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Moringa Oleifera Extracts and their Potential Use to Purify Wastewater in Mining Areas: A Review

N'Dri Seiny Roger [1*], Gauly Légré Paul [1,2], Coulibaly Mariame [1], Bamba Drissa [1], Soro Ségnéninhinténin Bakary[1,2], Sanou Ali [1,3] Kouyaté Amadou [4], Yao N'Guessan Alfred [1]

[1] *Department of Science and Technology, Laboratory of Fundamental and Applied Physical Sciences (LSPFA), Ecole Normale Supérieure d'Abidjan, BP 10 Abidjan 08, Abidjan, Côte d'Ivoire*
[2] *Structure of Matter and Technology Sciences Training and Research Unit, Laboratory of Constitution and Reaction of Matter (LCRM), Félix Houphouët-Boigny University, BP 582 Abidjan 22, Abidjan, Côte d'Ivoire*
[3] *Felix Houphouet-Boigny National Polytechnic Institute, LAPISEN, Yamoussoukro, Yamoussoukro, Côte d'Ivoire*
[4] *Environmental Training and Research Unit, Environmental Science and Technology Laboratory (LSTE), Université Jean Lorougnon Guédé,), BP 150 Daloa Côte d'Ivoire*

**Corresponding author: ORCID ID: 0000-0001-8727-9582; Postal address BP 246 Abidjan 31;*
E-mail: ndri.roger@ensabj.ci; rogesny@yahoo.fr

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Abstract: Since independence, Côte d'Ivoire's economy has been based on the agricultural sector. In recent years, the share of the economy linked to the mining sector has increased significantly, particularly gold mining, due to the discovery of new deposits. There are two types of mining: industrial and artisanal. Both activities use large quantities of water, which is often discharged without prior treatment. Artisanal gold panning zones are remote areas that are not always connected to drinking water supply networks. The local population consumes water that has been polluted by agricultural, domestic and gold mining activities. They are therefore subject to water-borne diseases such as diarrhoea and cholera, as well as diseases of unknown origin. Treating this water before consumption could contribute to a substantial improvement in their health. As the usual methods of treating such water are not accessible to these populations, an alternative could be *Moringa oleifera*, which has been used extensively in the literature to purify wastewater. These benefits could improve water quality by preventing the resurgence of diseases inherent in physico-chemical water treatment methods. The aim of this article is to review the literature over the last three decades on the benefits of using Moringa extracts to purify wastewater, focusing on the specific case of wastewater from gold mining areas.

1. Introduction

Water is a vital resource (Morrissy *et al*., 2021; Kouakou *et al.*, 2022), and its availability in sufficient quality and quantity is a topical issue for every country in the world (WHO, 2022). Urbanisation and the development of human activities are putting a heavy strain on available water resources (Akhtar *et al*., 2021). Quality water resources are not always accessible, and even when they are, they are unfit for consumption because of the presence of toxic substances. Access to drinking water is a human right (Elgarahy *et al.*, 2021). Human activities such as gold panning use large reservoirs of water that are not always treated. Gold treatment processes are not environmentally friendly (Dong *et al.*, 2021 ; Hilson and Hu, 2022; Aramendia *et al*., 2023). The two main methods, cyanidation and mercury amalgamation, generate pollution from cyanide and trace metals such as mercury and zinc. Mercury is a toxic heavy metal with no known biological function (Sedighi *et al.*, 2023; Surimbayev *et al.*, 2023). It is known to harm humans even at low concentrations (Sanou *et al.*, 2021). Indeed, it is neurotoxic, genotoxic and reprotoxic (Goutam *et al.*, 2022). Zinc, on the other hand, is an essential metal for biological functions (Molenda and Kolmas, 2023). Zinc is necessary for healthy skin, wound healing and growth (Molenda and Kolmas, 2023). Its deficiency is responsible for the loss of taste perception, the appearance of edema, lack of appetite and disorders in the development of cognitive functions (Kouyaté *et al.*, 2021). However, excessive consumption of zinc over a long period can reduce copper absorption, cause anaemia and weaken the immune system (Kumar *et al.*, 2021).

Cyanide is toxic and lethal (Vaca-Escobar *et al.*, 2024). Gold mining waste is therefore very dangerous for the environment and for the entire ecosystem in the event of an accident (Prasad *et al.*, 2021). When an accident occurs, as was the case at the Ity gold mine in the Zouan-Hounien department in the Republic of Côte d'Ivoire on 23 June 2024. This incident resulted in the discharge of a large quantity of cyanide water into the Cavally River. It caused significant mortality in fish stocks. Cases of contamination (not quantified by analysis) have been reported. The local population is living in a state of psychosis due to the symptoms of diarrhoea, vomiting and headaches that have suddenly appeared. To mitigate the effects of this pollution, the Ivorian government has banned fishing and the consumption of surface and well water. Yet it is this water that these people drink. The decisions taken did not concern water treatment. The people therefore continued to drink this water because they had no other alternative. What's more, they have no mastery of the usual physico-chemical water treatment techniques, such as chlorination, ozonation and aluminium salts. These methods are increasingly accused of being responsible for certain resurgent diseases. The impact and scale of this pollution suggests that the problem is not one of large quantities of water, even if those responsible for the mine have decided to solve the problem they have created. The aim is to solve the problem of drinking water for local residents. By providing them with easy-to-implement methods that will not exacerbate their poverty by generating significant monetary costs. The alternative for personalised, family-based management of access to drinking water is based on the use of Moringa Oleifera extracts, with which the local people are familiar.

This plant is part of their daily lives. They are used to using it for nutrition or for its therapeutic properties. For a very long time, this plant has also been used to purify water and treat domestic wastewater (Yamaguchi *et al.*, 2021; Khalid and Ali, 2022; Wagh *et al*., 2022; Olaoye *et al*., 2024). Couldn't it be used as an urgent palliative solution to the problems faced by the local population? The aim of this study is not to add to the long list of literature reviews on the use of Moringa to purify wastewater, but to propose through the literature an urgent solution to this pollution and to areas not connected to the drinking water supply network. Above all, this review article will first focus on analyzing bibliometric data to determine trends, research priorities, hot topics, and important research areas on Moringa Oleifera. Then, the current state of the valorization of Moringa in the field of water treatment will be discussed.

2. Data collection method

The use of Moringa and its derivatives to treat water in low-income countries is abundant in the literature. The processes used by Moringa extracts to treat water have been identified. These include coagulation-flocculation by certain specific proteins. In addition, the adsorbent capacity of Moringa seed powder has been shown to eliminate a wide range of pollutants such as pesticides, heavy metals, dyes and pharmaceutical products. The use of Moringa oleifera for water treatment has increased in the literature in recent years, according to Yamaguchi et *al.* (2021).

The selected literature covers several decades. Moringa became part of everyday life several generations ago. The presence of drinking water in our taps has gradually wiped out all the accumulated knowledge about the purifying properties of water. Today's society is not immune to disasters that can cut off access to drinking water for several days. For people who do not have access to drinking water or who are far from drinking water distribution networks, this study could provide them with ways of solving their problem within their family circle. In the case of gold-panning areas, it will also provide an opportunity to share experiences.

2.1 Bibliometric analysis on Moringa Oleifera

The bibliometric analysis on Moringa Oleifera was carried out on 02/11/2024 using the Science Direct database. Science Direct is a website launched in March 1997 and managed by the publisher Elsevier. It is a database that covers around 3,800 international journals (Yandza Ikahaud and Hamad, 2021). Furthermore, Science direct provides sufficient and reliable information to make comparisons and different types of analysis in selecting relevant literature for a research area (Pranckuté, 2021). All forms of publications dealing with the subject have been listed for the period 1997 - 2024. The selected publications were analyzed according to the number of publications per year, type of document, areas of interest and languages of publication. The bibliometric analysis applied to the theme of *Moringa Oleifera*, carried out on 02/11/2024, made it possible to assess the scientific interest of this biomass. In total, 7666 publications were listed between 2000 and 2024.

2.2 Number of publications per year

The number of publications per year highlights the importance of research, thus playing a leading role in the justification of a given theme (Yandza Ikahaud and El Haddad, 2021). Interest in *Moringa Oleifera* began in 2000 with ten publications. Since 2006, interest in this biomass has continued to grow as shown in **Figure 1**. The publications having dealt with the theme from 2000 to 2024 number 7,666 with an overall average of 319.42 publications per year. Additionally, over the past five years, an average of 1001.18 posts appeared or 65.34% of all posts. The fairly dense number of annual publications reflects the constant interest aroused by the theme among researchers (Macías-Quiroga et *al*., 2021; Zheng et al., 2022; Brdarić et *al*., 2024). This increasingly growing interest in the study would probably be due to the increase in scientific activity in general (A. Sanou et *al*., 2024a). Furthermore, the growing interest in this biomass would probably be due to the need to develop this agricultural product into a product with high added value.

2.3 Number of publications by publication types

Bibliometric data indicate that researchers used several types of documents to popularize the different results obtained. The most common type of publication is the research article, with 59.79% of publications (**Table 1**). In addition, 19% or 1480 bibliographic review articles were produced on this biomass. The number of review articles was much lower than that of research articles. This observation is similar to that of several bibliometric studies (Ouattara et *al*., 2021; A. Sanou et *al*., 2024a; Uddin et *al*., 2024). This is likely due to the lower output of review articles compared to research articles (Brdarić et al., 2024). It is in this context that this bibliographical review takes place, which focuses on one of the areas of valorization of *Moringa Oleifera*.

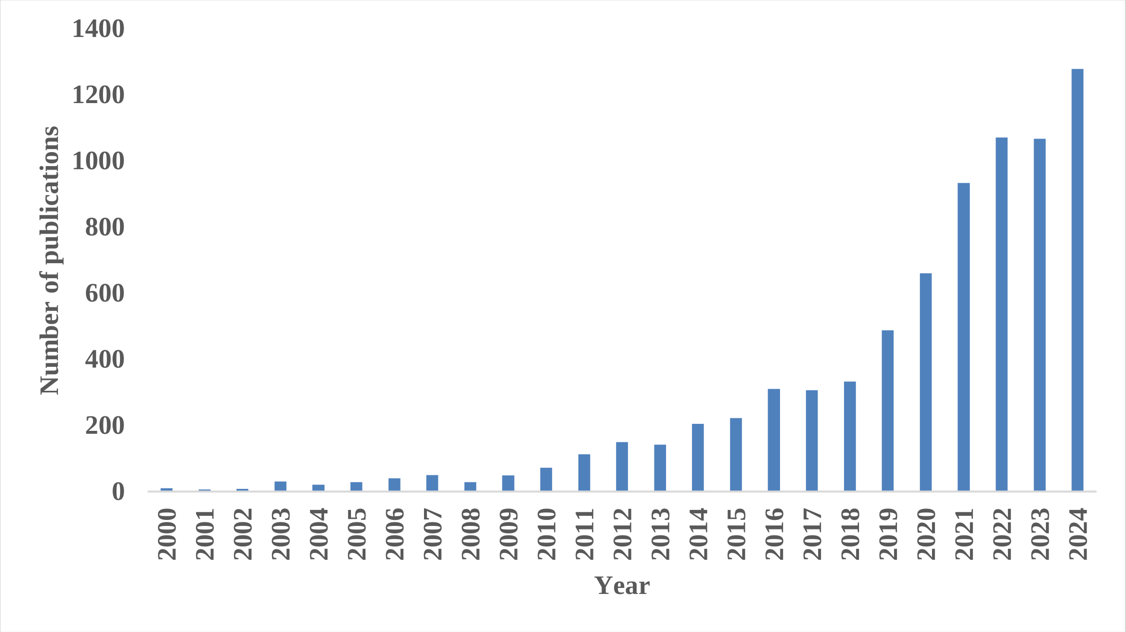

Figure 1. Number of publications per year relating to *Moringa Oleifera*

Table 1. Distribution of publications by publication types

Types of publications	Number of publications	Percentage (%)	Rank
Research articles	4584	59,796504	1
Review articles	1480	19,3060266	2
Book chapters	863	11,2575006	3
Others	349	4,5525697	4
Short communications	133	1,7349334	4
Conference abstracts	96	1,2522828	6
Encyclopedia	57	0,7435429	7
Case reports	23	0,300026	8
Data articles	21	0,2739368	9
Errata	16	0,2087138	10
Editorials	15	0,1956691	11
Mini reviews	15	0,1956691	12
Correspondance	6	0,0782676	13
Discussion	5	0,065223	14
Books reviews	2	0,0260892	15
Conference info	1	0,0130446	16

2.4 Areas of valorization for Moringa Oleifera

The valorization of *Moringa Oleifera* has attracted growing interest in several areas (**Figure 2**). These include agricultural and biological sciences, environmental sciences, biochemistry, genetics and molecular biology, pharmacology, toxicology and pharmaceutical science, materials sciences, medicine and dentistry, energy and immunology and microbiology. The large number of publications in these fields could be justified by the rich mineral and lignocellulosic composition of this biomass.

Indeed, agricultural products and by-products rich in minerals, lignin and cellulose are used in various fields such as soil fertilization, animal feed chemistry, electroanalysis and dye removal (Ouattara et *al.*, 2021; Kouakou et *al.*, 2024; N'Guessan et *al.*, 2024; I. Sanou et *al.*, 2024).

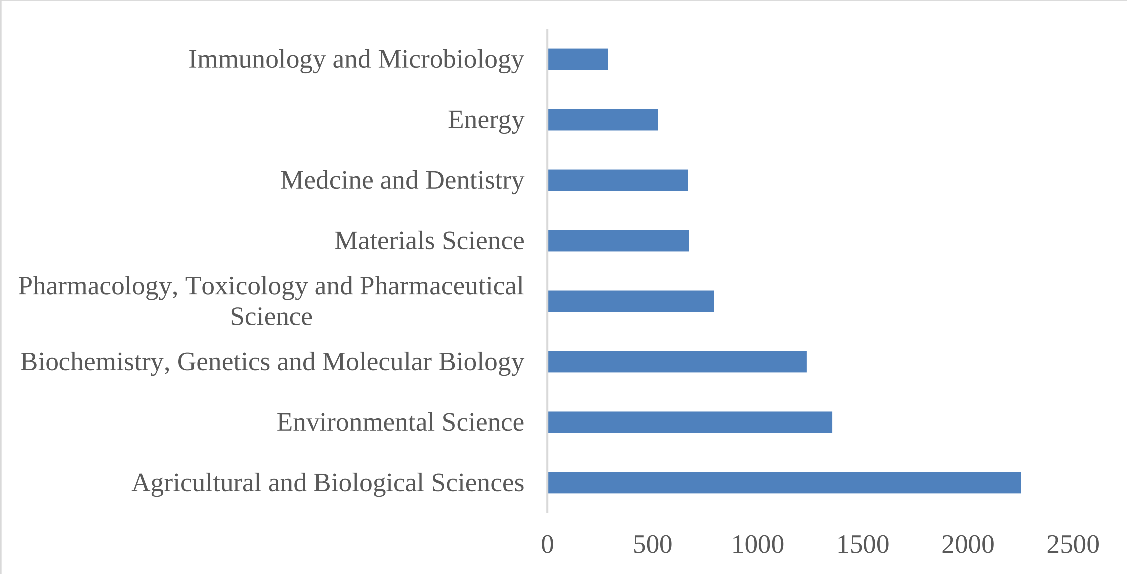

Figure 2. Number of publications per area

2.5 Number of publications by language and type of access to publications

The language of publication is an essential element in bibliometric research (Tchuifon et *al.*, 2024). The results of the bibliometric analysis indicated that there were five languages including English, French, Spanish, German and Indonesian. The distribution of languages is shown in **Table 2**. Analysis of the distribution of languages revealed that English was the predominant language. A total of 7647 articles (99.752% of 7666 articles) were published in English (**Table 2**). These results are in agreement with certain bibliometric studies which also revealed that the English language is the predominant language of publications (Aswal *et al*., 2023; Alazaiza *et al*., 2024; Tchuifon et *al*., 2024). Furthermore Monge-Nájera and Ho report that to have a broad reach, most publications are in English (Alazaiza *et al*., 2024). Of the 7666 articles listed up to now, the articles in access are 2283 with a percentage of 29.78%, suggesting that almost 70% of the articles on the theme are paid for. This situation limits the access of researchers in many developing countries to scientific documentation. Limited access to documentation could slow down the dynamics of researchers in these parts of the world.

Table 2. Languages of publications and types of access to publications

Languages	Number of publications	Percentage (%)	Rank
English	7647	99.752	1
French	13	0.1695	2
Spanish	4	0,0522	3
German	1	0,013	4
Indonesian	1	0.013	5

Access type of publications	Number	Percentage (%)
Open access & Open archive	2283	29.2467

2.6 Number of publications per journal

There are twenty-five (25) peer-reviewed journals used to publish the results obtained on *Moringa Oleifera*. Table 3 shows the distribution of output journals with at least 90 article publications. Among these journals, three have published at least 200 articles: Desalination and Water Treatment (333), Journal of Ethnopharmacology (233) and South African Journal of Botany (228). The second group: Heliyon, Industrial Crops and Products, International Journal of Biological Macromolecules, Food Chemistry and Chemosphere are the top 5 journals with at least 100 publications on *Moringa Oleifera*. Journal of Environmental Chemical Engineering (96) and Materials Today Proceedings (93) constitute group 3 with at least 90 publications. The journal in position 11, Science of The Total Environment, has 81 publications and the journal in last position is Asian Pacific Journal of Tropical Medicine with 50 publications. Although there are multidisciplinary journals such as Heliyon, there are also specific journals such as Desalination and Water Treatment, Journal of Water Process Engineering. These significant numbers of publications in the field of water treatment show the potential of *Moringa Oleifera* for the purification of contaminated water (**Figure 3**).

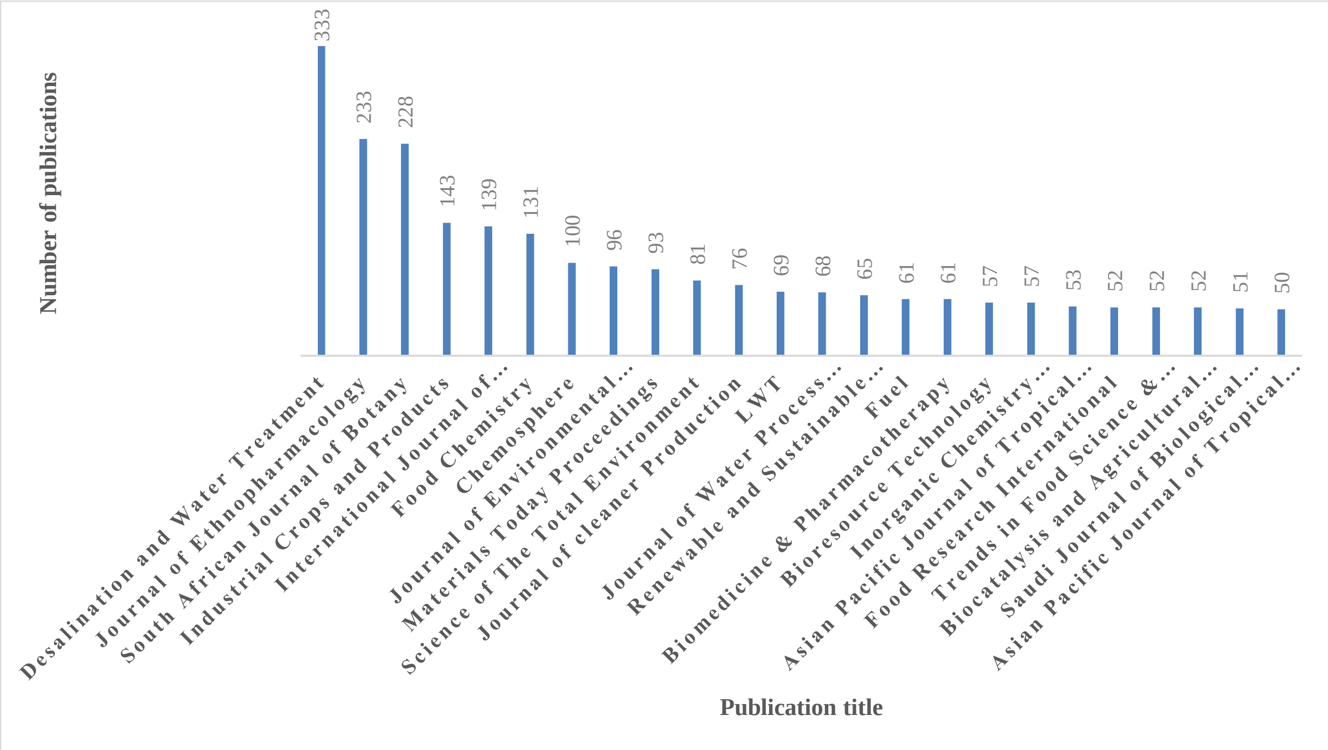

Figure 3. Publications in the field of water treatment

3. *Moringa Oleifera*

Moringa belongs to a monogeneric family of 13 species (including 9 African species) (Dzuvor *et al*., 2022). The name *Moringa* comes from muringa in Malayalam, an Indian language. *Moringa Oleifera* is therefore a species native to the Agra and Oudh regions of northern India, and to Pakistan on the edge of the Himalayas. Its use dates back to 2000 BC in northern India, where it was first described as a medicinal tree (Ercan, 2021), and it was introduced to East Africa at the beginning of the 20th century thanks to trade and maritime exchanges during this period. Today, it is grown in every tropical and subtropical region of the world, on three continents and in more than 50 tropical and subtropical countries. In these countries, it is used as a medicinal and food plant (Ercan, 2021; Samiksha *et al*., 2023), for humans and animals, and as a bio-pesticide and plant fertiliser. Its oil is used as a lubricant in the watchmaking and perfume industries.

3.1 Components of each part of the Moringa Plant

Moringa is a multi-purpose plant. All its parts are edible: leaves, bark, roots, gum, pods and seeds. **Figure 4** shows some of the parts of the *Moringa* plant.

Fig. 4. Some parts of the *Moringa* plant: (a) leaves and leaf powder, (b) *Moringa Oleifera* seeds (Behnas, 2021)

Moringa comes in various forms, each with its own advantages and interest [22]. The leaves are generally pulverised before use (Behnas, 2021; Khalid and Ali, 2022; Djeneba *et al*., 2023). Seeds are used fresh or dried. They are pulverised or pressed to extract a valuable oil (Djeneba *et al*., 2023; Al-Maqtari *et al*., 2024). The roots, bark, seed husks and flowers are dried and pulverised before use (Djeneba *et al*., 2023; Al-Maqtari *et al*., 2024). Charcoal from its parts is also used as required. Each part of this tree therefore contains treasures for health, well-being and other uses. **Table 3** summarises the common uses of *Moringa Oleifera*.

Table 3 shows that *Moringa Oleifera* is used in sectors other than its usual dedicated use, i.e. nutrition, water treatment and to treat diseases. It is also used as a fuel, lubricant, fertiliser, insecticide and in the paper industry. Moringa can generate additional resources and combat poverty. It is therefore an economic resource that Third World countries should not neglect. It is easy to produce, at low cost and has many uses.

Table 3. Plant parts of *Moringa oleifera*, their uses and benefits (Nwagbara *et al*., 2022)

Part of the tree	Uses or benefits
Leaves	Leaves Nutritional, medicinal, biomass, plant growth hormone, fodder
Flowers	Nutritional, medicinal, honey
Pods	Nutritional, medicinal
Bark	Medicinal, cordage,
Roots	Medicinal
Eraser	Medicinal
Wood	Paper, pet food, medicines, alcohol
Seeds	Water treatment, food, cosmetics, cooking oil, lubricants

3.2 Drinking water standards

Access to drinking water remains a major concern in sub-Saharan Africa, particularly in rural areas where people are faced with the problem of how best to manage water points. The lack of appropriate disinfection methods at family level (Kaboré *et al*., 2013) could lead to a breakdown in the water supply. Water for human consumption must be available continuously, in sufficient quantity, and must not present any health risks (Khalid and Ali, 2022). Drinking water is water that can be drunk or used for domestic or industrial purposes without risk to health. It can be distributed in the form of bottled water, tap water or in tanks for industrial use. 62% of tap water comes from groundwater (surface and deep aquifers), the remaining 38% from surface water (rivers, lakes). Groundwater is drawn from a borehole or well. The soil acts as a natural filter, ensuring good water quality. Treatment is required to provide drinking water that is completely free of impurities. The water passes through a treatment plant to decontaminate it, before being piped underground to storage tanks or water towers. Pumps are used to store the water above ground so that it can be distributed to homes. The water is then used for human consumption. Then, after use, the wastewater is sent to a treatment plant where it is cleaned. The cleaned water is then discharged back into the environment, before starting its domestic cycle all over again (Khalid and Ali, 2022). Drinking water must comply with certain standards. The chemical quality of water is assessed by comparing the results of quantitative analysis with guide values (WHO, 2022). According to the WHO, a guide value corresponds to the concentration of a constituent for which the risk incurred does not exceed the tolerable risk to health. The guide value or standard sets an upper limit that must not be exceeded or a lower limit that must be respected. The international standards according to the World Health Organisation (WHO) are given in **Table 4**.

Table 4 Extract from WHO guide values for the main parameters characterising drinking water (WHO, 2022)

Parameters		**Indicator Values**
	pH	6,5 - 8,5
	Temperature	≤ 25°C
Physics	Conductivity	180-1000 µS/cm
	Salinity	≤ 0,1‰
	Dissolved oxygen	5-8 mg/L
	Sulphate	250 mg/L
	Sodium	200 mg/L
Mineral salts	Potassium	12 mg/L
	Magnesium	50 mg/L
	Calcium	100 mg/L
	Nitrate	50 mg/L
	Nitrite	3 mg/L
Nutritive salts	Orthophosphate	0.5 mg/L
	Ammonium	0.5 mg/L
	Copper	2 mg/L
	Manganese	0.4 mg/L
	Mercure	0.001mg/L
	Lead	0.01 mg/L
Heavy metals	Iron	0.3 mg/L
	Boron	0.5 mg/L
	Zinc	3 mg/L
	Nickel	0.02 mg/L
	Cadmium	0.003 mg/L
	Chrome	0.05 mg/L
	Arsenic	0.01 mg/L

The extract in **Table 4** presents some limit values for heavy metals that should not be exceeded in drinking water. This extract was selected because of the presence of these elements in mining water. Mining water is loaded with heavy metals and certain dissolved substances because of the agricultural activities that take place nearby. The mining areas are very remote from the drinking water distribution networks, which means that there is no access to drinking water. In addition, local people are not trained to use the usual water treatment methods so that there are no consequences for them. The usual processes are still of interest. However, the resurgence of disease linked to these processes suggests that other materials should be sought. Plant-based materials such as *Moringa oleifera* are the first choice. All parts of the Moringa plant, especially the "leaves", "seeds", "bark" and "pod" are effective in wastewater treatment (Benettayeb *et al*., 2022; Gomes et al. 2022).

3.3 Eliminating hardness and turbidity with Moringa

The use of natural coagulants in water purification is well known in Asia and Africa, where these organic polymers have been used for decades to reduce water turbidity (Khalid and Ali, 2022). *Moringa's* depollution activity has been tested in various types of wastewaters. *Moringa* has been used to treat water from rivers (Araujo *et al*., 2022; Toi Bissang *et al*., 2024), wells (Trigueros *et al*., 2023; Zea Cobos *et al*., 2024), swimming pools (Toi Bissang *et al*., 2024) and ponds (Toi Bissang *et al*., 2024) . Different parts of the tree have been used for different purposes. Different parts of the tree have been used on their own or modified with chemicals to give them certain properties. Seed powder and leaf powder are the most widely used. Seed powder has been used to improve the turbidity and hardness of river water, well water, swimming pool water and pond water. Hard water consumes more soap during washing (Zea Cobos *et al*., 2024). Seed powder reduces turbidity by up to 90% while improving hardness within one to two hours. Optimum doses range from 150 mg/L to 160 mg/L (Toi Bissang *et al*., 2024). Water with low turbidity consumes more seed powder than water with high turbidity (Wagh *et al*., 2022; Toi Bissang *et al*., 2024). The water obtained after treatment has the physico-chemical characteristics of drinking water (Wagh *et al*., 2022; Toi Bissang *et al*., 2024).

The ability of Moringa seeds to reduce water turbidity is primarily due to the presence of cationic proteins (Bouchareb *et al*., 2022). These substances act as natural flocculants. These proteins carry a positive electrical charge that attracts the negatively charged suspended particles in the water. When these particles come into contact, they form heavier flocs that sediment to the bottom of the container (Koul *et al*., 2022; Al-Jadabi et al. 2023). In addition to cationic proteins, several other compounds are involved in improving turbidity, including phenolic derivatives called tannins, which also contribute to water clarification (Ibrahim *et al*., 2021). Finally, although their role in water clarification is less understood, saponins contribute to the stability of the formed flocs (Ibrahim *et al*., 2021).

The effectiveness of clarification with seed powder depends on several factors (Yamaguchi *et al*., 2021). The first factor is the concentration of seed powder. It influences the quality of coagulation of all suspended particles. An insufficient quantity does not allow for good coagulation, while an excessive quantity leads to the formation of very small flocs that are slow to sediment. The second factor is the pH at which coagulation occurs. This parameter varies depending on the nature of the particles. The water temperature also affects the effectiveness of clarification, as it influences the reaction rate and the size of the flocs. The last factor affecting coagulation is the nature of the suspended particles (size, density, and charge).

Proteins are more effective coagulants than aluminium sulphate. As a coagulant, *Moringa* is non-toxic and biodegradable (Ng and Elshikh, 2021; Al-Jadabi et al. 2023). It is environmentally friendly, unlike aluminium sulphate. It does not significantly affect pH or conductivity. The sludge produced by coagulating *Moringa* is not only harmless but also four to five times smaller than the sludge produced by coagulating aluminium sulphate (Wu *et al*., 2023). The above results are improved when the seed is oven dried at 45 °C or the oil is extracted from the seed powder before use (Wagh *et al*., 2022). Water treated with seed powder generates an increase in the quantity of dissolved organic matter (Islam *et al*., 2021; Ng and Elshikh, 2021), some of which is soluble in water. This presence of organic matter suggests that the proteins probably diffuse into the water. Wastewater from health facilities has also been treated with moringa extracts with good results. Moringa can be used to treat water from different environments and produced by different activities.

3.4 Moringa eliminates heavy metals

Heavy metals appear in water and sediments as a result of human activities (Sanou *et al*., 2020; N'Dri *et al*., 2024). Some of these metals are useful for biological functions. Their absence creates functional disorders (Sanou *et al*., 2022). But some are toxic, whatever the dose. They have an impact on human and animal health, and on the environment (A. Sanou *et al*., 2024b; Fort *et al*., 2024). The main heavy metals and their impact on health are presented in **Table 5**. Analysis of the table reveals that heavy metals affect the main organic functions useful to humans. It is therefore important to eliminate them from matrices. The literature contains trials on the treatment of water containing heavy metals in well and surface water using moringa. When these metals came into contact with moringa seed powder, their content was reduced or completely eliminated (Soumaoro *et al*., 2021; Ng and Elshikh, 2021; Abalaka *et al*., 2021; Koul *et al*., 2022; Khalid and Ali, 2022; Benettayeb *et al*., 2022).

For example, after treatment with *Moringa* seed powder, a reduction of almost 99% in the concentrations of iron, copper, aluminium and lead was observed (Desta and Bote, 2021; Yamaguchi *et al*., 2021; Noori, 2021). For other ions such as manganese, cadmium, chromium and arsenic, the reduction is greater than 50% of the concentration.

Table 5. Main effects of heavy metals (Doyo *et al*., 2023)

Elements	Effects
Arsenic	Toxic, possible carcinogen
Cadmium	Hypertension, liver damage
Chrome	Carcinogenic in the form of Cr (VI)
Copper	Irritant effect on inhalation, allergy on contact ; Long-term oral liver damage
Mercure	Chronic and acute toxicity
Nickel	Skin allergies, respiratory diseases possible carcinogen
Lead	Toxic
Selenium	Essential in low doses, toxic in high doses
Zinc	Zinc chromate is carcinogenic

The ability of Moringa seed powder to remove heavy metals is primarily due to adsorption (Gomes et al. 2022). Heavy metals, due to their positive charge, are attracted to the negatively charged active sites present on the surface of the proteins contained in Moringa seeds (Abatal *et al*., 2021). This process occurs in three steps.

First, there is the contact stage, when Moringa seed extracts are brought into contact with a solution containing heavy metals, the metal ions collide with the seed surface (Benettayeb and Haddou, 2023). Then comes the adsorption stage, where the metal ions bind to the active sites on the protein surface through chemical bonds (ionic, covalent, or coordination). Finally, the complexation stage occurs. The ability of Moringa seeds to complex heavy metals is the result of a synergy of several organic compounds, acting together to form stable bonds with metal ions (Sera *et al*., 2021).

Although research is still ongoing to identify all the compounds involved and understand the exact mechanisms of complexation, several families of molecules have been particularly cited in studies (Geng *et al*., 2022). The most cited molecules are proteins, especially cationic proteins. They play a major role in the adsorption of heavy metals thanks to their active sites rich in nitrogen and oxygen atoms. These atoms can form coordination bonds with metal ions, thus immobilizing them.

Next come polysaccharides, such as arabinogalactans. Their long sugar chains can also bind to heavy metals. The hydroxyl groups of these sugars act as coordination sites, forming stable complexes. Phenolic compounds such as tannins are also cited in the adsorption mechanism by complexation. Tannins are present in Moringa seeds, and they can form covalent bonds with heavy metals (Nobaha *et al*., 2021). These bonds are very stable and difficult to break. Finally, the last elements involved are free amino acids, such as glutamic acid and aspartic acid (Stanikina, 2023). These compounds can also contribute to the complexation of heavy metals thanks to their carboxyl and amine groups.

Several mechanisms may be involved in the complexation of heavy metals by the organic compounds of Moringa seeds (Benettayeb *et al*., 2022). These organic compounds can form chelates with metal ions. A chelate is a cyclic complex in which the metal ion is surrounded by several donor atoms of the same ligand (Benettayeb *et al*., 2022; Diver *et al*., 2023). The metal ions involved can exchange ions present on the active sites of the organic compounds. And in some cases, complexation can lead to the formation of insoluble precipitates, thus removing heavy metals from the solution. The molecular structure of organic compounds plays a crucial role in their ability to complex heavy metals. The presence of specific functional groups (carboxyl, amine, hydroxyl), the size of the molecules, and their spatial conformation influence the strength and stability of the complexes formed (Jin and Wei, 2024).

The efficiency of adsorption and complexation depends on certain factors such as pH, initial concentration of the metal ion, biomass dose, temperature, and particle size. These factors influence the kinetics of adsorption.

In the case of seed powder, the chelating effect of the matrix was used to make a carbon paste electrode modified with seed powder to preconcentrate mercury (II) (N'Guessan *et al*., 2024). Activated carbon produced from Moringa has also been shown to remove heavy metals (Bilal *et al*., 2021).

3.5 Elimination of other substances

Studies report that seed powder has been used to remove many other toxic substances at low and high doses. Fluoride (Khalid and Ali, 2022), chloride (Yamaguchi *et al*., 2021; Khalid and Ali, 2022) and cyanide (Kouakou *et al*., 2024) ions have been treated with moringa seed powder. Cyanide is a powerful poison that kills even at low doses. Fluoride and chloride ions, when present in excess in aqueous environments, are responsible for serious illnesses because they can react with dissolved substances to produce toxic forms (Jha and Tripathi, 2021; Kashyap *et al*., 2021; Solanki et al., 2022). The substances responsible for eliminating these ions are cationic polypeptides that attract negatively charged particles (Abarca-Cabrera *et al*., 2021; Zhang *et al*., 2023).

The elimination of chloride, fluoride and cyanide ions by seed powder is an advantage. In fact, it could be used to depollute water previously treated with aluminium salts or chlorine when the presence of chlorine or aluminium is suspected. This would guarantee the drinkability of the water. The leaves and seeds also eliminate fluoride ions (Chowdareddy *et al*., 2023).

3.6 Elimination of waterborne disease pathogens

The antimicrobial power of the seed powder has been tested on wastewater (Anzano *et al*., 2022; Pareek *et al*., 2023). It showed complete efficacy in eliminating many pathogens such as coliforms (Behnas *et al*., 2021; Pareek *et al*., 2023), streptococci, bacteria (Anzano *et al*., 2022), Pseudomonas aeruginosa (Royani *et al*., 2023), Escherichia coli, Enterobacter cloace, Proteus vulgaris, Staphylococcus aureus and Micrococcus kristinae (Anzano *et al*., 2022). The antimicrobial activities of Moringa oleifera leaves, roots and bark have been studied in vitro against bacteria, yeasts, dermatophytes and helminths pathogenic to humans These extracts inhibit antimicrobial activities (Anzano *et al*., 2022).

Moringa seed powder is recognized for its antimicrobial properties. It is capable of inactivating a wide spectrum of pathogens present in water (Andrade et al. 2021). This activity is attributed to a combination of factors and active compounds acting synergistically (Fontana *et al*., 2022). The main compounds involved include cationic proteins, phenolic compounds, saponins, and isothiocyanates (Fontana *et al*., 2022).

Proteins play a central role in the inactivation of microorganisms. They disrupt the cell membrane of bacteria, viruses, and fungi, leading to their death (Tavares *et al*., 2023). Phenolic compounds (tannins, flavonoids) have strong antioxidant and antimicrobial activity (Andrade et al. 2021; Aourabi et al. 2021; Nouioura *et al.*, 2024; Bouslamti , 2023). They can inhibit microbial growth by damaging the proteins and nucleic acids of pathogens. Saponins, on the other hand, have hemolytic properties and can form complexes with the membrane sterols of microorganisms, thus disrupting their integrity (Banik *et al*., 2021). Finally, isothiocyanates, although less studied in moringa, are known for their antimicrobial properties and may contribute to the overall activity of the powder (Jubair *et al*., 2021).

The mechanisms of action of the active compounds in moringa are multiple and can vary depending on the type of pathogen (Chis *et al*., 2023). These mechanisms include disruption of the cell membrane, inhibition of protein synthesis, damage to DNA, and the formation of free radicals. Cationic proteins and saponins present in Moringa interact with the lipids of the cell membrane, creating pores and leading to a loss of cellular content (Jikah and Edo, 2023). Phenolic compounds can also inhibit enzymes involved in protein synthesis, thus preventing the multiplication of microorganisms (Said *et al*., 2021). Some of these compounds can damage the DNA of microorganisms, thus disrupting their replication and survival (Said *et al*., 2021). Finally, phenolic compounds can generate free radicals that damage the biomolecules of microorganisms (Rani *et al*., 2021).

The effectiveness of Moringa seed powder against pathogens depends on factors such as the concentration of active compounds, pH, temperature, and the nature of the pathogen (Dzuvor *et al*., 2022). Indeed, a sufficient concentration of active compounds is necessary to obtain optimal antimicrobial activity. The solubility and activity of the active compounds are influenced by the pH of the solution. Temperature affects the reaction rate and the efficiency of inactivation of microorganisms. And the sensitivity of different pathogens to the active compounds of Moringa varies.

To improve the decontamination of wastewater, a filter consisting of a layer of fine sand associated with two layers of gravel of different sizes was made. In the sand layer is introduced degreased and non-degreased Moringa grains. This association has shown its effectiveness in eliminating pathogens from wastewater. This filter showed good removal of Clostridium and Streptococcus D, with a reduction of 96% and 81% respectively in water treated with defatted seeds, and 81% and 97% in the filter based on non-defatted seeds respectively (Arhab and Chebli, 2021). A literature review shows that all parts of the Moringa plant have wastewater depollution properties. In order to improve this depollution activity, researchers combine the different parts of the Moringa plant simultaneously. This combination of different materials from the Moringa plant has produced results that are much better than those obtained by using the material alone (Anzano *et al*., 2022; Toi Bissang *et al*., 2024). Moringa extracts can therefore be used to treat mining water containing metal ions and cyanide.

Conclusion

The analysis of the bibliography showed that Moringa oleifera extracts could depollute all qualities of wastewater from various activities and various environments. It thus contributes to the fight against waterborne diseases. On the other hand, the extracts have shown specific properties against certain harmful substances whose high threshold generates serious diseases. Cyanide and trace metal elements belong to this category. These elements are abundant in mining areas. Men and women, due to the distance from the distribution circuit, are forced to consume water that is unfit for consumption. This creates health problems. Moringa, due to its properties and its availability and low cost becomes a resource to have drinking water in quantity and quality for these populations. It is biodegradable and non-toxic to humans and the environment. All this makes Moringa a future material for drinking water.

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