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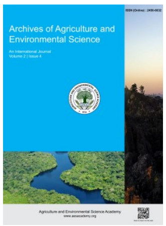

REVIEW ARTICLE

Potential of natural coagulants for bioremediation of persistent organic pollutants in wastewater in sub-Saharan Africa: A review

Ahimbisibwe Michael[1*], Ssebugere Patrick[2], Nagawa Christine Betty[3], Henry Matovu[4] Nakawuka Prossie[1], Kabenge Isa[1] and Ahamada Zziwa[1]

[1]Department of Agricultural and Biosystems Engineering, Makerere University, Kampala, UGANDA
[2]Department of Chemistry, Makerere University, P.O. Box 7062, Kampala, UGANDA
[3]Department of Forestry, Biodiversity and Tourism, College of Agricultural and Environmental Sciences, Makerere University, P.O. Box 7062, Kampala, UGANDA
[4]Department of Chemistry, Gulu University, P.O Box 166, Gulu, UGANDA
[*]Corresponding author's E-mail: turyamat@gmail.com

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ABSTRACT

Sub-Saharan Africa (SSA) is a significant user of pesticides, relying on agriculture for economic development. Pesticides and agrochemicals contribute to the presence of Persistent Organic Pollutants (POPs) in the environment. This review addresses knowledge gaps in monitoring and quantification of POPs, the application of natural coagulants for bioremediation, and associated environmental and health risks in SSA. Findings reveal inconsistencies in monitoring methods and analytes, hindering the identification of temporal trends. Legacy POPs show decreasing concentrations in soil/sediment and aquatic organisms, while some POPs increase in water, fish, fruits, and vegetables. Some river systems exceed acceptable ranges for PCBs according to USEPA standards. PFASs, particularly PFOA and PFOS, are prevalent. Natural coagulants, like Moringa oleifera and chitosan, are gaining popularity for water treatment due to their environmental sustainability and effectiveness in POP remediation. Trivalent cations in natural coagulants show promise for POP bioremediation. However, challenges remain in scaling up natural coagulant applications for commercial water treatment. This review highlights the need for standardized monitoring procedures and emphasizes the potential of natural coagulants in POP remediation efforts.

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INTRODUCTION

Water pollution from pesticides, metals, and persistent organic pollutants (POPs) poses major environmental and public health threats globally, particularly in Sub-Saharan Africa (SSA). Rapid industrialization, population growth, and inadequate waste management exacerbate these issues in SSA (Miglioranza *et al.*, 2021). Despite rich natural resources, SSA struggles with sustainable development due to poverty, limited investment in pollution prevention, and poor waste management infrastructure. Agricultural reliance adds to the problem, as agrochemicals contaminate water sources with POPs like polychlorinated biphenyls (PCBs) and dioxins, which are persistent, bio-accumulative, and harmful to health. Studies show higher POP contamination in urban and industrial areas than in rural settings. Wastewater from industrial discharges, agricultural runoff, and domestic sewage is a major pollution source, with inadequate treatment exacerbating the issue. Effective remediation is crucial to mitigate health risks. Conventional methods like coagulation-flocculation are used, but natural coagulants offer a safer, sustainable alternative due to their biodegradability, low toxicity, and pH compatibility (Alshemmari, 2022; Luzardo *et al.*, 2014). However, research on natural coagulants for POP removal in SSA is limited. This review addresses this gap by examining POP levels in SSA, bioremediation techniques, and the potential of natural coagulants, aiming to inform future research and policies to improve water quality and public health.

METHODOLOGY

The literature reviewed in the paper was obtained from various resourceful academic databases such as Web of Science, ACS Publications, Elsevier, Wiley, Taylor and Francis, Springer, ScienceDirect, Google Scholar, Access Science, ProQuest eBook Central, Government Documents, and Electronic Books. The relevant facts from all the platforms listed were obtained with key different search combinations (such as: "POPs, wastewater and in Sub Saharan Africa (SSA)", "challenges of POPs in SSA", "Bioremediation of POPs from wastewater, Application of Natural Coagulants, trends of POP bioremediation and environmental pollution control" etc.) while searching for relevant information. Any article during the process of the search was considered as a related document on the condition that it comes with the phrase "POPs" or "bioremediation", leaving out the remaining part of the title. Essentially, problems emanating from POPs in SSA, the benefits of Natural Coagulants, potential hazards associated with POPs, and bioremediation approaches were exhaustively studied. The articles explored in this study were from 2010 to December 2023. At the end of the search, more than 200 documents were evaluated in this review where the number of documents reviewed was about 220 exclusives of considering other references. By evaluating 220 published articles basically, the review presents a recent record to researchers, policymakers, academia, government, and nonprofit organization expansively.

Persistent Organic Pollutants (POPs) in Sub-Saharan African

The most commonly reported persistent organic pollutants (POPs) in wastewater from Sub-Saharan Africa (SSA) include organochlorine pesticides like DDT (Miglioranza *et al.*, 2021), industrial chemicals such as polychlorinated biphenyls (PCB) (Onu *et al.*, 2023), and by-products of industrial processes like dioxins (Ayele *et al.*, 2022; Chovancová *et al.*, 2014). Studies over the past five years show increased POP levels in the environment (Rivière *et al.*, 2014; Shin *et al.*, 2015; Kilunga *et al.*, 2017; Onu *et al.*, 2023; Vaccher *et al.*, 2020). Growing electronic waste and imports of second-hand electronics exacerbate POP pollution (Lin *et al.*, 2022; Tembhare *et al.*, 2022). E-waste significantly contributes to environmental contamination by PCBs, dioxins, and PAHs (Analysis *et al.*, 2012; Mansour, 2009; Miglioranza *et al.*, 2022; Wahlang, 2018). Contamination levels in SSA are comparable to or lower than those reported internationally (Alshemmari, 2022; Luzardo *et al.*, 2014; Fan *et al.*, 2021; Kim *et al.*, 2013; Kiviranta *et al.*, 2004; Shen *et al.*, 2012; Song & Li, 2014; Wei *et al.*, 2023).

The prevalent POPs in Africa include organochlorine pesticides (OCPs) like DDT, per- and polyfluoroalkyl substances (PFAs), PCBs, and polyaromatic hydrocarbons (PAHs), which are typically metabolized without bioaccumulation (Gaur *et al.*, 2018; Wenjing *et al.*, 2019). Remediation approaches vary by POP type, but some coagulants can address multiple organic pollutants (Gaur *et al.*, 2018). PFAS detection and sampling pose challenges due to adsorption and desorption issues (Dixit *et al.*, 2021), with polyethylene or polypropylene materials preferred for sample handling (Kidd *et al.*, 2022). Proper storage conditions are critical, with freezing at −20°C recommended (Coggan *et al.*, 2019; Woudneh *et al.*, 2019). Electrostatic and hydrophobic interactions primarily govern PFAS adsorption, influenced by molecular structure, adsorbent properties, and liquid phase composition (Cai *et al.*, 2022). Bioventing enhances the natural degradation of hydrocarbons and other pollutants by increasing oxygen flow into the soil (Marín-García *et al.*, 2023). This aerobic bioremediation process is the most common form of oxidative bioremediation (Marín-García *et al.*, 2023).

The Stockholm Convention on Persistent Organic Pollutants (POPs) since 2004 aims to regulate and phase out substances such as DDT, PCBs, and dioxins due to their persistent, bioaccumulative, and toxic nature (Mansour, 2009; Templeton, 2020). Recent amendments have expanded the list to include new chemicals, reflecting ongoing research findings on hazardous substances originating from human activities (Zhang *et al.*, 2022). Decabromodiphenyl ether (c-DecaBDE) and short-chain chlorinated paraffins were added in 2017, followed by perfluorooctanoic acid (PFOA) and its derivatives in 2019, and Perfluorohexane sulfonic acid (PFHxS) in 2023, among others (Sheriff *et al.*, 2022). In sub-Saharan Africa, limited adoption of Stockholm Convention recommendations is observed, with only a few countries implementing National Implementation Plans (NIPs) (Adebusuyi *et al.*, 2022). The convention classifies POPs into three categories - Elimination, Restriction, and Unintentional Production - to mitigate their adverse effects on humans and the environment. Initially, twelve POPs were listed, later expanded to twenty-eight at the 2019 Convention (Fiedler *et al.*, 2019). Innovation in the circular economy and bioremediation can aid in waste management and POP removal, offering sustainable solutions to pollution challenges.

POPs in water and wastewater across sub–Saharan Africa

Multiple studies have investigated the prevalence of Persistent Organic Pollutants (POPs) in water across West African nations (Rose *et al.*, 2012; Akoto *et al.*, 2016; Fosu-Mensah *et al.*, 2016; Essumang *et al.*, 2017; Unyimadu *et al.*, 2018). Perfluoroalkyl acids (PFAAs), resistant to water treatment, are among the most commonly detected POPs, particularly PFOA and PFOS in river and tap water (Essumang *et al.*, 2017). Nigeria experiences PCB contamination in the River Niger exceeding safety limits (Unyimadu *et al.*, 2018). Lake water studies in Ghana, Cameroon, and Nigeria reveal high POP levels within WHO and USEPA standards, though exceeding the EPA's allowable limits for drinking water (Adebusuyi *et al.*, 2022; Bruce-Vanderpuije *et al.*, 2019; EPA, 2022). West African countries, including Benin, Ghana, and Nigeria, have assessed PFAS prevalence in various mediums like food, water, and air (Vaccher *et al.*, 2020; Bruce-Vanderpuije *et al.*, 2019; Garrison *et al.*, 2014; Fång *et al.*, 2015;

Hierlmeier *et al*., 2022; Mansour, 2009; White *et al*., 2021). Studies in East Africa detect elevated POP levels in water from industrial zones and waste sites, with Uganda noting POP bioaccumulation in breast milk (Matovu *et al*., 2021). PFASs, synthetic organofluorine compounds, are found in numerous products, with PFOS and PFOA being predominant in Africa. South Africa reports POP presence in air, water, and sediments, with levels in some areas exceeding regulatory limits (Olisah *et al*., 2021). PFASs are also found in various consumer products across Africa (Arinaitwe *et al*., 2020; Bruce-Vanderpuije *et al*., 2019; Londhe *et al*., 2022; Shikuku *et al*., 2022). A review of wastewater streams in Africa identifies several common POPs, emphasizing the importance of robust regulation and waste management strategies (Arinaitwe *et al*., 2020; Bruce-Vanderpuije *et al*., 2019; Londhe *et al*., 2022; Shikuku *et al*., 2022).

Effects POPs of Human health

Humans encounter persistent organic pollutants (POPs) via multiple routes, primarily through food consumption and air inhalation, both indoors and outdoors (Guo *et al*., 2019; Wahlang, 2018). These chemicals, present in everyday products for various purposes like flame retardancy, are ubiquitous worldwide and bioaccumulate in organisms, with higher concentrations in those at the top of the food chain (Islam *et al*., 2018). Even low exposure levels can lead to adverse health effects, including cancer, reproductive disorders, immune system alterations, neurobehavioral impairments, and endocrine disruption (Encarnação *et al*., 2019).

Understanding the physical and chemical properties of per- and polyfluoroalkyl substances (PFAS) is vital for understanding their environmental behavior. PFAS are characterized by strong C–F bonds, granting them significant thermal stability, and exhibit hydrophobic and lyophobic properties due to the low polarizability of fluorine atoms (ITRC, 2017). Their chemical stability is further enhanced by terminal functional groups attached to the fluoroalkyl chain. PFAS become more chemically inert with longer carbon chains but more water-soluble with shorter ones. PFAS also resist thermal, biological, and chemical degradation and are widely used in various industries due to their stability and redox stability.

The adverse effects of POPs include cancer, reproductive impairments, skin issues, and memory loss (Mrema *et al*., 2013; Dhir, 2022; Dosis & Kamarianos, 2017). Water utilities may opt for biodegradable natural coagulants to reduce sludge production without increasing toxicity (Dorca-Preda *et al*., 2022). However, caution is needed as organic residues from natural coagulants could interact with disinfectants, potentially forming carcinogenic byproducts (Ahmed *et al*., 2016). Proper management of secondary waste from chemical-based processes is crucial for environmental sustainability (Figure 1).

Application of natural coagulants in POPs removal

Recently, natural or green coagulants have gained attention in SSA for water and wastewater treatment (Table 1). Unlike chemical coagulants, natural coagulants maintain water pH during sorption processes and do not add metals to effluents, resulting in lower sludge volume and disposal costs (Feria-Díaz *et al*., 2016; Sukmana *et al*., 2021). They are classified into plant-based and non-plant-based coagulants, with plant-based options being more affordable and widely studied (Ahmad *et al*., 2021; Speranza *et al*., 2022). Various natural coagulants, including Moringa seeds, algae, banana peel, and cassava peel starch, have shown promising results in water treatment (Akhter *et al*., 2021; Daverey *et al*., 2019; Asharuddin *et al*., 2019). Powdered forms are typically added directly to water or wastewater, with preparation methods varying based on their source (El Foulani *et al*., 2022; Gaur *et al*., 2018). Natural coagulants are renewable, non-toxic, biodegradable, and cost-effective, efficiently removing turbidity in water or wastewater with medium to high turbidity levels (Oladoja, Unuabonah, Amuda, *et al*., 2017; Dayarathne *et al*., 2022). They have been successfully applied in treating various wastewater types, including dairy, textile, and sugar industry effluents, and are recommended for eco-friendly and simplified wastewater treatment processes (George *et al*., 2016; Owas, 2017; Pambi & Musonge, 2016).

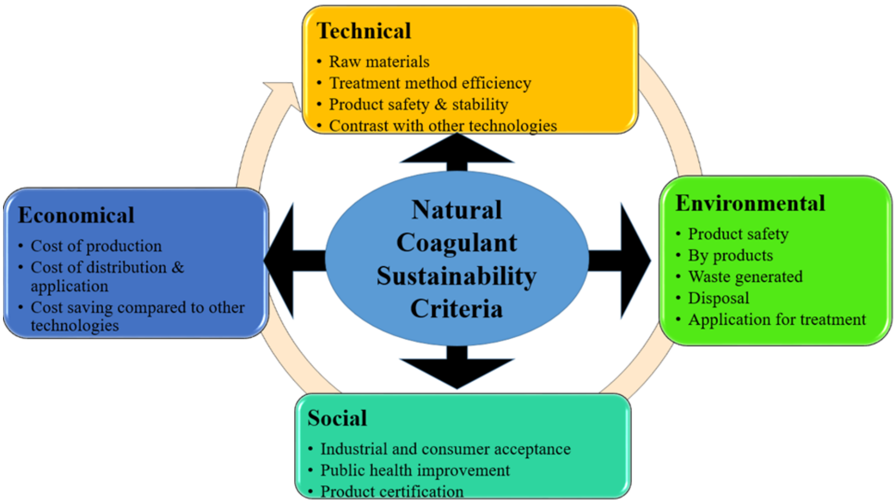

Figure 1. *The economic, environmental, technical and social factors influencing the sustainability and application of Natural coagulants.*

Plant-based coagulants

The recent surge in utilizing natural or green coagulants for water and wastewater treatment in Sub-Saharan Africa (SSA) has garnered considerable interest. These coagulants, notably plant-based ones, maintain water alkalinity and pH during sorption, unlike their chemical counterparts (Feria-Díaz *et al.*, 2016; Sukmana *et al.*, 2021). Derived from diverse sources such as Moringa seeds, algae, and banana peel, they offer affordability and effectiveness (Ahmad *et al.*, 2021; Daverey *et al.*, 2019; Sibartie & Ismail, 2018). Commonly added in powder form, their preparation methods vary based on the source material (El Foulani *et al.*, 2022; Ibrahim *et al.*, 2021). These coagulants boast renewability, non-toxicity, and biodegradability, proving efficient in turbidity removal and cost-effectiveness (Oladoja *et al.*, 2017). Their application spans various wastewater treatment contexts, effectively reducing parameters like turbidity, COD, and salinity, thus offering a sustainable, eco-friendly solution for wastewater treatment in the region (George *et al.*, 2016; Owas, 2017; Pritchard *et al.*, 2009; Parmar *et al.*, 2012).

Moringa oleifera

Moringa oleifera (MO), a fast-growing, drought-resistant tree native to the Indian subcontinent, holds promise beyond its culinary and medicinal uses, particularly in water purification (Putra *et al.*, 2021). Widely cultivated for its seed pods and leaves, MO presents opportunities for improving nutrition, food security, rural development, and sustainable land management in developing countries (Gopalakrishnan *et al.*, 2016; Razis *et al.*, 2014; Khan *et al.*, 2023; Ogbuagu *et al.*, 2014). Utilizing Moringa seed cake, a byproduct of seed oil extraction, for water filtration via flocculation has shown efficacy in producing potable water for both humans and animals (Aboamer *et al.*, 2020; El-Hadidy *et al.*, 2022; Emmanuel & Zaku, 2011). The proteins present in Moringa seeds act as effective coagulants, neutralizing colloidal charges in turbid water and facilitating impurity removal through settling or filtration (Ndabigengesere *et al.*, 1995; Shebek *et al.*, 2015). This method proves particularly valuable in regions like South Africa and Namibia, where water pollutants pose significant challenges (Mashamaite *et al.*, 2021; Haiyambo *et al.*, 2016; Traore *et al.*, 2022). The widespread use of *Moringa oleifera* seed, leaves, and extracts in water purification has been extensively documented, with MOCP playing a crucial role in coagulation by attracting impurities and aiding in their separation from water (Nhut *et al.*, 2021; Bhatt *et al.*, 2023; Ghebremichael *et al.*, 2005; Ahmad *et al.*, 2021; Varkey, 2020). As a result, sedimentation of suspended particles occurs, followed by filtration to obtain clear water (Varkey, 2020).

Moringa seed extraction dynamics

The extraction process of Moringa for coagulation-flocculation and sedimentation begins with seed powder production, achieved through various instruments like pestles, grinders, mixers, and blenders (Braham *et al.*, 2022; Ibrahim *et al.*, 2021; Soo *et al.*, 2021). Coagulation's mechanism relies on electrostatic forces between colloidal particle charges. Initial Moringa seed processing involves different methods and solvents, with sun-dried or oven-dried fully mature Moringa being preferred (Braham *et al.*, 2022; Ibrahim *et al.*, 2021; Soo *et al.*, 2021). Particle size reduction, typically using pestles and grinders, is critical for enhancing coagulation efficiency by increasing the surface area for sorption (Shen & Zhu, 2016).

Challenges in Moringa application and extraction stem from plant tissue and coagulating agents in the powder, rich in organic constituents, which can elevate organic loads in treated water (Dara, 2017; Elsergany, 2023). Elevated organic loads may reduce treatment efficiency, emphasizing the need to optimize coagulant combinations (Bhuptawat *et al.*, 2007; Gandiwa *et al.*, 2020; Shebek *et al.*, 2015). Post-treatment, an increase in dissolved organic carbon (DOC) can alter water color, odor, and taste (Bopape-Mabapa *et al.*, 2020; Bopape-Mabapa *et al.*, 2020a). Purifying Moringa seeds from active proteins is recommended to reduce organic matter, a precursor to chlorination by -products during disinfection (Díaz *et al.*, 2020) (Figure 2). Extraction methods aiming for higher protein content can decrease residual organic compounds, indicators of methanolic extract (MOE) disinfection by-products (Albasher *et al.*, 2020). Shorter extraction times are advised to minimize organic material deposition from *Moringa oleifera* seeds (Ghebremichael *et al.*, 2005). Comparing water-based and salt-based extractions, salt solution extraction results in better coagulant properties due to increased ionic strength and solubility of active ingredients (Du *et al.*, 2022; Megersa *et al.*, 2019).

Moringa seed protein for coagulation and flocculation

Moringa oleifera, a natural polymer rich in cationic proteins, effectively removes organic pollutants and suspended impurities from water through coagulation, aggregation, and precipitation processes (Nordmark *et al.*, 2016; Ngounouno *et al.*, 2021; Rajalingam *et al.*, 2021; Tsaknis *et al.*, 1998) (Table 2 and 3). These proteins play a key role in coagulation and flocculation (Okuda *et al.*, 2001; Sciban *et al.*, 2009; Baptista *et al.*, 2017). The coagulant properties of mature Moringa seeds are attributed to cationic and water-soluble proteins, with enhanced efficacy through cation addition (Azoulay *et al.*, 2023). Processing methods vary, employing solvents like water, NaCl, KCl, hexane, or ethanol, with extraction conditions tailored to water source and impurities (Fahey *et al.*, 2002; Bichi, 2013). Moringa seeds, harvested optimally during the dry season, exhibit fluctuating protein content and coagulation potential influenced by environmental factors (Fahey *et al.*, 2002). Compared to other natural coagulants, *Moringa oleifera* seeds offer efficient, eco-friendly, low-cost options (Megersa *et al.*, 2019; Katayon *et al.*, 2006). Specific peptides from Moringa seeds aid sedimentation of suspended particles and possess antibacterial properties (Noumi & Manga, 2011). Oladoja & Pan demonstrated the effectiveness of Moringa seeds with reduced oil content as coagulants in water treatment, suggesting oil extraction is unnecessary for coagulation processes (Oladoja & Pan, 2015). To address increased COD and nutrients, purified protein application is recommended over crude water extract (Soin & Gupta, 2020).

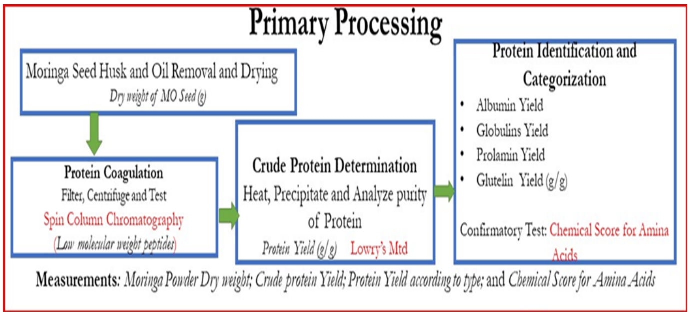

Figure 2. *Moringa Seed primary processing for Protein fraction extraction.*

The potential of Cactus in water treatment

Cactus, a member of the Cactaceae family, specifically *Opuntia ficus-indica*, is traditionally valued for its edible fruit and pads. Recent studies highlight its efficacy in water purification through various methods, including direct application, powder extraction, and sap addition. Cactus has demonstrated the ability to remove up to 98% of bacteria within 15 minutes by aggregating contaminants into filterable flocs (Table 4). Additionally, it shows promise in sedimentation processes, effectively reducing bacterial content, such as *Bacillus cereus*. Utilizing cactus as a coagulant or flocculant involves extracting its inner gum, which, when mixed with water, facilitates the settlement of bacteria and sediments, resulting in contaminant removal. Boiling cactus slices with water is another effective method, offering a simple and affordable approach to water purification where other technologies are unavailable. In wastewater treatment, cactus-based solutions have shown efficacy in reducing turbidity, chemical oxygen demand (COD), and biological oxygen demand (BOD) (Megersa *et al*., 2019; Katayon *et al*., 2006). By enhancing aggregation and settling properties, cactus-based coagulants and flocculants aid in the removal of various pollutants, including oil, grease, fats, proteins, and suspended solids. Combining aluminum salts with natural polyelectrolytes from cactus has resulted in significant pollutant removal percentages, demonstrating its potential for treating diverse effluents. From domestic to industrial wastewater, cactus-based treatments have proven effective across different applications. Optimization of preparation methods and dosage ensures enhanced efficiency, making cactus a promising candidate for eco-friendly water treatment solutions (Azoulay *et al*., 2023). Cactus, particularly Opuntia ficus-indica, has been historically significant as a food source, with both its fruit (tuna) and pads (nopal) consumed (Humphries *et al*., 2022; Novoa *et al*., 2015). Certain cactus species contain psychoactive compounds (Novoa *et al*., 2015). Studies demonstrate cactus's efficacy in improving water quality through various methods like direct immersion, powder extraction, or sap addition, with the potential to eliminate up to 98% of bacteria within 15 minutes (Beyene *et al*., 2016; Cordova-Torres *et al*., 2022; Deshmukh *et al*., 2018; Kalibbala *et al*., 2023; Lopez *et al*., 2011). Cactus acts as a flocculant, settling bacteria and sediments, achieving a 98% contaminant removal rate (Rebah & Siddeeg, 2017). It offers a cost-effective water purification method (Gebrekidan *et al*., 2013). In wastewater treatment, cactus effectively reduces turbidity, COD, and BOD levels (Amari *et al*., 2019). The combination of cactus-derived coagulants and aluminum salts facilitates the removal of contaminants (Al-Saati *et al*., 2016). Cactus has been successfully applied in treating various wastewater types (Cordova-Torres *et al*., 2017). Detailed methods and optimal conditions for cactus application are provided (M. T. F. de Souza *et al*., 2016; DR.T. Kannadasan, 2013; Vishali & Karthikeyan, 2015; Costa *et al*., 2012).

Application of Clearing-nut/ nirmali tree

The application of the Clearing-nut or Nirmali tree (*Strychnos potatorum*) in water treatment within Sub-Saharan Africa has garnered significant attention due to its effectiveness as a natural coagulant (Novoa *et al*., 2015). *S. potatorum* seeds contain bioactive compounds, particularly polysaccharides and proteins, which facilitate the coagulation and flocculation of suspended particles in water. These seeds, when processed and applied correctly, can enhance water quality by reducing turbidity, color, and microbial load. Studies have demonstrated that the coagulant properties of Nirmali seeds are comparable to conventional chemical coagulants like alum, but with the added benefit of being environmentally friendly and sustainable (Jahn, 1988; Tripathi *et al*., 1976). The process typically involves drying and pulverizing the seeds to a fine powder, which is then added to contaminated water. The active agents in the seeds neutralize the charges on suspended particles, leading to their aggregation and subsequent removal through sedimentation or filtration (M. T. F. de Souza *et al*., 2016; DR.T.Kannadasan, 2013; Vishali & Karthikeyan, 2015).

In Sub-Saharan Africa, the use of Nirmali seeds for water treatment is particularly advantageous due to the local availability of the tree and the low-cost nature of the treatment process. Research conducted in various countries within the region has shown promising results in using Nirmali seeds for treating both drinking water and wastewater. For instance, studies in Ethiopia and Kenya have highlighted the potential of Nirmali seeds in improving water quality in rural areas where access to conventional water treatment facilities is limited (Beyene *et al* ., 2016; Cordova-Torres *et al*., 2022; Deshmukh *et al*., 2018; Kalibbala *et al*., 2023). The ease of use and the non-toxic nature of the seeds make them an ideal candidate for community-based water treatment solutions. However, challenges such as the need for standardized processing methods, seed supply consistency, and public awareness about the benefits and use of Nirmali seeds remain. Further research is needed to optimize extraction techniques, determine appropriate dosages for different water qualities, and integrate Nirmali-based treatments with existing water management practices in the region (Gebrekidan *et al*., 2013). Continued collaboration between researchers, policymakers, and local communities will be crucial in scaling up the use of Nirmali seeds for sustainable water treatment in Sub-Saharan Africa.

Table 1. Natural coagulants and their application forms for water and wastewater treatment source.

Natural coagulant	Application form	Reference
Moringa oleifera	Seed paste	(Zaki & Rady, 2015)
	Press cake (solid)	(Kapse & Samadder, 2021)
	Powder (leaf/seed/back)	(Gollapudi *et al*., 2017)
Chitosan	Powder	(Szymonowicz *et al*., 2017)
	Stock Solution (0.1 M HCl)	(Bratskaya *et al*., 2004)
	Solution (1% acetic acid)	(Bratskaya *et al*., 2004)
	Stock Solution (0.1 HCl and distilled water)	
Rice Starch	Starch solution	(Teh *et al*., 2014)
Jatropha curcas	Press cake (solid)	(Abidin *et al*., 2011)
Watermelon seeds	Oil-free powder	(I. M. Muhammad *et al*., 2015)
Banana pith	Powder	(Kakoi *et al*., 2016)
Ocimum basilicum	Mucilage	(Ekren *et al*., 2012)
Cactus (*Opuntia ficus-indica*)	Powder	(Nharingo & Moyo, 2016)
	Inner gum	(Kalibbala *et al*., 2023)
Clearing-Nut Tree (*Strychnos potatorum*)		(Gandhi & Sekhar, 2014)

Table 2. *Moringa oleifera* coagulation performance for different water and wastewater parameters.

Type of water/pollutant treated with MO	*Moringa oleifera* removal efficiencies						Reference
	Color	Turbidity	COD	BOD	pH	Total dissolved Oxygen	
Municipal wastewater		94.44%	68.72%	57.61%	7.26	57.61%	(Culver *et al*., 2012)
Domestic wastewater	70.9%	85.1%			7.86	55.9%	(Buscio *et al*., 2016)
Urban wastewater		62%	71%	85%	7.01		(L. Shen & Zhu, 2016)
Urban wastewater			64%			59.9%	(Bhuptawat *et al*., 2007)
Bath wastewater (greywater)	75.64%	98.14%	43.11%	88%	7.66		(Freytez *et al*., 2019)
Dairy industry wastewater	53%	60%	11%	60.17	7–9		(Formentini-Schmitt *et al*., 2013)
Wastewater of dairy cattle		44.60%	43.38%		4.0–5	57.7%	(P. Díaz *et al*., 2021)
Slaughterhouse wastewater			64%		9		(Artuch-Garde *et al*., 2017)
Coffee Wastewater		56.6%	1–25%	79.0%	3–7 5		(Pomba *et al*., 2017)
Palm oil mill effluent		95%	52.2%			55.9%	(Bhatia *et al*., 2007)
Hospital wastewater		60.12%	86.11%		7		(Soin & Gupta, 2020)
Raw water		82.53%		42.53%	7.91	56.8%	(Soin & Gupta, 2020)

Chitosan

Chitosan, a naturally occurring biodegradable and biocompatible polysaccharide, is derived through the deacetylation process of chitin, a polysaccharide abundantly present in the exoskeletons of crustaceans and insects (M, 2017). Its industrial-scale production is achieved through the alkaline deacetylation of chitin, which stands as one of nature's most prevalent biopolymers (Inamdar & Mourya, 2010). Chitosan and its derivatives are favored as flocculants in water treatment due to their wide availability, eco-friendliness, biodegradability, and distinctive structural attributes. The material's versatility enables its utilization in various forms, ranging from water-soluble to solid forms, gels, fibers, and hollow fibers tailored for polymer-enhanced ultrafiltration and sorption processes (Zubareva *et al*., 2011). Despite its advantages, chitosan faces limitations that impede its optimal utilization, including inert chemical properties and poor solubility in neutral or alkaline aqueous solutions (Muzzarelli & Muzzarelli, 2005) (Van den Broek & Boeriu, 2019). Chitosan exhibits the capability to coagulate various molecules through chelation, where different ions are adsorbed onto the amine groups of chitosan in near-neutral solutions. In the case of metal anions, sorption occurs via electrostatic attraction to protonated amine groups in acidic solutions. The sorption performance is intricately governed by additional structural parameters of the polymer, such as the degree of deacetylation and crystallinity, which regulate the swelling and diffusion properties of chitosan (Iber *et al*., 2022; Ul-Islam *et al*., 2023; R. Zhang & Tian, 2020).

Gelatin

Gelatin stands out as another frequently utilized animal-based coagulant/flocculant in industrial wastewater treatment (Badawi *et al*., 2023). Sourced from animal by-products like bones and hides, gelatin emerges as a by-product of the meat industry, thus contributing to waste reduction and aligning with sustainability objectives in water treatment (Hameed *et al*., 2018). Derived from collagen present in animal connective tissues, gelatin proves highly effective in water purification owing to its capacity to form a gel-like substance that facilitates the aggregation and settling of suspended particles (Mahmoud, 2015). In water treatment applications, gelatin finds common use in clarifying turbid water by fostering the formation of flocs,

Table 3. Performance of different extraction solvents and media.

Role of moringa treatment process	Seed processing	Extraction Solvent	Optimal conditions	Extraction time	Reference
Coagulant		With tap water	2 g/L	Rapid 100 rpm for 1 min, Slow 25 rpm for 20 min, Settling for 30 min	(Alo *et al.*, 2012)
Coagulant	Drying, sieving and Extraction with Distilled water	Distilled water	250 mg/L		(E, 2014; Madrona *et al.*, 2012; Subramanium *et al.*, 2011)
Coagulant		Salt NaCl (1 M)	2 g/L	rapid 160 rpm for 30s and settling for 2hrs	(Oria-Usifo, 2014; Yahaya *et al.*, 2011)
Coagulant		Ethanol		30–45 min	(Kini *et al.*, 2017)
Coagulant	Peeling manually, Drying, Grinding, Sieving (0.5 mm) Drying of cake at 50 °C	Hexane	150 mg/L	45min	(Fuglie, 2000)
Coagulant		KCl(1M) or $Ca(OH)_2$ (0.011 M))	2 g/L	Slow 15 rpm for 15 min, Settling for 2 h	(L. Shen & Zhu, 2016)
Flocculant	Grounding, Sieving with 600µm and Extraction	Distilled water	2 g/100 Ml	Rapid 100 rpm for 2 min, Slow 20 rpm for 10 min, Settling for 30 min	(Bhuptawat *et al.*, 2007)
Coagulant	Grinding of MO seeds, extraction and Filtering	KCl (1M)	3000 mg/L	Rapid 100 rpm for 2 minSlow 20 rpm for 10 min,Settling time of 60 min	(dos Santos *et al.*, 2017)
Coagulant	Dehulling, Drying at 45 °C for 24 h, Grinding and then Extraction	Water 50 g of seeds in 1 L of water	60 mL/L	Manual Mixing for 10min	(J. J. F. Díaz *et al.*, 2020)
Coagulant	Drying, Deshelled by hand, Grinding, Sieving with 0.51 mm		7 g/L	Manual Mixing for 20 min	(Artuch-Garde *et al.*, 2017)
Coagulant	Peeling, Crushing to a coarse powder. Extraction and then Filtering by cheesecloth	Distilled water.	Dose (0–4) g/L	Slow 20 rpm for 10 min, Settling time of 60 min	(Artuch-Garde *et al.*, 2017)
Coagulant	Drying, Peeling manually, Extraction and Filtration with muslin cloth	n-Hexane (96%) with Distilled water5% (w/v)	6000 mg/L	Rapid 150 rpm for 5 min slow 30 rpm for 30 min Settling time of 90 min	(Bhatia *et al.*, 2007)
Coagulant	Drying, Ground coagulant, extraction and then Vacuum filtering	(integral, mechanical, Hexane, Ethanol), Extraction with (NaCl1M)	13.78 mg/L	Rapid 100 rpm for 3 min.Slow 15 rpm for 15 min. Settling for 30 min.	(Soin & Gupta, 2020)
Coagulant	Drying, Crushing, Extraction, Filtration	Hexane and NaCl 1 M,	320 mg/L MOP ratio of 0.54and aluminum dosage in MOP-PACl coagulant of 4.32 mg/L	Rapid 200 rpm for 3 min.Slow 45 rpm for 30 min.Settling for 1 h.	(Soin & Gupta, 2020)

which encapsulate impurities and streamline their removal through sedimentation or filtration (Harguindeguy *et al.*, 2021). This natural coagulant is prized for its biodegradability and minimal environmental footprint, rendering it a sustainable option for specific water treatment scenarios. The protein structure of gelatin, derived from collagen, comprises amino acids with charged groups capable of attracting and binding with both positively and negatively charged particles in water (Thakur *et al.*, 2017). Gelatin molecules adsorb onto the surface of suspended particles, establishing bridges between them. This process neutralizes the repulsive forces between particles, allowing them to draw closer and form larger aggregates (Shi *et al.*, 2021). In the water treatment process, the formation of stable flocs by gelatin provides a scaffold for particles to adhere to one another. These larger and denser flocs facilitate their settling or filtration, thereby aiding in the removal of impurities from water. An exceptional advantage of gelatin lies in its biodegradability—a natural and eco-friendly attribute that sets it apart. Unlike certain synthetic coagulants, gelatin undergoes natural decomposition over time, minimizing its long-term environmental impact (Silva *et al.*, 2009).

Performance comparison for chemical and natural coagulant in SSA

The transition from chemical to natural coagulants in Sub-Saharan Africa (SSA) represents a critical step towards sustainable water treatment technology, reducing health risks, and mitigating environmental pollution (Rebah & Siddeeg, 2017). Natural coagulants, sourced from plants or animals, were historically used before the advent of chemical coagulants. However, their application declined with the development of chemical

Table 4. Comparison of the preparation and optimal conditions for applying Cactus in water treatment.

Effluents	**Cactus preparation**	**Optimal conditions**	**Removal efficiencies (%)**	**Reference**
Jeans laundry effluent : - COD =1094.20 mg/L - Turbidity = 104 FTU	Extraction from *O. ficusindica* using NaCl	Cactus extract at 2.60 mg/L and pH 5 used with floculant (FeCl3) at 160 mg/ L and pH 5	COD:64.8 Turbidity: 1.25	(T. C. De Souza *et al.*, 2017)
Fabric dyeing mesh effluent : - COD = 1264 mg/ L - Turbidity = 31.5 FTU	Extraction from *O. ficusindica* using NaCl	Cactus extract at 160 mg/ L and pH 6 used with floculant (FeCl3) at 640 mg/ L and pH 6	COD:87.19 Turbidity: 3.61	(T. C. De Souza *et al.*, 2017)
Dye industry effluent: - Turbidity : 2250 ppm - pH 9.23	Coagulant: catcus (Opuntia) powder, dried under sunlight and then at 800°C for 6 hours.	2 g/L at pH 8	Turbidity : 80-85	(DR.T. Kannadasan, 2013)
Tannery wastewater - BOD : 933.33 mg/L - COD : 1400 mg/L - Sulfate : 135.19 mg/L	Cactus dried and grinded	6 mg/L at pH 7.9	COD :70 BOD: 70 Sulphate 90	(Swathi *et al.*, 2014)
Simulated industrial paint effluent : - pH: 7.6 - Colour : 0.4583 - COD : 7693 mg/L - Turbity : 7760 NTU	Cactus (*O. ficusindica*) dried at 100°C for 2 h, powdered and sieved through a 0.2-mm sieve. The coagulant was extracted using 3N NaCl	3 g/L at pH 7.2–7.8	Colour:88.37 COD:78.20 Turbidity: 82.60	(Vishali & Karthikeyan, 2015)
Tannery effluent: - COD :8000-180000 mg/L - pH 5.5	Dry Opuntia (60 °C for 24 h) powder grinded and sieved to get particles size of 600 µm	0.2 mg cactus/500 mL and pH 5.5.	Turbidity: 8.54 COD : 80.65	(Kazi *et al.*, 2013)
Textile effluent : - COD : 2350 mg/L - Turbidity : 38 NTU - Abs at 630 nm : 10.67	Mucilage of O. ficusindica : washed with distilled water and sun dried for 3h, cutted into small pieces, then powdered and dried at 60°C for 24h	Mucilage as flocculent at 40 mg/L combined with coagulant ($Al_2(SO4)_3$)	Colour: 99.84 COD : 88.76 Turbidity : 91.66	(Bouatay & Mhenni, 2014)
Poultry slaughterhouse effluent: -pH: 6.6 – 7.4; - Suspended solid (SS): 623- 2027 mg/L -COD: 992-3350 mg/L - Oil and grease : 210- 1746 mg/L	Extraction of viscous natural polyelectrolytes from *O. ficusindica* by maceration in water (32 g of cactus in 750 ml H_2O_2)	Aluminium salt (300- 600 mg/L) combined with cactus ployelectrolyte (0.6 – 0.8 mg/L at pH : 6-7)	COD : 86 SS: 93 Oil and grease : 93	(Ikeda *et al.*, 2002)
Municipal effluent : - Turbidity : 453 NTU -COD : 827 mg/L	Mucilage of cactus cladodes separated using a rough sieve.	50 mg/L at pH 10	COD : 65	(Cordova-Torres *et al.*, 2017)
Food industry effluent : -pH: 4.94; -SS: 230mg/L -COD 2376 mg/L	Crude cactus juice ground with a grinder and filtered	Cactus as floculant at dose of 0.056 g/L, pH 3.92; used with alum at 4 g/L	SS: 88.7 COD : 69.1	(Sellami *et al.*, 2014)
Glue industry effluent : - pH: 6.7; - SS: 270 mg/L - COD 99200 mg/L	Flocculant: crude cactus juice ground with a grinder and filtered	Cactus as floculant at dose of 0.616 g/L, pH 4.21; used with alum at 5 g/L	SS: 83.3 COD : 59.1	(Sellami *et al.*, 2014)
Leachate from controlled discharge: -COD :92 g/L, -SS :0.37 g/L -pH : 9.97	Flocculant: crude cactus juice ground with a grinder and filtered	0.081 g/L	COD : 88 SS : 91	(Khadhraoui *et al.*, 2019)
Leachate from controlled discharge : -COD :92 g/L, -SS :0.37 g/L -pH : 9.97	Flocculant : dried cactus juice at 60°C	0.180g/L	COD : 82 SS : 85	(Khadhraoui *et al.*, 2019)
Petrochemical effluent - COD : 45 g/L, - SS: 0.29 g/L - pH : 9.23	Flocculant: crude cactus juice round with a grinder and filtered	0.081 g/L	COD : 72 SS : 85	(Khadhraoui *et al.*, 2019)
Petro-chemical effluent: - COD : 45 g/L, -SS: 0.29 g/L - pH : 9.23	Flocculant: dried cactus juice at 60°C	0.180g/L	COD : 69 SS : 75	(Khadhraoui *et al.*, 2019)
Municipal effluent: -COD: 725-1325 mg/L.	Opuntia mucilage		COD : 44.2-44.4	(Carpinteyro-urban *et al.*, 2013)
Cosmetic industrial effluent: -COD: 16700 mg/L - Turbidity 3390 NTU - pH: 5.6.	Mucilage obtained by boiling small pieces of cladodes.	21.1 mg COD/mg polymer pH 5.6.	Turbidity : 67.8 COD : 38.6	(Carpinteyro-urban *et al.*, 2013)

alternatives (M. Bopape-Mabapa *et al.*, 2020; Wahlang, 2018). The recent interest in green water treatment technology and environmental concerns related to chemical coagulants has renewed the focus on natural coagulants. Table 5 outlines the criteria for choosing between natural and chemical coagulants, considering specific water treatment goals, local conditions, and environmental impacts. Natural coagulants offer sustainability benefits (W. L. Ang & Mohammad, 2020), but chemical coagulants may provide more consistent and cost-effective performance in certain scenarios. The selection must be based on a comprehensive assessment of specific water treatment requirements (Table 5). Studies have shown that natural coagulants can be competitive in pollutant removal efficiency (Kumar & Quaff, 2019). For example, a study found that combining alum and banana peels achieved 94% turbidity removal, compared to 73.1% and 65.6% for alum and banana peels alone, respectively (Boulaadjoul *et al.*, 2018). Despite the limited application of natural coagulants for emerging pollutants, the available data indicates a promising future for bio-coagulants (Daci-Ajvazi *et al.*, 2016; del Real-Olvera *et al.*, 2016; Garika *et al.*, 2022; Lee *et al.*, 2023). Advantages of natural coagulants include lower required dosages, less sludge production, and low/no toxicity (del Real-Olvera *et al.*, 2016). However, transitioning from chemical to natural coagulants for persistent organic pollutants (POPs) remediation requires further research to develop reliable extraction methods, establish new natural sources, determine optimal conditions for POP removal, and evaluate environmental parameters (Boulaadjoul *et al.*, 2018).

Various natural coagulants have been explored for removing heavy metals, turbidity, pathogens, and other contaminants from water. Studies indicate that plant-based extracts can replace chemical coagulants effectively (Nonfodji *et al.*, 2020; Perumal *et al.*, 2021; T. H. Ang *et al.*, 2020). For instance, fenugreek seed extracts achieved up to 98% turbidity removal compared to 85% for alum (T. H. Ang *et al.*, 2020). Natural coagulants produce less sludge, reducing environmental impact and handling costs, and are less toxic, posing no significant environmental threats (Dotto *et al.*, 2019). In a study, natural coagulants such as *Moringa oleifera*, Pinus halepensis seeds, Opuntia ficus indica, and Algerian Aloe vera produced significantly lower sludge volumes compared to ferric chloride and alum (Hadadi *et al.*, 2022). Cost analyses in India showed that natural coagulants had lower operating costs than alum (Thirugnanasambandham & Karri, 2021). Despite these advantages, the acceptance of natural coagulants in water and wastewater treatment plants remains low due to concerns about efficiency and consistency (W. L. Ang & Mohammad, 2020). Plant-based coagulants require processing before use, unlike readily available chemical coagulants (Ali *et al.*, 2010; Azhar Abd Wahid *et al.*, 2016). Simplifying extraction processes and improving storage longevity are crucial for practical applications (Kurniawan *et al.*, 2020). Additionally, competing uses for natural coagulant resources, such as food and medicine, may impact their availability for water treatment (Kurniawan *et al.*, 2020). Large-scale commercial application may require large plantations to ensure a steady supply. Some natural coagulants are effective for high turbidity but less so for low turbidity water (Asrafuzzaman *et al.*, 2011). Industrial confidence in natural coagulants is limited due to performance consistency concerns for large-scale water treatment (W. L. Ang & Mohammad, 2020). Lab-scale studies dominate the performance data, with limited industrial application (W. L. Ang & Mohammad, 2020). Addressing the challenges of natural coagulant degradation, consistent supply, and commercial viability is essential for broader adoption. Future research should focus on processing improvements, adding preservatives, and ensuring long-term storage stability to enhance the use of natural coagulants in water treatment (Abidin *et al.*, 2011; Hoong & Ismail, 2018).

Table 5. Comparison of the performance of natural-based coagulants and chemical-based coagulants in water treatment across some key factors.

Attribute	Natural coagulant	Chemical coagulants	Reference
Effectives	Natural coagulants, such as chitosan, tannins, and gelatin, can be effective in destabilizing and aggregating suspended particles, leading to the formation of larger flocs for easier removal.	Chemical coagulants like aluminum sulfate (alum) and ferric chloride are often highly effective due to their strong charge neutralization and bridging capabilities, resulting in efficient particle removal.	(Koul *et al.*, 2022)
Application Flexibility	Natural coagulants may exhibit variability in performance depending on factors like water quality and pH. They may be more suitable for specific applications and may require adjustment of dosage based on water	Chemical coagulants usually offer more predictable performance across a wide range of water conditions, providing greater flexibility in application.	(Abujazar *et al.*, 2022; Alazaiza, Albahnasawi, Ali, *et al.*, 2022; Nimesha *et al.*, 2022)
Cost	In some cases, natural coagulants can be more expensive than chemical alternatives. However, cost-effectiveness may vary based on factors like local availability of raw materials and the specific water treatment requirements.	Chemical coagulants are often more cost-effective due to their widespread production and availability. They may be preferred in large-scale water treatment plants.	(Alazaiza, Albahnasawi, Ali, *et al.*, 2022; Bahrodin *et al.*, 2021; Mohd-Salleh *et al.*, 2019)
Environmental Impact	Natural coagulants are generally considered environmentally friendly and biodegradable. Their use aligns with sustainable practices and can contribute to reducing the environmental footprint of water treatment processes.	Chemical coagulants, especially those containing metals like aluminum, may pose environmental concerns if not properly managed. Residual chemicals in treated water may require additional processes for removal.	(A. Ahmad *et al.*, 2022; El-taweel *et al.*, 2023)
Residuals and By-products	Natural coagulants often produce fewer harmful residuals and by-products compared to chemical alternatives, contributing to the overall safety of the treated water.	Some chemical coagulants may leave residual elements in the treated water, and their presence needs careful monitoring to ensure compliance with regulatory standards.	(A. Ahmad *et al.*, 2022; Gautam & Saini, 2020; Othmani, Rasteiro, *et al.*, 2020)

Bioremediation of POPs in SSA

Bioremediation utilizes living organisms to degrade organic contaminants in soil, groundwater, sludge, and solids. These organisms break down contaminants either by using them as an energy source or metabolizing them with an energy source. They also facilitate adsorption, coagulation, or complex formation, leading to precipitation and filtration. These techniques effectively remove agricultural chemicals leaching into groundwater and subsurface environments. In water treatment, bioremediation can eliminate toxic metals and oxides such as selenium and arsenic compounds (Vaxevanidou *et al* ., 2008). Advanced testing methods like colorimetric comparison, photometric test kits, or spectrophotometers measure contaminant concentrations in water (Barreto *et al*., 2022). Water quality assessment considers dissolved oxygen, turbidity, bio-indicators, nitrates, pH, and temperature (Olajuyigbe *et al*., 2020). In water treatment, natural coagulants represent an eco-friendly and sustainable approach to mitigating water pollution, with natural coagulants like chitosan, tannins, and plant-based extracts playing a dual role in water treatment and bioremediation. For instance, cassava peel has been tested for treating mine water in Mozambique (Pondja Jr. *et al*., 2017). Natural coagulants exhibit coagulation and flocculation properties, aiding in removing suspended particles and impurities from water (Shah, 2018). Evaluating their bioremediation potential requires considering their role beyond treatment processes and their ability to assist in forming larger flocs (Conventions *et al*., 2017).

Bioremediation involves microorganisms or biological agents to degrade or neutralize pollutants in water. Natural coagulants can serve as substrates for microbial activity, with microorganisms utilizing the organic components of these coagulants as nutrients, facilitating pollutant breakdown (Alegbeleye *et al*., 2017). The biodegradability of natural coagulants reduces chemical residues in treated water, minimizing environmental impact and aligning with sustainable water treatment practices (Oladoja, Unuabonah, Amuda *et al*., 2017). Combining coagulation, flocculation, and bioremediation highlights the potential of natural coagulants in promoting a holistic and environmentally friendly approach to water treatment. This integrated approach enhances water quality through particle removal and supports natural processes contributing to pollutant remediation in aquatic ecosystems (Oladoja, Unuabonah, Amuda *et al*., 2017).

Bioremediation also offers a sustainable opportunity for remediating persistent organic pollutants (POPs). Techniques like biostimulation, bioattenuation, and biosparging are employed for in situ and ex-situ remediation of pollutants like hydrocarbons, organic pollutants, and some inorganic pollutants. Biostimulation eliminates factors facilitating bioremediation by introducing nutrients and oxygen to increase the activity of autochthonous microorganisms in groundwater and saturated zones (Kakavandi *et al*., 2014), effectively treating hydrocarbon spills (Xu *et al*., 2018). Bioattenuation uses living organisms or their extracts to reduce pollutant concentrations or their environmental effects, relying on indigenous microbes to degrade pollutants naturally, often with added nutrients or bacteria (Yin, 2018). Biosparging involves injecting oxygen and nutrients into contaminated groundwater to stimulate indigenous bacteria for pollutant breakdown (Lippincott *et al*., 2015), particularly effective for hydrocarbon-contaminated groundwater (Kao *et al*., 2008).

Ex-situ bioremediation techniques like biopiles, windrow systems, and land farming involve excavating contaminated soil and applying microbial activity to degrade pollutants. These techniques promote aerobic degradation by enhancing aeration and microbial activity (Arias *et al*., 2023; Bhattacharjee & Tollner, 2016; Irfan *et al*., 2020; Okonofua *et al*., 2021). Bioremediation offers a promising and sustainable approach to remediate pollutants in various environmental matrices, including water and soil. By leveraging natural processes and microbial activity, bioremediation techniques can effectively degrade pollutants, contributing to environmental protection and ecosystem restoration.

Bioremediation techniques applied to wastewater treatment in SSA

Natural coagulants are increasingly favored for their health and environmental benefits, addressing issues associated with chemical coagulants (Abujazar *et al*., 2022). Common plant-based coagulants include *Hibiscus sabdariffa* (M. Ahmad *et al*., 2023; Chen *et al*., 2023; Hoong & Ismail, 2018; Zheng *et al*., 2021), *Moringa oleifera* (Bina *et al*., 2010; George *et al*., 2016; Khattabi Rifi *et al*., 2023; Mehdinejad & Bina, 2018), Nirmali seeds (Maruthi *et al*., 2013; Mohan, 2014; Yin, 2010), watermelon seeds (Chikomo & Manyuchi, 2016; Joaquin *et al*., 2022; Kukwa *et al*., 2017; I. M. Muhammad *et al*., 2015), and cactus species (Choudhary *et al*., 2019; Deshmukh *et al*., 2018; Rachdi *et al*., 2017; RISS *et al*., 2022; Shilpa *et al*., 2012). While effective in water and wastewater treatment, their industrial application is limited by processing costs and performance consistency (Nimesha *et al*., 2022). Coagulation involves interactions between the coagulant, impurities, and water alkalinity, forming insoluble flocs (Nimesha *et al*., 2022). Success depends on coagulant characteristics, water properties, and mixing process parameters (W. L. Ang & Mohammad, 2020; I. Kumar & Quaff, 2019). Natural coagulants, which include microbial polysaccharides (Saleem and Bachmann, 2019), bio-wastes (Atchudan *et al*., 2020), alginate, gelatin, cellulose-based materials, and chitosan (Vigneshwaran *et al*., 2020), are non-toxic to aquatic environments. In solution, they carry a positive charge, binding negatively charged particles to form removable flocs.

Coagulation and flocculation, often using aluminum and iron salts and polyelectrolytes, effectively remove water turbidity. Living organisms enhance this process (Goudjil *et al*., 2021). Combining coagulation with bioremediation improves water treatment efficiency. For example, advanced oxidation and chemical coagulation in paper mill wastewater bioremediation showed COD removal of 35–98% and TSS removal of 12–89%, with nearly 20% heavy metal removal. UV oxidation and lime coagulation achieved up to 100% removal of COD, TSS, and color (Goudjil *et al*., 2021). Natural coagulants also treat persistent organic pollutants (POPs) through adsorption, coagulation, and electrocoagulation, effectively meeting discharge regulations in sub-Saharan Africa (Titchou *et al*., 2021). Eggshells have been used to reduce wastewater parameters, including organic pollutants like PCBs, though with low efficiency (Titchou *et al* ., 2021). Advanced oxidation processes (AOP), such as those generating OH radicals from natural coagulants, oxidize recalcitrant organic contaminants to inert end products. AOP combined with hydrodynamic cavitation is promising for removing POPs from water, wastewater, and leachate (Badmus *et al*., 2018).

Challenges and opportunities for natural coagulants in SSA

The commercialization of natural coagulants depends on their ability to perform comparably or better than traditional chemical coagulants at a lower cost. However, comparing coagulant types, processing stages, and costs across different regions is challenging due to varying factors such as currency rates, inflation, and cost value accuracies (C. D. T. Freitas *et al*., 2019). Financial dependence and investor skepticism often hinder the commercialization process. Understanding the associated risks and weaknesses is essential, yet most studies are limited to laboratory scale, which may not translate to real-world applications (Bahrodin *et al*., 2021).

A potential breakthrough lies in emphasizing the synergy between natural and chemical coagulants. Regulatory approval from regional governing bodies is crucial for commercialization, although stringent requirements can be a barrier. Introducing tax refunds and subsidy programs could incentivize the adoption of natural coagulants by water treatment operators (Choy *et al*., 2014). Collaboration between research institutions and industries or municipalities is essential to conduct pilot studies for assessing large-scale treatment performance and determining optimal conditions (Choy *et al*., 2014). Providing loans for cultivating plants like *Moringa oleifera* and Elephantorrhiza goetzei can support large-scale production of natural coagulants. The main challenge in sustainable implementation is large-scale plant cultivation to meet industrial demands. Initially, this may increase costs due to technological adjustments, new machinery, and professional training. However, over time, process costs and associated pollutants are expected to decrease significantly, also creating job opportunities through extensive land cultivation (T. K. F. S. Freitas *et al*., 2015; James *et al*., 2021). For natural coagulants to be commercialized like chemical coagulants, research should focus on processing them into powder form and ensuring a consistent market supply to build industrial confidence (Kurniawan *et al*., 2020; I. M. Muhammad *et al*., 2015; Pritchard *et al*., 2009).

Sustainability of natural coagulants

The sustainability of natural coagulants is constrained by industrial acceptance and public health improvements, encompassing four key aspects: social, technical, economic, and environmental (Koul *et al*., 2022). Social sustainability is linked to industrial acceptance, dependent on natural coagulants delivering results comparable to chemical coagulants. In many Sub-Saharan economies, limited real or pilot-scale use and the lack of regulatory guidelines for water and wastewater treatment hinder industrial adoption. Despite the proven efficacy of several natural coagulants, technical sustainability involves treatment efficiency, product stability, material availability, and compatibility with other techniques, making their application less cost-effective. Concerns about the toxicity of organic coagulants to humans and the environment necessitate further research, careful selection, and dose optimization to ensure environmental safety (Koul *et al*., 2022; Sulaiman *et al*., 2017).

Economic sustainability assesses the cost-effectiveness of coagulants, considering not only initial investments but also processing, maintenance, and regional variations (Vijayaraghavan & Sivakumar, 2011; Koul *et al*., 2022). While natural coagulants may have a cost advantage over chemical alternatives, factors such as production, processing, distribution, packaging, transportation, and preservation remain unclear (Mohd Asharuddin *et al*., 2021). An effective strategy to enhance economic sustainability is to use a combination of coagulants, which can offset procurement costs, meet consumption demands, and synergistically improve cleanup efficiency (Sulaiman *et al*., 2017).

Future directions and research needs

The efficacy of natural coagulants faces four primary barriers: financial capability, regulatory approval, market awareness, and research development (Choy *et al*., 2016). Their cationic, anionic, and non-ionic properties have been studied, but much of this research remains at the laboratory scale, limiting industrial applications. Challenges in bulk production of plant raw materials necessary for coagulation further hinder commercial viability (Choy *et al*., 2016). Addressing these challenges requires economically feasible extraction methods and life cycle assessments of plant- and animal-based coagulants (Choy *et al*., 2016; Nimesha *et al*., 2022). Comprehensive studies are also needed to elucidate the coagulation mechanisms of various natural coagulants. Regulatory approval is impeded by limited data availability, which is crucial for product launches. Compliance with standards is often overlooked due to insufficient awareness of green chemistry concepts among developers (Nimesha *et al*., 2022). Unlike widely available chemical coagulants, the scarcity of raw materials for natural coagulants hampers their large-scale production. Expert support and new equipment are essential for commercialization, albeit at increased production costs (Hadadi *et al*., 2022; A. Ibrahim *et al*., 2021).

Various extraction processes for plant and animal-based coagulants need careful analysis to develop simplified and economically feasible methods. Further studies are warranted to assess the conversion, handling, storage, preservation, and toxicity of coagulant powders (A. Ahmad *et al*., 2022). Blended coagulants could offer commercial breakthroughs. For example, Moringa seeds, rich in lipids and protein, can form flocs with chitosan molecules, aiding impurity removal through physicochemical processes (Vigneshwaran *et al*., 2020). Dual coagulants, like chitosan and aluminum chloride, have shown efficacy in removing toxic cyanobacteria from water (Ma *et al*., 2016). Studies on the efficacy of water extracts from *Moringa oleifera* (MO) and

Strychnos potatorum (SP) seeds in turbid water purification have shown promising results, with MO outperforming SP in high turbidity water (Y. Lee *et al*., 2013). Various studies have highlighted the successful removal of contaminants, with turbidity removal efficiencies exceeding 90% using plant-based extracts (Hussain *et al*., 2019; Shan *et al*., 2020; Sarma *et al*., 2019). However, achieving high efficiencies in low turbidity water remains challenging, necessitating further research into optimal treatment methods with natural coagulants (Packialakshmi *et al*., 2023; Sudha *et al*., 2017; Swathi *et al*., 2014).

Conclusion

Persistent organic pollutants (POPs) from the disposal of agrochemicals and industrial chemicals are increasingly being detected in water, wastewater, leachate, and soils in Sub-Saharan Africa. Advanced oxidation processes (AOP) are the most common method for bioremediation. However, the application of reactive oxygen species for the complete mineralization of pollutants under AOP is still limited in most SSA countries. On the other hand, natural coagulants, particularly those derived from plants, have gained significant traction in the water and wastewater industry in the region. These coagulants are increasingly being used as primary coagulants or coagulant aids for heavy metal removal and are now being explored for POPs. Understanding the significance of POPs in wastewater highlights the need for comprehensive management strategies, regulatory frameworks, and ongoing research to mitigate their environmental and health impacts. Natural coagulants present environmentally friendly, inexpensive, and less hazardous alternatives to chemical coagulants. Plant-based and animal-based coagulants are leading in application, with some cases of microorganism-based coagulants being used in water treatment. This review summarizes the prevalence of POPs, specifically PFAS, in the region, and examines the coagulation efficiency of three plant-based coagulants (Moringa, cactus, and Nirmali seeds) and two animal-based coagulants (chitosan and gelatin) in water treatment. *Moringa oleifera* seeds and extracts have been widely applied for chemical removal, though there are no successful studies recorded for POP removal. Other plant-based species have shown good efficiencies in removing turbidity, color, organic matter, and pathogens from water. Challenges related to economically feasible extraction methods, government approval of coagulation methods, effective conversion and handling of powdered forms of coagulants, and details of storage, preservation, and toxicity continue to limit large-scale operations. However, there are limited studies on these barriers, and this review recommends more investigations and assessments to identify and address these constraints through scientific approaches. Studying plant-based coagulants or their extracts for POP removal in tertiary treatment of water and wastewater could be an exciting area for future research.

DECLARATIONS

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