018). Most nanocomposites have been manufactured from metals and agricultural waste materials and have been found to work exceptionally well in water treatment (Okello et al., 2017).

Regarding the characterization, adsorbents are characterized to determine their textural and surface characteristics before and after adsorption. This includes surface area, porosity, crystallite size, particle size, thermal stability, surface morphology, and functional groups responsible for adsorption (Oyewo et al., 2016). High porosity (and consequently an extensive surface area with more specific adsorption sites and faster kinetics) is the fundamental characteristic of a good adsorbent. Polar adsorbents are hydrophilic and possess a higher affinity to polar substances such as water or alcohols and examples are aluminosilicates such as zeolites, geopolymers, porous alumina, silica gel or silica-alumina. Non-polar adsorbents are mostly hydrophobic examples being carbonaceous adsorbents, polymer adsorbents and silicalites. They have a higher affinity to oil or hydrocarbons (Schoutteten, 2012).

Several characterization methods can be conducted on adsorbents including X-ray diffraction, which has been employed for mineralogical phase identification and quantification and measurement of crystallite size. The scanning electron microscope, and transmission electron microscopy are used for inspecting surface morphology, and Fourier Transform infrared spectrometry have also been used for the determination of surface functional groups of adsorbents pre- and post-adsorption (Choina et al., 2015; Onwuka et al., 2016; Oyewo et al., 2016; Souza et al., 2017).

3.3. Recent studies using different waste-derived sorbents for pollutant removal from aqueous solutions in Africa

Using a bibliometric approach based on the method described in Olisah et al. (2019), it was observed that more research has been dedicated to the use of bio-based sorbents in the recent past in Africa. In general, the last decade (2011–2020) produced the highest number of studies with an approximate of 373 publications on the use of biosorbents in wastewater treatment. It is worth noting that records for 2021 ($n = 30$) are underestimated as these indicate the output for four months only (January to April).

The many international initiatives and funding agencies established to reduce water pollution in Africa may be responsible for the high research outputs in the last two decades. Some of the funding initiatives include the establishment of Rural Water Supply and Sanitation Initiative (RWSSI) in 2003, funded by the African Development Bank Group (ADBG) and other international agencies, and the adoption of the Sustainable Development Goals by the United Nations in 2015, particularly the Clean Water and Sanitation Goal. Other reasons for the high research output may be linked to the emergence of sophisticated analytical instruments for scientific research, the advent of new research ideas, and the establishment of international collaboration programs between the government of African countries and high-income countries. A strong positive correlation between the number of publications and the year of article production fitted into a polynomial model ($R^2 = 0.7543$, $y = 0.2529x^2 - 2.1691x + 4.1759$ as shown in Fig. 3. This suggests that articles in this area of study are likely to increase in the future.

On the other hand, Table 3 illustrates, with relevant information like country, and maximum adsorption capacity, varied bio-based and waste-derived materials used in the removal of various pollutants from selected studies from the year 2016 to 2021.

3.4. Most prolific countries in scientific productivity on wastewater research in Africa

A bibliometric survey as described in Olisah et al. (2019) was used to recognize the most prolific countries in the subject area. As displayed in

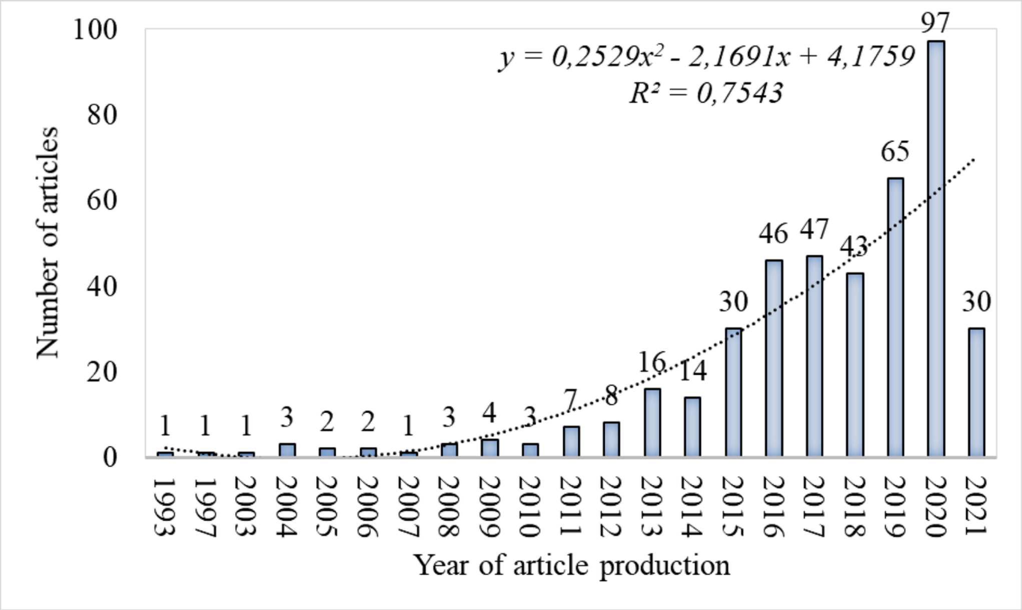

Fig. 3. The annual production of articles related to the usage of adsorbent in wastewater treatment in Africa published between 1993 and 2021.

Table 3

Recent studies that have used different sorbents from waste materials to remove various pollutants in Africa.

Sorbents and precursors	Pollutants	Country	Removal rate (%) or Maximum adsorption capacity (mg/g)	Ref.
Vinegar-Treated eggshell Waste Biomass	Nickel (ii) and Cobalt (ii) ions	Botswana	78.70% and 76.53% respectively	Stevens and Batlokwa (2017)
Sugarcane Bagasse-derived Biochar	Sulfamethoxazole	Kenya	78%	Shikuku and Jemutai-Kimosop (2020)
Banana peels	Lead (ii) ions	South Africa	98.146%	Afolabi et al. (2021)
Biochar and Fe_2O_3–biochar nanocomposite derived from pulp and paper sludge	Methylene blue	Zimbabwe	50 mg/g and 33 mg/g respectively	Chaukura et al. (2017)
Activated carbon from sawdust	dye	Nigeria	98.5%	Eletta et al. (2018)
Tyre-based powdered activated carbon	microcystin-LR	South Africa	100%	Mashile et al. (2018)
Fish scales	Heavy Metals	Nigeria	Above 50%	Eletta and Ighalo (2019)
Eggshells and fish scales	Chromium (vi) ions	Uganda	Not indicated	Bamukyaye and Wanasolo (2017)
Agro-waste (*Musa paradisiaca* peels)	Toxic metal ions	Nigeria	Above 90%	Ibisi and Asoluka (2018)
Magnetic Iron Modified Carbonized Baggasse	Carbamazepine pharmaceutical	Kenya	60.9%	Okello et al. (2017)
Corn and rice husks in raw form, pyrolyzed form, and chemically modified form	Lead (ii) ions	Tanzania	>90%	Rwiza et al. (2018)
Fish scales biochar	Copper (II) ions	Kenya	39.39 mg/g	Achieng and Shikuku (2020)
Rice husk, rice straw, sugarcane bagasse and sawdust; cement kiln bypass dust and marble powder.	Chromium (III) ions	Egypt	>99% for cement kiln	Abdelkader et al. (2021)
Raw coconut shell, activated carbon and activated nanocomposite	Lead, copper, and color	Nigeria	Not indicated	Sarkingobir et al., 2020
Water hyacinth biochar	Caffeine and ciprofloxacin pharmaceuticals	Kenya	>60%	Ngeno et al. (2016)
Moringa stenopetala seeds	Antibiotics	South Africa	>70.4% for all samples.	Kebede et al. (2019)
Raw and surface-modified *Adansonia digitata* fruit pericarp	Fluorides	Tanzania	67.61 and 91.91% respectively	Mihayo et al. (2021)
Banana peels nanosorbent	Radioactive minerals from real mine water	South Africa	27.1 mg g^{-1} , 34.13 mg g^{-1} for uranium and 45.5 mg g^{-1} , 10.10 mg g^{-1} for thorium in synthetic and real mine water, respectively	Oyewo et al. (2016)
Chemically and Thermally Modified Coconut (Cocos nucifera) Husks	Crude oil	Nigeria	Between 12.11 g/g and 16.84 g/g	Agarry et al. (2020)

Table 4, we ranked author countries based on the total number of articles and citations accumulated over the survey period (1993 to 2021). Egypt had the highest number of publications (n = 115), representing 27.12% of the total number of articles retrieved. This was followed by South Africa (n = 71, 16.75%), Nigeria (n = 32, 7.55%), Algeria (n = 27, 6.37%), and Tunisia (n = 18, 4.25%). Five of the top 10 most productive countries are among the most developed countries in Africa (Africa HR Solutions,2019).

Table 4
Top 10 author's countries on studies related to the usage of adsorbent for water treatment in Africa. SCA – single country articles. MCA – multiple country articles. MCA/A – multiple country articles per article.

Most productive countries								Total number of citations per country			
Rank	Countries	Articles	% of 424	Freq	SCA	MCA	MCA/A Ratio	Rank	Country	Article citations	Citation average
1	Egypt	115	27.12	0.271	88	27	0.24	1	Egypt	2153	18.72
2	South Africa	71	16.75	0.167	51	20	0.28	2	South Africa	1607	22.63
3	Nigeria	32	7.55	0.075	17	15	0.47	3	Nigeria	605	18.91
4	Algeria	27	6.37	0.064	22	5	0.19	4	Tunisia	374	20.78
5	Tunisia	18	4.25	0.042	13	5	0.28	5	Algeria	263	9.74
6	Morocco	16	3.77	0.038	12	4	0.25	6	Zimbabwe	194	38.80
7	Ethiopia	7	1.65	0.017	3	4	0.57	7	Morocco	149	9.31
8	Zimbabwe	5	1.18	0.012	1	4	0.80	8	Ethiopia	38	5.43
9	Ghana	3	0.71	0.007	1	2	0.67	9	Ghana	10	3.33
10	Kenya	3	0.71	0.007	3	0	0.00	10	Mauritius	4	4.00

Scientific research productivity largely depends on economic and technological advancement, availability of research funds, existence of a serene research environment as well as the presence of state-of-the-art equipment (Qu et al., 2018). This may be the reason why most studies are generated from the more developed countries. Categorization based on geographic regions revealed that countries in North Africa were more prolific, having four countries in the top 10 author's countries (Egypt, Algeria, Tunisia, and Morocco).

Fig. 4 displays the collaboration strength between countries in the aforementioned research area. The network line thickness depicts the frequency of countries' collaboration, while the red circles indicate the number of countries. The larger the circle, the higher the collaboration strength of the indicated country. The line connectivity indicates the number of collaborations that exist between countries.

This figure shows that African countries are increasingly getting involved in international collaboration in this research area. This network pattern was in tandem with Hoekman et al. (2010) observation that "scientific knowledge is increasingly dependent on collaborative efforts". Egypt has the highest collaboration strength patterning majorly with European (France, Germany, Spain, and United Kingdom) and Asian countries (Saudi Arabia, China, Malaysia, India, and Japan). This was followed by South Africa, Nigeria, Tunisia, and Algeria. The collaboration dominance of North African countries may be attributed to the strong historical ties with European countries (Onyancha and Maluleka, 2011).

3.5. *Citation analysis of studies done in Africa*

The number of citations an article gets typically reflect the degree of interest it attracts from scholars. However, the acquired citations do not necessarily show equal author's visibility in a region because citation tends to accumulate over time. The top 5 African countries based on accumulated citations are Egypt ($n = 2153$), South Africa ($n = 1607$), Nigeria ($n = 605$), Tunisia ($n = 374$), and Algeria ($n = 262$) with an annual citation average of 18.72, 22.63, 18.91, 20.78 and 9.74% (Table 5). As shown in this table, the ten most cited articles in wastewater research in Africa, with relevant information such as the author's first name and initials, publication title, names of the publishing journal, total citation (TC), and total citation per year (TC/Y). All the top-cited articles were published between 2003 and 2016. It can be noticed that the most cited article was "A review of biochar as a low-cost adsorbent for aqueous heavy metal removal" ($n = 478$). This review paper evaluated existing literature that demonstrate the sorption behavior of metals on biochar. "Potential of using green adsorbent of heavy metal removal from aqueous solutions: adsorption kinetics, isotherm, thermodynamic, mechanism and economic analysis" authored by Ali et al. (2016) was ranked second, and "Cellulose: a review as natural, modified and activated carbon adsorbent" (Gupta et al., 2016) ranked third with 298 and 250 citations, respectively.

3.6. *Advantages and challenges of using waste materials in Africa*

Large quantities of waste materials, often bio-based ones, to be used as sorbents are readily available. The reuse of these bulky biowastes, which are currently a public health concern due to disposal problems, causes waste minimization and reduce waste loads on landfills (Bhatnagar and Sillanpää, 2010). They have also been found to be highly efficient in dilute solutions with high possibilities of regeneration (Omo-Okoro et al., 2018). Another advantage is the conservation of limited and valuable feedstock such as coal, lignite and petroleum coke,

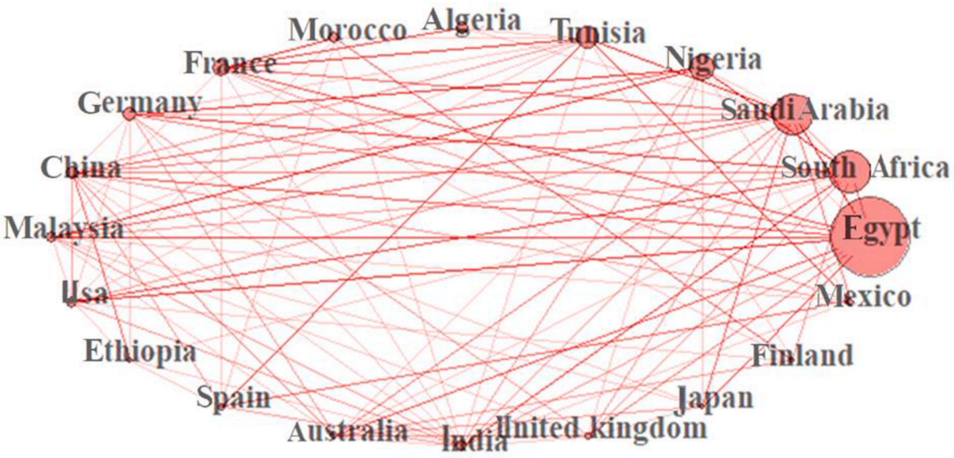

Fig. 4. Top 20 countries collaboration network on studies related to the usage of adsorbent for water treatment in Africa (node depicts countries, node sizes represents collaboration strength, and the line connectivity shows the number of collaborations that exist between countries).

Table 5
Top 10 most cited articles on the usage of adsorbent for water treatment in Africa.

Rank	First Author Names, Initials and Publication Year	Article Title	Journal	TC	TC/Y
1	Inyang et al. (2016)	"A review of biochar as a low-cost adsorbent for aqueous heavy metal removal"	Crit Rev Environ Sci Technol	478	79.67
2	Ali et al. (2016)	"Potential of using green adsorbent of heavy metal removal from aqueous solutions: adsorption kinetics, isotherm, thermodynamic, mechanism and economic analysis"	Ecol Eng	298	49.67
3	Gupta et al. (2016)	"Cellulose: a review as natural, modified and activated carbon adsorbent"	Bioresour Technol	250	41.67
4	Shahat et al. (2015)	"Functional ligand anchored nanomaterial based facial adsorbent for cobalt(II)" detection and removal from water samples	Chem Eng J	172	24.57
5	Daifullah et al. (2003)	"Utilization of agro-residues (rice husk) in small waste water treatment plans"	Mater Lett	147	7.74
6	Thakur et al. (2016)	"Development of a sodium alginate-based organic/inorganic superabsorbent composite hydrogel for adsorption of methylene blue"	Carbohydr Polym	143	23.83
7	Boujelben et al. (2008)	"Phosphorus removal from aqueous solution using iron coated natural and engineered sorbents"	J Hazard Mater	139	9.93
8	Selatnia et al. (2004)	"Biosorption of Cd^{2+} from aqueous solution by a naoh-treated bacterial dead *Streptomyces rimosus* biomass"	Hydrometallurgy	139	7.72
9	Repo et al. (2013)	"Aminopolycarboxylic acid functionalized adsorbents for heavy metals removal from water"	Water Res	138	15.33
10	Elkady et al. (2011)	"Assessment of the adsorption kinetics, equilibrium and thermodynamic for the potential removal of reactive red dye using eggshell biocomposite beads"	Desalination	137	12.45

which are mostly used for commercial activated carbon production. These merits align with the millennium development goals of sustainable development and zero waste (Schoutteten, 2012).

The disposal of the used adsorbents is the main challenge that researchers are still grappling with. Incineration and landfilling could be considered as options. However, disposal of the so-produced pollutant-laden ash presents another unresolved environmental challenge. Other uses include being used as fillers in road surfacing and in amending soils (Chaukura et al., 2016) or as precursors for eco-cement (geopolymers) development (Tome et al., 2020).

Most of the adsorbents do not work in natural conditions (Ali et al., 2012) and that is why parameters like pH and temperature must be varied. Some may also require a longer contact period for maximum adsorption. They may also require larger concentrations of pollutants, that is, in the mg/mL range contrary to the µg/mL concentration range in real environmental media.

Large-scale application of adsorption can be costly and requires capital investment. Furthermore, over time, the adsorption beds age and become saturated and less efficient and no amount of regeneration can salvage the adsorption sites. This requires replacement with new sorbents.

There can also be an issue of desorption especially if the contaminant concentration is low so as to maintain equilibrium. Desorption can also be caused by competition for the adsorption sites by different pollutants and other adsorbed species (Grandclément et al., 2017).

It is also important to note that removal efficiencies of organic micropollutants rely on several factors including the physico-chemical properties of the compound, process-specific parameters like batch versus continuous, temperature, pH, Ultra-Violet radiation, and precipitation rate (Grandclément et al., 2017). The consequence of these variables will be varied removal efficiencies with others performing below average.

4. Life cycle assessment: guidelines for the use of wastewater treatment technologies for low-and middle-income economies

Overall, the goals for wastewater treatment ranges from human health and aquatic life protection, reducing loss of scarce resources, minimizing on use of water and energy, recycling of nutrients as well as reducing waste emissions into the environment (Lundin et al., 2000). Wastewater technologies, however, may have some drawbacks. For instance, effluents from wastewater treatment facilities contains both a diversity of pathogens and different chemical pollutants from the wastewater itself. These threaten public health and accumulate in the food chain when wastewater is re-used. Additionally, high-energy use in wastewater treatment processes would result in increased energy cost and carbon generation. These plants are also known to emit the greenhouse gases (GHG) such as the CO_2, CH_4, NO_2 and SO_2. The release of limiting nutrients like nitrogen and phosphorus results in eutrophication in the recipient water bodies. With this in mind, a number of water science researchers have embarked on affordable technologies for wastewater treatment using waste material-based products as alternative technologies to promote wastewater re-usability and curb water scarcity as well as preserve the fresh water resources (Choudhury and Hashmi, 2020).

While the use of these technologies is an economical and environmentally friendly approach, their ecological impacts and potential effects need to be well understood. This implies that WWTPs need to be designed to minimize their impacts on the environment. This can be achieved by monitoring and evaluating the whole life cycle of the wastewater treatment system including the individual components of the operational unit's raw materials and chemicals added, as well as the energy utilized in the process (Lundin et al., 2000). This way, the quality of treatment will be enanced, and the risks associated with wastewater treatment plants will be mitigated.

4.1. *Environmental management tools*

A number of tools in environmental management such as environmental impact assessment (EIA), risk assessment (RA), material flow analysis (MFA), strategic environmental assessment (SEA) and life cycle assessment (LCA) have been established to safeguard the environment and also assess the risks and impacts associated with WWTPs (Harder et al., 2015; Tabesh et al., 2019).

Environmental Impact Assessment (EIA) is a critical examination of the effects of a project or its alternative on the environment. An EIA identifies both negative and positive impacts of any developmental activity or project, how it affects people, their property and the environment. EIA also identifies measures to mitigate the negative impacts, while maximizing on the positive ones. EIA is a preventive process since it ensures that decisions on proposed projects and activities are environmentally sustainable. It seeks to minimize adverse impacts on the environment and reduces risks. Since EIA generates baseline data for monitoring and evaluating impacts, including mitigation measures during the project cycle, it can guide policy makers, planners, stakeholders and government agencies in making environmentally and economically sustainable decisions.

If a proper EIA is carried out, then the safety of the environment can be properly managed at all stages of a project planning, design, construction, operation, monitoring and evaluation as well as decommissioning.

Risk assessment (RA) is a scientific process that depends on the following three factors:

- (i) How much of a stressor is present in an environmental medium (e.g., soil, water, air) over what geographic area.
- (ii) How much contact (exposure) a person or ecological receptor has with the contaminated environmental medium.
- (iii) How it affects the health of humans (e.g., toxicity) or ecological receptors (e.g., fish killed by lack of oxygen).

Material flow analysis (MFA) and strategic environmental assessment (SEA) will not be discussed further as they are not the topics of concern.

4.2. Life cycle assessment

Life cycle assessment (LCA), our topic of focus, is a technique used to assess environmental characteristics and potential consequences of a product's life from its raw material through its processing, transportation and its use, commonly referred to as 'from cradle to grave' (Joshi, 1999). Accordingly, LCA is a tool that estimates the impacts of a product throughout all stages of its life cycle. Examining waste-based materials for wastewater treatment through their life cycle can give precise estimates of their cumulative impacts and the overall effects of such techniques (Abyar et al., 2020). For an LCA process to meet international standards, there is need to define the goal and scope, carry out a life cycle inventory analysis (LCI) as well as life cycle impact assessment (LCIA) and interpret the results from the inventory and the impact assessment procedures (Abyar et al., 2020). Following are the steps of conducting a LCA:

4.2.1. Defining the goal and scope of the product

The first step of LCA is the definition of goal and scope of the product. The goals of the waste material-based products for wastewater treatment are usually stated and specific to the kind of contaminants that are aimed at. The efficiency in the removal of those contaminants in the specific method under study are also usually known.

4.2.2. Life cycle inventory analysis (LCI)

The LCI, which involve the compilation and quantification of inputs and outputs for a product throughout the entire life cycle, is the second phase that is mostly missing in LCA. This is partly because they have not been put in for practical usage in real wastewater treatment plants and also the LCA as a tool is a relatively new practice that is developing in recent times (Arcese et al., 2013). The data obtained from the inputs and outputs of a waste-based material and its energy analysis should be fitted onto simplified (linear) systems for analysis. The LCI for waste-based materials should observe a number of principles.

The first principle is the law of conservation of mass which states that mass in any system is neither created nor destroyed by chemical process or physical changes (Milanovic and Trivic, 2017). Therefore, the net mass of the reactants must be equal to the mass of the products. The law of conservation of mass is important in solving for unknown masses and therefore determining the amount and number of different gases produced or used up in any chemical reaction.

The second principle is the law of conservation of energy; the first law of thermodynamics that states that energy is neither created nor destroyed, and can only be added from external source (Tatar and Oktay, 2011). This means that in any system, isolated or open, the same amount of energy is conserved such that the only way to use energy is transform it from one form to another. This principle is well defined by the equation: $\Delta U = q + w$; where w is the work done on a system, and q is the energy transferred as heat to a system. This is applicable in all parts of LCA process just as it is applicable to chemical thermodynamics (Kralisch et al., 2015).

The third principle is the second law of thermodynamics, which states that as energy is being transformed, more of this energy is wasted. It also suggests that there is a tendency of an isolated system to degrade into a disordered state with time. This law was better put by Kelvin-Planck as: "It is impossible to construct a device which operates on a cycle and produces no other effect than the production of work and the transfer of heat from a single body (Zohuri and McDaniel, 2019). This principle is applicable to specific assessment of a chemical reaction and therefore relevant in LCI especially for the production and conversion of chemicals. For instance, in the determination of CO_2 loads during combustion of plastics, more of the heat energy is used in comparison to the number of plastics converted into carbon (IV) oxide gas (Singh et al., 2020).

The fourthprinciple is the law of stoichiometry, which is the basis of all chemical reactions. This principle looks into determination of the number of reactants to products consumed or produced in a given chemical reaction. If any species does not take part in the chemical equation, then it has a stoichiometric coefficient of zero (Morel and Morgan, 1972). The principle of stoichiometry is normally based on the law of conservation of mass. In anaerobic digestion, weak acid/base chemistry is applied in stoichiometric biological half reactions (Brouckaert et al., 2021).

The fifth principle is based on the Einstein's equation $E = mc^2$ that relates to equivalence of mass (m) and energy (E). This simply means that energy and matter (mass) are interchangeable. Under favorable conditions, energy can just become mass (Okun, 2009). The five principles that govern the LCI help in estimations of the relevant maximal quantities of product, and the energy released/necessary for a minimum chemical reaction to occur during production process (Milanovic and Trivic, 2017).

4.2.3. Life cycle impact assessment

Life cycle impact assessment (LCIA) is the third phase in LCA that aims to understand and evaluate extent and significance of the possible environmental impacts of a product throughout its life cycle (Muñoz et al., 2008). Impact assessment aims to derive potential environmental impacts from the inventory data of the specific product given as inputs and outputs per functional unit (FU) (Lotteau et al., 2015). This requires more assessment of the different defined inputs and outputs that interact with the environment.

From the inventory analysis, numerous data on mass flows, emissions, resource consumption and energy demand are available, including listing of raw input and output data. This information is numerous and difficult to handle, hence the need to cluster it through impact assessment (Lotteau et al., 2015). The impact assessment phase groups and organizes the information obtained from the inventory as the sum of parameters. This is used as a measure for the material passing through a system, and also gives a reference value to the first and foremost the technical field of waste disposal (Muñoz et al., 2008).

4.2.4. Life cycle interpretation, reporting and critical review

Interpretation is the fourth phase of LCA where conclusions are drawn from the results of the inventory and the impact assessment and recommendations are made according to the objectives of the study (ISO 14040:2006). The results are expected to be consistent with stated goals and within the scope of the project, reaching relevant conclusions and giving explanations as well as providing recommendations (Rebitzer et al., 2004). Interpretation therefore justifies the achievement of the assessment tool. It forms the final step that refers to the reason for the accomplishments of the project under study (Rebitzer et al., 2004). The steps of interpretation according to ISO 1404410 are composed of identification of the significant issues based on the results of the LCI and LCIA. It also checks on completeness, consistency and sensitivity of the project as well as drawing conclusions, stating the limitations experienced and suggesting recommendations (Rebitzer et al., 2004).

4.3. Life cycle assessment in the context of waste-based materials, wastewater treatments and sustainability

Defining wastewater treatment using waste-based materials sustainability, one needs to think of the process of designing these products in order to make them efficient in energy usage, flexibility, health effects to humans and should be used for a long time. They should be produced in a way that they minimize the environmental impacts and maximize their re-usability (Fiksel, 2003). To examine the environmental impact of such products, we must consider the four life cycle stages which include the production, usage, transportation and disposal or recyclability (Kakadellis and Harris, 2020). A LCA is able to generate a list of a producst's negative and positive impacts to the environment hence achieve a products sustainability. These impacts are assessed in each stage of the products life, indexing the waste and emissions generated as well as the resources being used at any particular stage (Arena et al. 2003). This helps in making scientific decisions on a suitable method at the design stage, and choosing appropriate technologies that minimize the environmental impacts of the end product.

Connection to the sewer line in emerging economies remain scarce especially for peri-urban areas and rural settlements. Small-scale wastewater treatments , also called distributed or decentralized technologies have therefore come up in an effort to decentralize conventional systems (Reymond et al., 2018). These technologies include the use of constructed wetlands (CW), septic tanks, ponds and latrines, which are common due to their relative reliability, simplicity and cost efficiency (Kivaisi, 2001). Other technologies include eutectic freeze crystallization and evaporative crystallization for high salinity wastewater treatment from mining activities carried out in South Africa by Fernández-Torres et al. (2012). These technologies should be designed with a view to carrying out LCA, consequently assessing the products environmental sustainability.

4.4. Life cycle assessment and wastewater

LCA in wastewater is used to inform policies and decisions in managing the diverse environmental impacts emanating from the different stages of wastewater treatment resulting from the construction to the demolition of a facility or a technology (Abyar et al., 2020). It also gives a wide perspective to the array of impacts upstream and downstream of the treatment process where the environment is most affected, it would also offer comparison of various methods based on chemical and energy usage, amount of sludge generation, emission of GHG, construction and maintenance costs and land requirement.

Most of the LCA studies in wastewater have been concentrated in developed countries with minimal contribution emanating from developing countries (Gallego-Schmid and Tarpani, 2019). Dong (2012) performed a general model for the carbon footprints analysis of WWTPs, using an LCA approach in Spain. The research concluded that "more than half of the carbon footprints from the La Gavia WWTP are from the indirect emissions of CO_2, which is caused by the intensive energy consumption. The direct emissions of CH_4 and N_2O combined contribute more than 30 percent of GHG emission and although the La Gavia WWTP increased the total carbon footprints, it has much better control of eutrophication potential (EP)". Ün (2009) also did a critical review of how LCA can be used in evaluating the environmental advantages and expenses of different wastewater treatment technologies and standards. The study concluded that for an environmentally sound wastewater treatment option to be chosen, methods like LCA would be appropriate in assessing their suitability. Tarpani and Azapagic (2018), after carrying out LCA concluded that advanced treatment options like granular activated carbon (GAC), nanofiltration (NF), solar photo-Fenton (SPF) and ozonation have lesser environmental impacts as compared to conventional wastewater treatment methods.

As previously illustrated in Table 3, a wide variety of waste-based materials have been developed and applied for wastewater purification. Nonetheless, it is highly important to highlight the fact that although most of those studies show that these wastes are indeed effective in the removal of contaminants in wastewater, few of them have been integrated into wastewater treatment processes, and their LCA was hardly carried out to establish their overall impact to the environment. Furthermore, most of these studies do not report the LCIA of the adsorbents from preparation, utilization to fate of the pollutant-laden sorbent especially in the emerging economies.

Gallego-Schmid and Tarpani (2019) carried out a review of LCA of wastewater treatment in developing countries where 43 articles in those countries were investigated, and the results are shown in Fig. 5.

The results depicted in Fig. 5 shows that almost all studies have the goal and scope well defined, but very few pursue all the steps in LCA. Some studies have the LCI phase considered but either the measured data mostly lacked details that can allow reproducibility, or the details did not support the results reported. Data on the requirements of materials, chemicals and energy without proper description and evaluation of how they influence the goal and scope were presented in some studies. Some of the environmental impacts like global warming, acidification or photochemical oxidation (Khoo, 2009; Zhou et al., 2011), are considered to be as a result of indirect emissions associated mainly to the production of the purchased electricity for the operation of the WWTP (Machado et al., 2007). Eutrophication is the most relevant environmental impact of wastewater treatment system (Gallego-Schmid and Tarpani, 2019) while terrestrial ecotoxicity potential is mainly due to effect of the heavy metals' presence in the sludge applied for agricultural purposes (Muñoz et al., 2008; Teoh and Li, 2020). An important consideration is the water use impact, a measure of the potential effects on fresh water availability for both humans and biota in emerging economies (i Canals et al., 2009). This is especially because they suffer from water shortage and limited access to clean freshwater (Cohen, 2006; Curry, 2010). From Fig. 5, of the studies done, 34 had the emissions observed and their implication well elaborated. The energy usage and the possibility of any alternative were also suggested. The use of data analysis tools should improve on outcome and reliability of an LCA done in any WWTP (Gallego-Schmid and Tarpani, 2019). The comparison of other literature reports and assessment make significant conclusion of the data.

4.4.1. Discrepancies between LCA and RA

The main differences between LCA and RA are listed in Table 6. Both methodologies were designed to fulfil different goals and can therefore not replace each other. However, they both can be used to guide the reduction of chemical impact on the environment. The main difference is that (environmental) RA typically addresses a single use situation of a single substance. In contrast, LCA attempts to assess the ecotoxicity impact of a functional unit covering all emissions occurring along the life cycle.

4.4.2. Comparisons between EIA and LCA

Both EIA and LCA are comparable as their principles are founded on the same system definition and yardsticks. Furthermore, in both LCA and EIA procedures, the environmental impacts related to activities in a specific societal system must be assessed.

LCA is, however, an analytical tool characteristically formulated to gauge the environmental effects of a product's whole cycle whereas EIA is a procedure accompanying decision making with respect to environmental aspects of a wider range of activities for instance decisions on waste management plans, process installations, and site choices.

One other contrast is the fact that LCA is majorly used as a comprehensive tool for a particular type of comparison, i.e., of alternative product systems while EIA deals with an expansive set of comparisons, and emphasizes on the decision-making procedure. Because EIA procedures handle a broad range of comparison, the system choice and impact assessment cannot be described exhaustively: they depend entirely on the specific EIA. In conventional project EIAs, the system

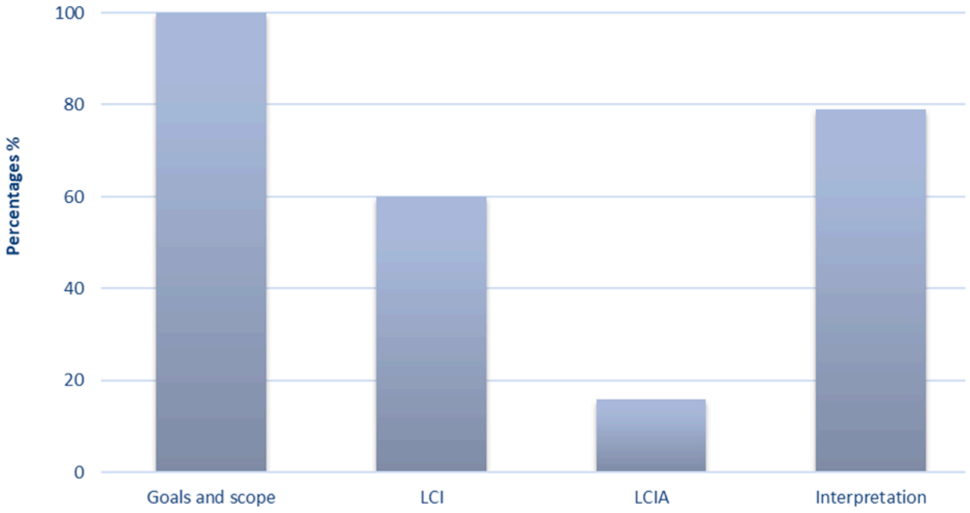

Fig. 5. The occurrence percentages of life cycle assessment-related elements in some 43 studies done in low-and middle-income countries by Gallego-Schmid and Tarpani (2019). LCI-lifecycle inventory, LCIA- lifecycle impact assessment.

Table 6
Summary of the main differences between LCA and RA (adapted from Olsen et al. 2001).

	LCA	RA
Aim – General	Compare / hotspot identification	Inform about safe use of chemicals
Objective – Ecotoxicity	Quantify ecotoxic impact	Establish need for risk management
Object of assessment / Scope	A functional unit – Emissions of all substances related to the entire life cycle of a product or service.	The single use of a single chemical
Result	Score – numerical expression for quantifying impact	Risk characterization ratio – numerical expression of the comparison of chemical exposure versus the environmental effect threshold
Statement	Typically, relative to alternative options	Absolute
Geography/ Temporality	Generic unit environment – not reflecting a specific situation in time and space. Not explicit in time and space.	Lower tier assessment of industrial chemicals: not specific in time and space. Higher tier assessments can be more specific.
Scale	Functional units	Risk characterization ratio (or Global production and use?) for actual emission volumes
Strategy for efficiency in assessment	Use of partial emission inventories from databases for establishing emission inventory for the functional unit	Tiered approach: Start assessment with low-level data, refine if needed.
Dealing with uncertainty of data / results	Uncertainties are not explicitly addressed.	Apply safety factors to low-level data with safety factors; safety factors are reduced when refined data are used; refine input data when needed.

chosen is usually restricted to a solitary industrial plant, and impact assessment is usually concentrated on the effects on the immediate surroundings. LCA is designed to compare the impacts related to a central product function.

Hence, the whole system related to that product function is included, and the impact assessment is generic and time and location independent. The two can complement each in that applying an LCA-like comparison of alternatives in EIA may be productive. In conventional project EIAs, process and abatement alternatives, that have direct impacts on the surrounding environment, are paramount. In that case, an LCA-like system approach, which takes into account all relevant effects, is necessary for a reliable comparison.

5. Conclusions and outlook

Researchers worldwide are continuously endeavoring to develop more efficient and techno-economic wastewater treatment options. Adsorption tops the list due to its simplicity and cost effectiveness. The use of locally-available wastes, especially bio-based materials, in the adsorption of pollutants from wastewater is one that carries dual benefits: waste management and water treatment. Additionally, both the water and the adsorbent could be reused.

Different pollutants can indeed be targeted for adsorptive removal from aqueous media due to the versatility of these sorbents. They can be used as dried biomass, carbonized and activated to increase efficiency. As shown in this review, numerous studies conducted in Africa and around the world have demonstrated their effective performance. Thus, the use of such sorbents is a viable alternative of special interest for emerging economies. This implies that in the future, most water treatment techniques will involve the use of these low-cost adsorbents.

It was observed that removing heavy metals using an adsorbent has attracted more studies from African scholars. However, other ubiquitous pollutants such as the persistent organic pollutant groups should also attract future studies due to their persistence in the African environment. As well, emerging pollutants such endocrine disruptors, pharmaceuticals, flame retardants, and algal toxins should receive more attention from African researchers especially with the increased detection of these contaminants in African wastewaters (Necibi et al, 2021). There seem to be paucity of data on the use of wastewater-based epidemiology (WBE) as an intelligence tool for surveillance of prohibited substances such as cocaine and anti-doping substances in Africa. The fate of such substances in WWTPs needs further research.

It is observed that most studies are done in laboratory-scale using batch mode experiments. In the future, more field pilot-scale experiments should be explored. Large-scale use of these sorbents should be the target of more research and funding. They should be piloted in industries to ascertain their efficiencies. The use of the column should also be considered more as there are fewer studies on the use of column membranes packed with waste-derived sorbents. Additionally, the cost of production of the adsorbents is rarely reported and their cost-effectiveness is assumed.

For further efficiency, hybrid methods of contaminant removal could be considered for multi-component systems. Since sorbents may not entirely remove some pollutants, more research should be geared to making a hybrid of adsorption and biodegradation or with the use of biofilms. This could lead to exciting results since those pollutants not removed by biodegradation will be eliminated through adsorption. The technicalities of such a process however may be costly. It is noted that a significant number of adsorption studies do not use environmentally relevant concentration of pollutants. Additionally, besides recycling of the adsorbent, disposal methods for the exhausted contaminant-laden adsorbent is hardly reported.

Furthermore, these studies in the future should focus on collaborating with government agencies concerned with water management so that the developed methods can be incorporated into wastewater treatment. For efficient biosorption in the future, proper plant design parameters should be modeled in such a way that they are fast, cost effective, and environmentally benign.

Finally, designing wastewater treatment plants to be aligned with sustainable development should take advantage of LCA methodology as a decision tool in designs especially in developing countries. The development of best practice guidelines and inclusion of advanced wastewater treatments for the removal of emerging contaminants should be looked into during the construction phase. Well-defined functional units would go a long way into improving the life cycle databases and the interpretation of the impacts on land use change and greenhouse gas emissions.

Declaration of Competing Interest

The authors declare that the present work has no conflict of interest of any kind, and is not being considered for publication elsewhere.

CRediT authorship contribution statement

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