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Evaluation of the effectiveness of some local plant extracts in improving the quality of unsafe water consumed in developing countries

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This study highlights the possibility of using plant extracts as biocoagulants to replace aluminum sulfate in the process of raw water potabilization. For this purpose, nine plants were identified by an investigation and their effectiveness was evaluated in the laboratory by coagulation/flocculation on surface waters. Out of the nine plants identified, five extracts showed a very low coagulant activity in the reduction of water samples turbidity (maximum abatement of 1.03%): These were the seeds of *Acacia nilotica*, *Adansonia digitata*, *Balanites aegyptiaca*, *Tamarindus indica* and leaves of *Capparis corymbosa.* Two extracts showed an average activity, namely *Aloe vera* sap (20.7%) and *Opuntia ficus indica* sap (32.25%). Two other extracts which are *Moringa oleifera* seeds and *Boscia senegelensis* seeds, showed a very good activity (84.83% and 82.97%, respectively after 1 h of decantation). By fixing the optimal concentration of 1 g/L for the treatment with *Moringa oleifera* seeds, a water of 4.6 NTU was obtained after 2 h of decantation, which was about 98% of abatement. The treatment with *Boscia senegelensis* seeds also allowed us to obtain for 2.5 g/L a water of 4.9 NTU after 2 h of decantation. The combined action of Moringa and Boscia biocoagulants, and cactus and Aloe mucilages reduced the decanting time to 15 min. These two treatments induced a slight increase of the minerals initially present in the water and a reduction of almost 99% of the pathogenic microorganisms. Thus, *Boscia senegelensis* and *Moringa oleifera* seeds appear as very effective biocoagulants compared to aluminum sulfate, hence they constitute an alternative to the lack of access to drinking water especially for developing countries.

KEYWORDS
unsafe water, biocoagulant, coagulation/flocculation, turbidity, quality

1 Introduction

Despite the progress made in recent decades around the world, many regions still face serious drinking water supply problems (Kettab et al., 2008). Thus, access to drinking water remains a major concern, particularly for developing countries, and especially for their populations living in rural areas (Carrard et al., 2019). The latter are indeed confronted with an optimal management of the water points, with an insufficiency of hygiene, and with a lack of appropriate methods of disinfection of the raw water (surface or underground) (Kabore et al., 2018).

These deficiencies unfortunately have serious health consequences such as deaths due to diarrhea caused by the consumption of unsafe water; and economic consequences due to the lack of access to water and sanitation. (Fuente et al., 2020; McClelland et al., 2022). The treatment of raw water before consumption is essential for the preservation of the health and the wellbeing of the populations (Sharma and Bhattacharya, 2017).

Coagulation/flocculation is one of the most widespread potabilization processes, which allows the improvement of the quality of the treated water (Zheng et al., 2011; Djeffal et al., 2021; Khettaf et al., 2021). Its implementation requires the use of coagulants, of which the most used at present are the inorganic coagulants and mainly aluminum sulfate (Zemmouri et al., 2012; Park et al., 2016). The aluminum sulfate makes it possible to achieve the objectives of the treatment, but has important disadvantages. Firstly, although it is relatively cheap, it is still quite expensive for developing countries (Konkobo et al., 2021); secondly, from an environmental point of view, its use inexorably generates metallic residues (Krupińska, 2020; Fouad et al., 2021); and finally, its use exposes humans to a possible risk of contracting Alzheimer's disease, because the aluminum residues that remain in the water after treatment are suspected to be responsible for the said disease (Kandimalla et al., 2016; Zhang et al., 2019).

Considering all these facts, the replacement of this synthetic chemical coagulant by effective and harmless biocoagulants is considered an urgent need (Yin, 2010; Choy et al., 2014). This is why it is increasingly necessary to find alternative coagulants, such as natural organic coagulants based on plant extracts (Kurniawan et al., 2020; Alazaiza et al., 2022).

Indeed, the treatment of water with plant extracts is a heritage of the peoples of Asia and Africa (Pan et al., 2014). Formerly used in a traditional way, this technique is presented in this new age of "bio" as a sustainable alternative because of the non-toxicity of plants compared to aluminum sulfate and other chemical coagulants commonly used (Cardoso Valverde et al., 2018; Shewa and Dagnew, 2020).

Thus, in recent years, studies have been conducted on the ability of *Moringa oleifera* seeds to make raw water potable (Delelegn et al., 2018; Varkey, 2020). However, Moringa is not the only plant with potabilization properties and current knowledge about its capabilities is unsatisfactory and lacks optimization.

Therefore, this study proposes to search for plants, whose extracts could be used as biocoagulant and to evaluate their efficiency by coagulation/flocculation in the process of raw water potabilization.

2 Materials and methods

2.1 Investigation of plants traditionally used in water treatment

The investigation consisted of collecting information from people living in rural areas of Burkina Faso on their knowledge of traditional water treatment with plant extracts. It covered four regions of the country with the lowest rates of access to drinking water namely East, Sahel, Mouhoun loop and Cascades regions. In these regions, 12 localities were taken into account, namely Djibo, Dori, Sebba, Fara, Pompoi, Tougan, Fada, Kantchari, Pama, Banfora, Niangologho, and Mangodara (Figure 1).

2.2 Samples collection

Once the survey was completed, the samples were collected across the country. The seeds of *Accacia nilotica*, *Adansonia digitata*, *Balanites egyptiaca*, *Moringa Oleifera*; *Tamarindus indica, Aloe vera*, and *Opuntia ficus indica* were obtained at the National Forest Seed Center (NFSC). *Boscia senegalensis* seeds and *Capparis corymbosa* leaves were collected in the urban park "bangr weeogo" of Ouagadougou (Figure 2).

The raw water samples used in this study were surface water collected in the Loumbila dam (12° 29 N, 01° 24 W). The collected samples were kept in the refrigerator at 4°C.

2.3 Preparation of plants extracts for coagulation/flocculation process

For the preparation of the solutions based on seeds of *Accacia nilotica*, *Adansonia digitata*, *Balanites egyptiaca*, *Moringa Oleifera, Tamarindus indica*, and *Boscia senegalensis*, the different seeds were ground into a fine powder. 100 g of the powder obtained in each case was diluted in 1 L of distilled water and placed under magnetic stirring for 1 h, to allow the release of the active molecules. The final concentration of each prepared solution was 100 g/L.

The solution based on *Capparis corymbosa* leaves were obtained by reducing them to a fine powder of which 100 g were macerated in 1 L of distilled water during 2 h.

For the preparation of the solutions containing *Aloe vera*, and *Opuntia ficus indica*, 50 g of their stems were cleaned, and crushed in 1 L of distilled water, to extract their sap. Thus, 02 stock solutions of 50 g/L each of their extracts were obtained.

2.4 Evaluation of effectiveness of biocoagulants by jar tests

After the preparation of different solutions based on plant extracts, their effectiveness was evaluated using the jar test. The jar test consists of carrying out small-scale potabilization tests in the laboratory using the coagulation-flocculation process. Thus, the previously prepared solutions were tested at different concentrations on the surface water samples using an electrically controlled six-station flocculator (brand name velp scientifica).

1 L of raw water was introduced into each flocculator beaker, followed by the addition of coagulant solutions at increasing concentrations. The agitation of the water after introduction of the coagulant was done in two phases: a fast agitation at 150 rpm for 5 min and a slow agitation at 45 rpm for 10 min. After at least 10 min of decantation, the supernatant of each beaker was taken and used to read the residual turbidity.

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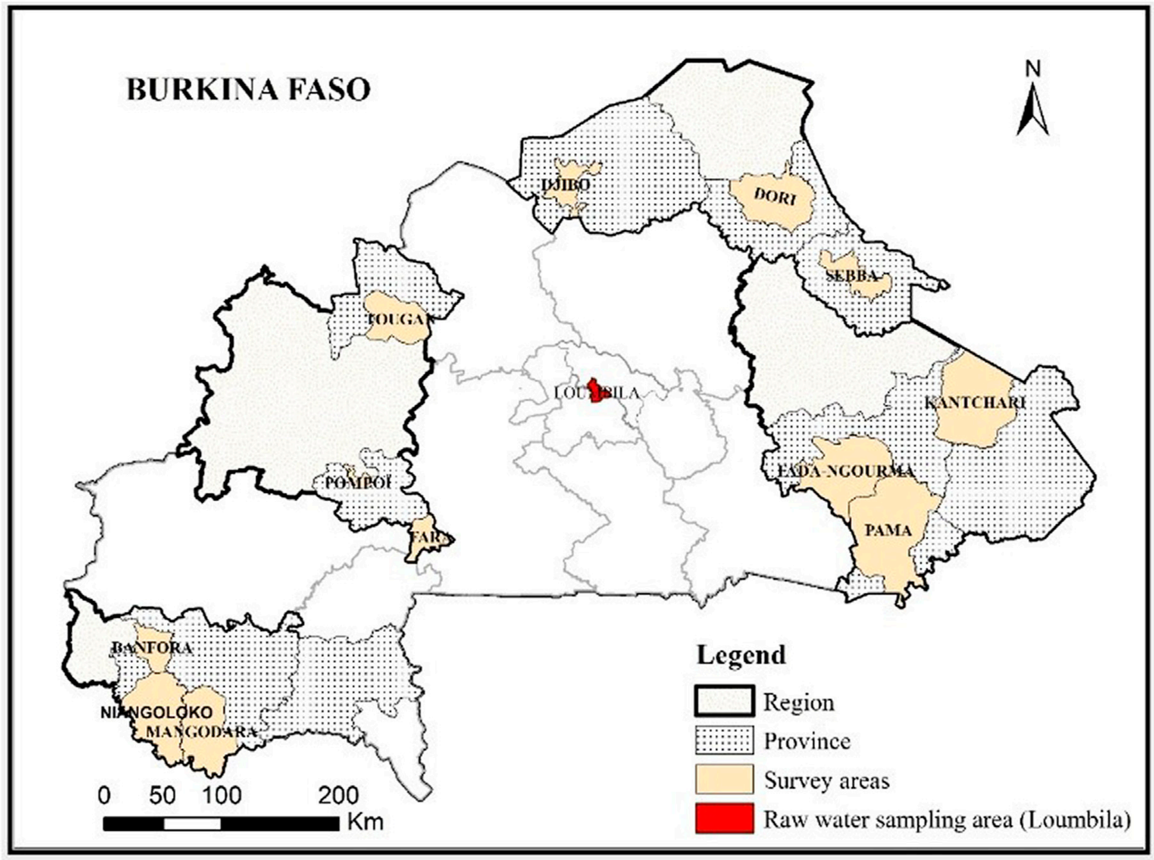

FIGURE 1
Localization of the different survey areas.

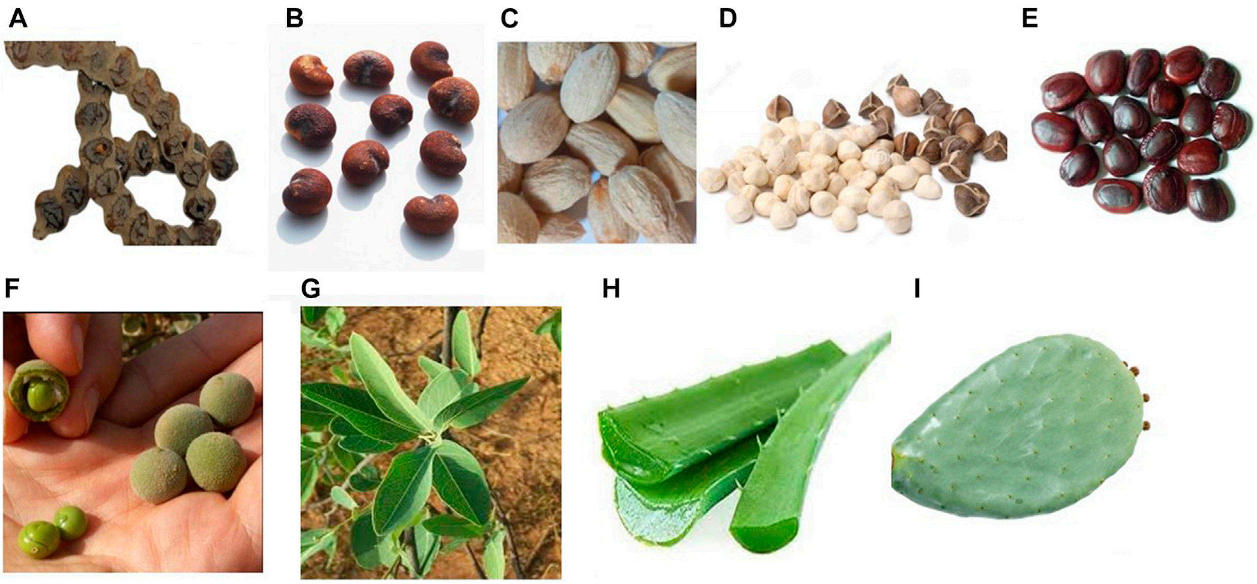

FIGURE 2
Accacia nilotica seeds **(A)**; *Adansonia digitata* seeds **(B)**; *Balanites aegyptiaca* seeds **(C)**; *Moringa Oleifera* seeds **(D)**; *Tamarindus indica* seeds **(E)**; *Boscia senegalensis* seeds **(F)**, *Capparis* corymbosa leaves **(G)**, *Aloe vera* **(H)**, *Opuntia ficus indica* **(I)**.

Coagulation/flocculation performance is evaluated by the turbidity removal rate, and our experiments were repeated in triplicate. Thus, the percent turbidity removal was noted (% T) and calculated by the following formula:

$$\% \mathrm{T} = \frac{\mathrm{Ti} - \mathrm{Tf}}{\mathrm{Ti}} \times 100$$

Where, Ti is initial turbidity of the water and Tf is the final turbidity after the jar test.

2.5 Determination of physicochemical parameters of water samples

The physicochemical parameters of water samples were measured before and after treatment with plants extracts. The turbidity of the samples was measured by a laboratory turbidimeter (WTW Turb 550 IR) in accordance to the French standard NF ISO 7027 (2000). The pH of the water was measured with a pH meter (330i WTW), according to the NF 10523 standard (1994). The Alkalimetric Title (AT), the Complete Alkalimetric Title (CAT), and the concentration of calcium and magnesium ions (Hydrotimetric Title, HT) were determined by titrimetry. Each parameter was determined in triplicate. The removal efficiency of the analyzed parameters was determined by the formula below where, Ci represents the concentration of the parameter in the raw water and Cf represents the concentration of the same parameter in the treated water:

$$\% \mathrm{C} = \frac{\mathrm{Ci} - \mathrm{Cf}}{\mathrm{Ci}} \times 100$$

2.6 Determination of microbiological parameters of water samples

The water treated with our various coagulants and flocculants must be free of germs, and particular emphasis is placed on microbiological analyses. Thus, the main indicator germs of fecal contamination were retained for this study in accordance with the regulations in force. These are *Escherichia Coli*, total coliforms, and streptococci. These germs were all determined using the membrane filtration method and spread on specific culture media according to the French standard NF EN ISO 9308-1 (2000). Thus, for the research of total coliforms and *Escherichia Coli*, the Chromocult coliform Agar ES medium was used at an incubation temperature of 37°C and for streptococci, the Enterrococus agar medium was used at a temperature of 44°C.

Each microbiological parameter was determined in triplicate, and the percentage reduction of microorganisms (% M) was determined by the following formula:

$$\% \mathrm{M} = \frac{\mathrm{Mi} - \mathrm{Mf}}{\mathrm{Mi}} \times 100$$

Where, Mi is the number of colonies of the microorganism initially present in the water and Mf the number of colonies of the same microorganism after the jar test.

2.7 Statistical analysis

Graphs and the different concentrations calculations were performed using Microsoft Excel software, version 2016. Data were subjected to the analyses of variance (ANOVA) using XLSTAT software (2016) and significant differences between means were revealed *via* the Tukey test ($p < 0.05$). Principal component analysis was performed with R software, version 4.0.2 (2020).

3 Results

3.1 Results of investigation

Of 200 people surveyed (Figure 3), 26.5% had no knowledge of traditional water treatment processes. 23% knew only of physical processes such as filtration, heating and sand filtration. 50.5% were able to identify plants whose extracts could be used for water purification. Thus, we were able to identify nine plants, namely *Accacia nilotica*, *Adansonia digitata*, *Aloe vera*, *Balanites egyptiaca*, *Boscia senegalensis*, *Capparis corymbosa*, *Moringa oleifera*, *Opuntia ficus indica*, and *Tamarindus indica* (Table 1).

3.2 Jars tests results

Preliminary tests in the laboratory showed a very insignificant turbidity reduction, or even almost zero for the solutions based on *Acacia nilotica*, *Adansonia digitata*, *Balanites aegyptiaca*, *Capparis corymbosa*, and *Tamarindus indica* (Figure 4). These solutions were all applied at increasing concentrations (0.1 g/L to 10 g/L) to waters ranging in turbidity from 241 to 386 NTU to observe kinetics. However, no significant reduction in turbidity was observed after 2 h of settling for any of the concentrations applied.

For the *Aloe vera* and cactus (*Opuntia ficus indica*) treatments, the turbidity abatement was low and not very satisfactory after 1 h of decantation (Figure 5). Application of the cactus-based coagulant solution to 184.8 NTU water reduced it to 125.0 NTU. The *Aloe vera* solution reduced to 167.0 NTU, a water whose initial turbidity was 210.6 NTU. Thus the turbidity abatement rate was 32.35% for the cactus-based treatment, and 20.7% for the *Aloe vera*-based treatment.

Solutions based on *Boscia senegalensis* seeds and *Moringa oleifera* seeds, on the other hand, showed a significant reduction in turbidity after only 1 h of decantation (Figure 6). The turbidity of the water treated by the first coagulant solution (*Boscia*) was reduced from 377.1 NTU to 57.2 NTU; i.e., an abatement of 84.83% obtained for a concentration of 2.5 g/L. The second coagulant solution (*Moringa*) reduced the turbidity of water from 276.6 NTU to 47.6 NTU; i.e., an abatement of 82.97%, obtained for a concentration of 1 g/L.

3.3 Optimization

3.3.1 Minimum decanting time

The previous treatments identified the optimal coagulant concentrations of Moringa and Boscia, which were 1 and 2.5 g/L respectively.

FIGURE 3
Number of people surveyed by area.

TABLE 1 Plants with a potential potabilization power on raw water identified during the survey.

Plants	Number of times cited	Parts used	Method of preparation
Acacia nilotica	3	Seeds	Maceration
Adansonia digitata L	2	Seeds	Maceration
Aloe vera	3	Sap	Maceration
Balanites aegyptiaca	7	Seeds	Maceration
Boscia seneglensis	16	Bark, seeds	Maceration
Capparis corymbosa	6	Leaves	Maceration
Moringa oleifera	61	Seeds	Maceration
Opuntia ficus indica	2	Sap	Maceration
Tamarindus indica	1	Seeds	Maceration

Thus, proceeding to the fixing of these concentrations, the time of decantation was varied (Figure 7) until a water whose turbidity met the standard of the WHO (≤5 NTU).

After 2 h of decantation, the treatment with *Moringa oleifera* seeds resulted in a water of 4.6 NTU and the treatment with *Boscia senegalensis* seeds resulted in a water of 4.9 NTU. That is to say an abatement of 98% for both treatments, after 02 h of decantation time.

3.3.2 Reduction of the minimum decanting time: Optimization with cactus and aloe mucilage

Opuntia ficus indica and *Aloe vera* mucilage have previously shown their limitations as a coagulant in the treatment of water samples. However, these two extracts were tested again, but this time as a flocculation aid in order to improve the efficiency of Moringa and Boscia extracts in water treatment. Thus, biocoagulants from *Moringa oleifera* and *Boscia senegalensis seeds* were combined with cactus and *Aloe vera* mucilages in the treatment of water samples. For this purpose, the previous optimal concentrations of Moringa and Boscia extracts were combined with increasing volumes of cactus and Aloe mucilages. These combinations showed that turbidity reduction is "volume-dependent" because as the volume of mucilage increased, water turbidity decreased rapidly. Thus, after application of 0.6 mL of cactus solution, after 15 min of decantation, water with turbidity within the standard for each combination was obtained: 4.19 and 4.58 NTU respectfully for the Moringa/Cactus treatment and the Boscia/Cactus treatment (Figure 8A). Adding increasing volumes of *Aloe vera* mucilage (ranging from 0.1 to 0.7 mL) to the optimal concentrations of Moringa and Boscia extracts was as effective as with cactus mucilage. Figure 8B shows that 0.7 mL of Aloe mucilage was sufficient to obtain water with a turbidity of less than or equal to 5 NTU for each Moringa/Aloe and Boscia/Aloe treatment after 15 min of decantation.

3.4 Comparison of the efficiency of *Moringa oleifera* and *Boscia senegalensis* seeds in aluminum sulfate

To compare the efficacy of Moringa and Boscia biocoagulants with that of aluminum sulfate, water samples of 352.80 NTU were

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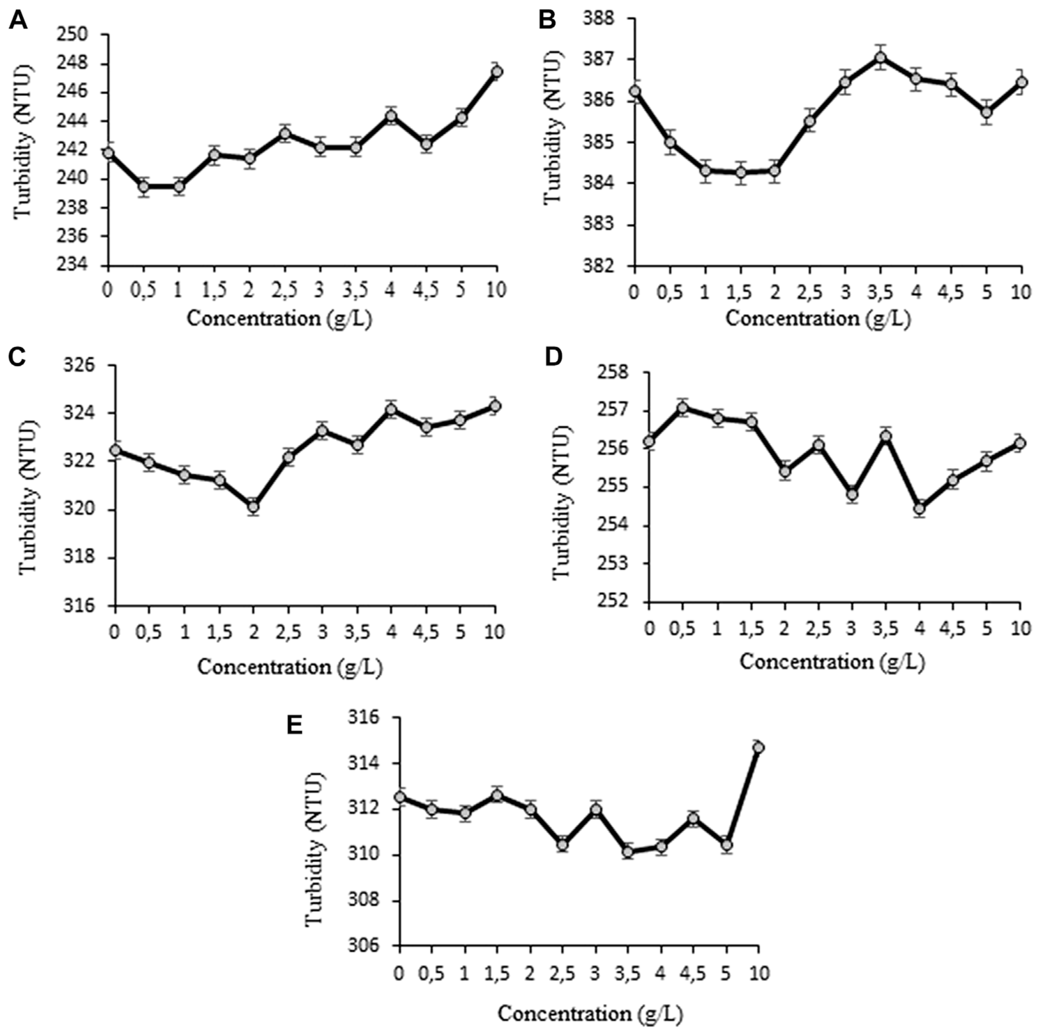

FIGURE 4
Measurement of the turbidity of water samples after 1 h of decantation according to the application of the different plant extracts: *Tamarindus indica* **(A)**; *Balanites aegyptiaca* **(B)**; *Acacia nilotica* **(C)**; *Capparis corymbosa* **(D)**; *Adansonia digitata* **(E)**.

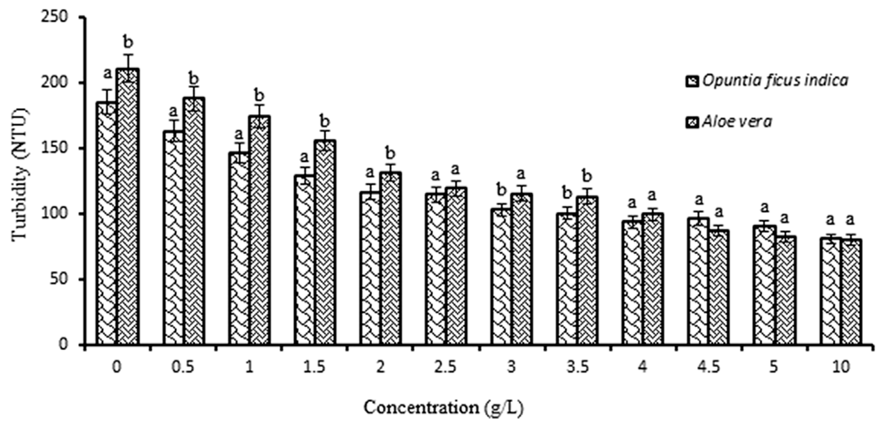

FIGURE 5
Measurement of turbidity of water samples treated with different concentration of cactus (*Opuntia ficus indica*) and *Aloe vera* sap.

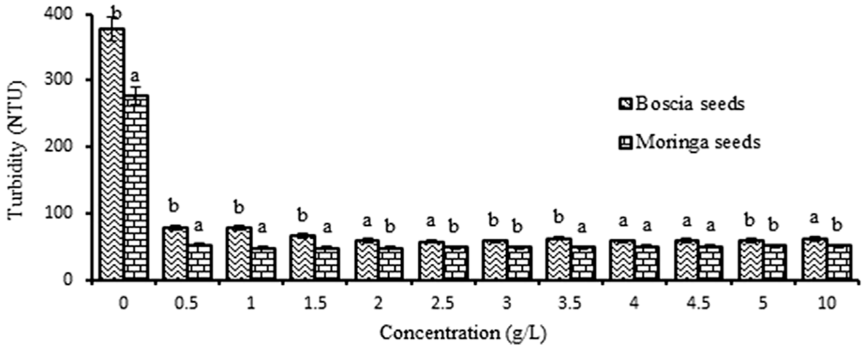

FIGURE 6
Measurement of turbidity of water samples treated with different concentrations of *Moringa oleifera* (Mo) seeds and *Boscia senegalensis* (Bs) seeds.

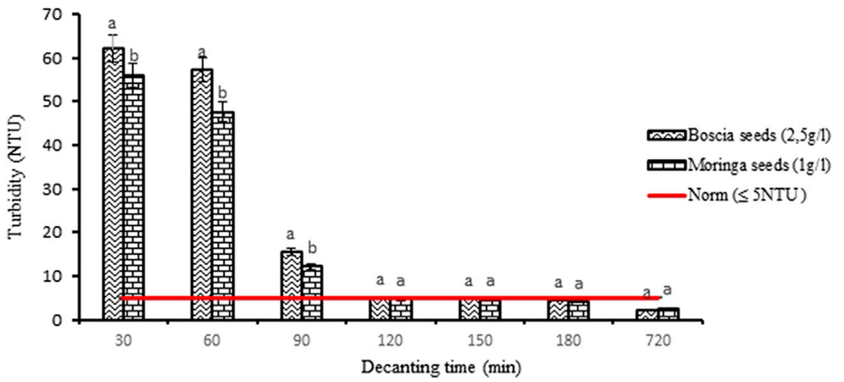

FIGURE 7
Measurement of turbidity of water samples treated with *Moringa oleifera* (Mo) and *Boscia senegalensis* (Bs), at different decanting time.

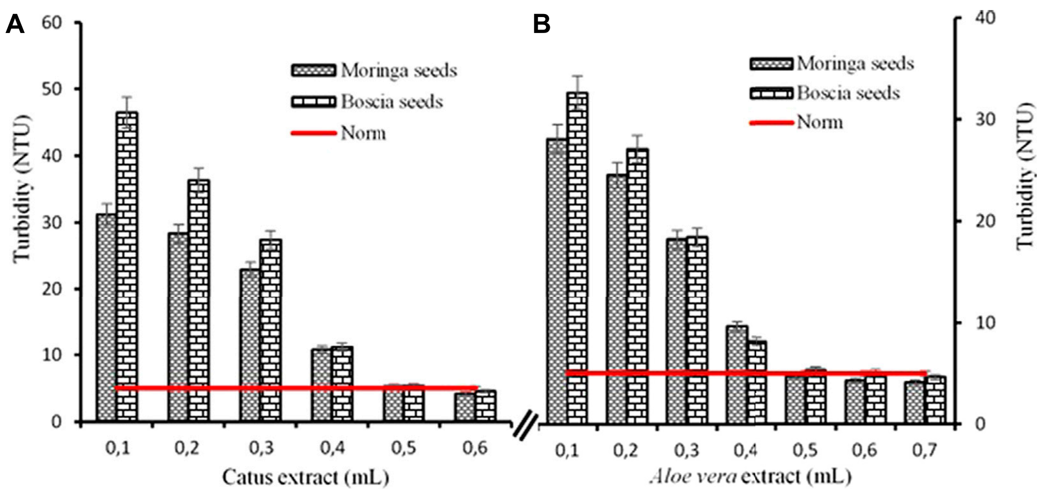

FIGURE 8
Evolution of turbidity of water samples as a function of the volume of cactus mucilage applied to the Moringa and Boscia seeds treatment **(A)**. Evolution of the turbidity of water samples as a function of the volume of *Aloe vera* mucilage applied to the treatment of Moringa and Boscia seeds **(B)**.

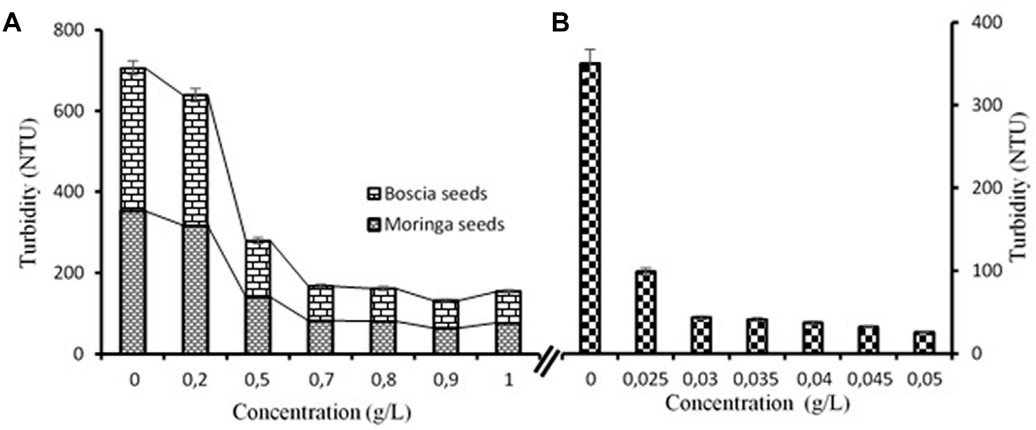

FIGURE 9
Evolution of turbidity of water samples as a function of *Moringa oleifera* and *Boscia senegalensis* seeds concentration **(A)**. Evolution of the turbidity of water samples as a function of the concentration of aluminum sulfate **(B)**.

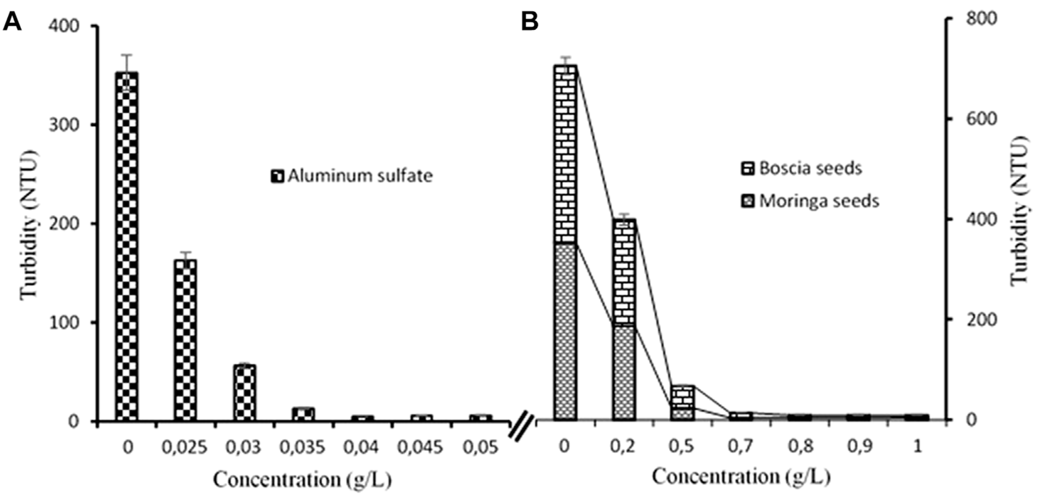

FIGURE 10
Evolution of turbidity of water samples as a function of aluminum sulfate concentration **(A)**. Evolution of the turbidity of water samples as a function of the concentration of *Moringa oleifera* seeds, then of *Boscia senegalensis* seeds **(B)**.

used for coagulation-flocculation tests with increasing doses of aluminum sulfate, *Moringa oleifera* seed extract, and *Boscia senegalesis* seed extract. The variations in residual turbidity are recorded in Figures 9A, B. Figure 9A allows us to observe a decrease in turbidity as a function of the concentration of aluminum sulfate used. As its concentration increases, the turbidity of the water decreases. However, this dependence is not linear. The maximum reduction in turbidity is 92.8% and was obtained with a dose of 0.05 g/L of aluminum sulfate solution.

Determination of the optimal concentration for Moringa and Boscia seeds show that at low doses, the turbidity of the water sample decreased with increasing biocoagulant concentration (Figure 9B). However, above 0.9 g/L of Moringa solution used, and 1 g/L of Boscia solution, a slight increase in turbidity was observed. Thus, the optimal concentration of Moringa coagulant needed to treat the raw water sample was 0.9 g/L, while that of *Boscia senegalensis* was 1 g/L. At these concentrations, we obtained a turbidity reduction of 82.06% for Moringa and 80.78% for Boscia, respectively.

These results thus show that aluminum sulfate, *Moringa oleifera* and *Boscia senegalensis* seeds are all effective coagulants in reducing raw water turbidity, although to different degrees. Indeed, for the same 352.80 NTU water, higher concentrations of biocoagulant (0.9 g/L for Moringa and 1 g/L for Boscia) than aluminum sulfate (0.05 g/L) were required to obtain the lowest turbidity.

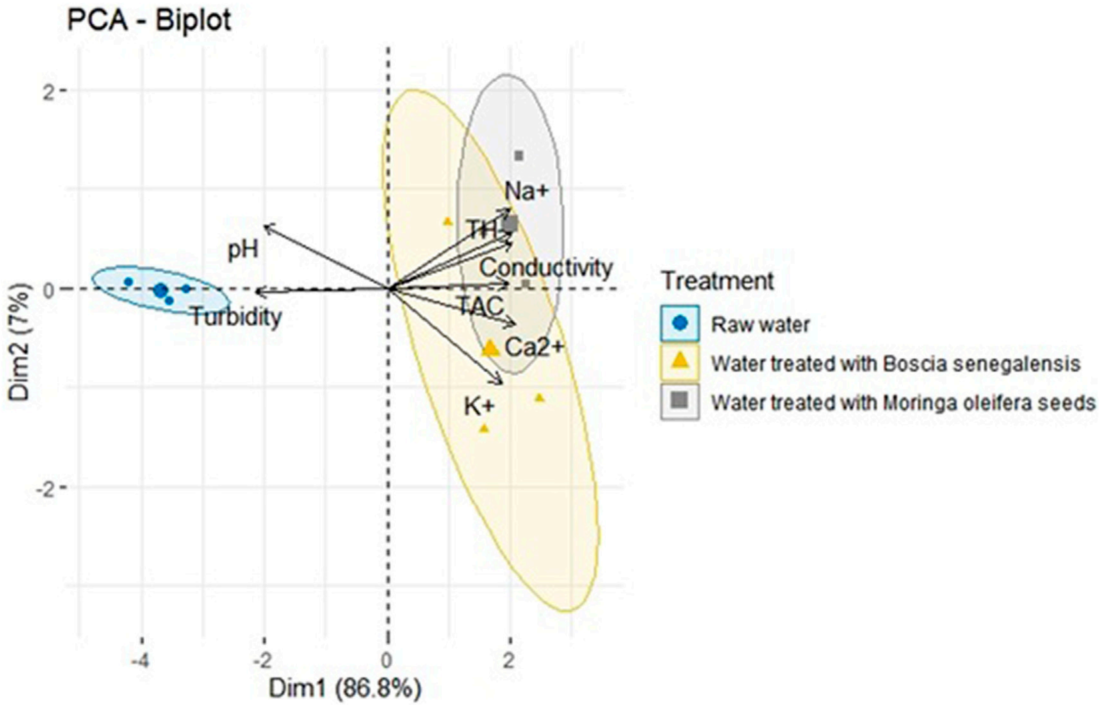

FIGURE 11
Principal component analysis of physicochemical parameters of water treated with *Moringa oleifera* and *Boscia senegalensis* seeds.

TABLE 2 Physico-chemical parameters of raw water and water samples treated with Moringa oleifera (Mo) and Boscia senegalensis (Bs).

Parameters	Raw water	Mo	Bs	Pr > F	Significant
pH	6.91 ± 0.13 ^{aa}	6.70 ± 0.13 ^{bb}	6.63 ± 0.13 ^{bb}	0.002	Yes
Conductivity (μS/cm)	66.07 ± 11.84^{bb}	89.73 ± 11.84 ^{aa}	87.50 ± 11.84 ^{aa}	0.001	Yes
HT (meq)	0.55 ± 0.13^{cc}	0.84 ± 0.13 ^{aa}	0.73 ± 0.13 ^{bb}	0.000	Yes
CAT (meq)	0.73 ± 0.15^{bb}	1.00 ± 0.15 ^{aa}	0.97 ± 0.15 ^{aba}	0.033	Yes
Ca^{2+} (mg/L)	0.25 ± 0.14^{bb}	0.50 ± 0.14 ^{aa}	0.53 ± 0.14 ^{aa}	0.001	Yes
Na^{+} (mg/L)	3.32 ± 1.45^{bc}	6.50 ± 1.45^{aa}	5.47 ± 1.45 ^{ab}	0.000	Yes
K^{+} (mg/L)	5.38 ± 2.24^{bb}	8.53 ± 2.24^{aa}	9.34 ± 2.24 ^{aa}	0.042	Yes

At the level of each line, values that have the same letter in common are not significantly different according to the Tukey test.

Figures 10A, B show that the Aluminum Sulfate/cactus, Moringa/Aloe and Boscia/cactus combinations provide considerable turbidity reduction after 15 min of decantation.

The comparison of these three (3) combinations reveals a clear improvement in the coagulation capacity of aluminum sulfate, Moringa seeds, and Boscia seeds. The turbidity obtained with these three (3) combinations after 15 min of decantation is in accordance with the WHO standard (≤5 NTU). In addition to the improvement of the water clarification speed, the addition of cactus mucilage (0.6 mL) and Aloe (0.7 mL) to the coagulation-flocculation process resulted in the reduction of the optimal concentration of aluminum sulfate. Thus, the optimal concentration of aluminum sulfate used to obtain a turbidity in compliance with the standard went from 0.05 g/L to 0.04 g/L, while the concentration of Moringa and Bocia remained the same (respectively 0.9 and 1 g/L). Even with the addition of mucilage, the coagulant requirement for Moringa and Boscia remains higher than that for aluminum sulfate to achieve turbidity that meets the standard.

3.5 Results of physicochemical parameters

In addition to turbidity, measurements of pH, conductivity, HT, CAT, calcium ions (Ca^{2+}), sodium ions (Na^{+}) and potassium ions (K^{+}) showed a slight increase (Figure 11), after treatment of the water with *Moringa oleifera* seeds and *Boscia senegalensis* seeds (Table 2).

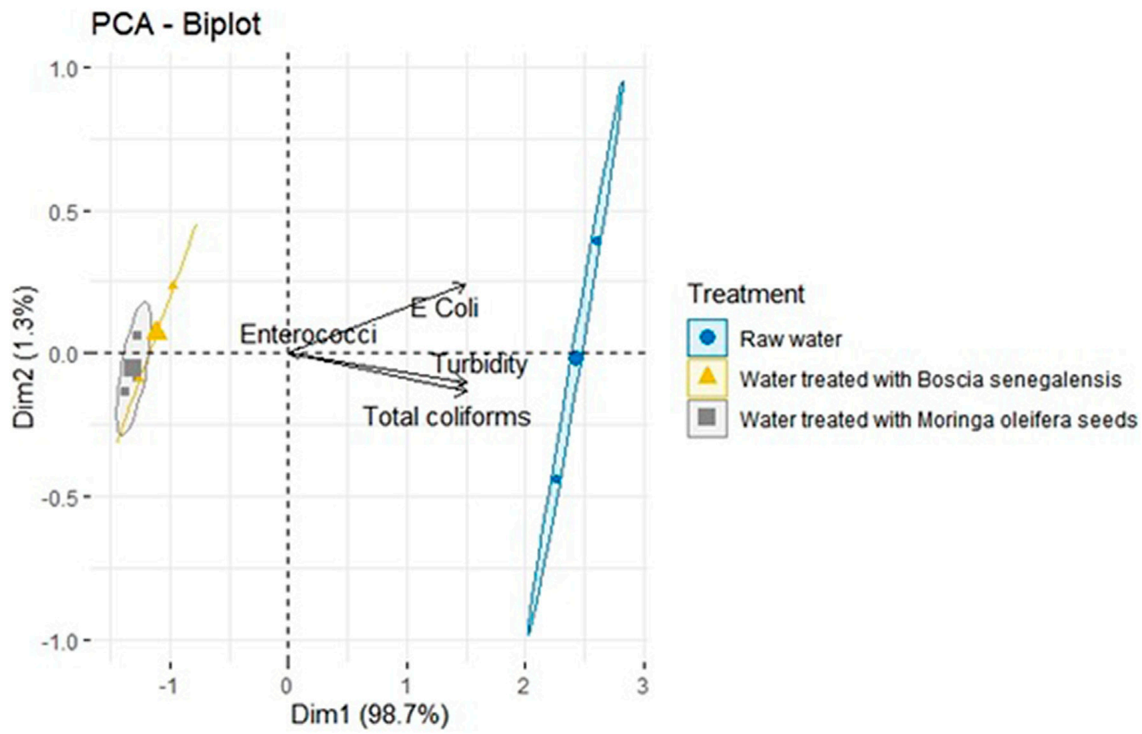

FIGURE 12
Principal component analysis of microbiological parameters of water treated with *Moringa oleifera* seeds and *Boscia senegalensis* seeds.

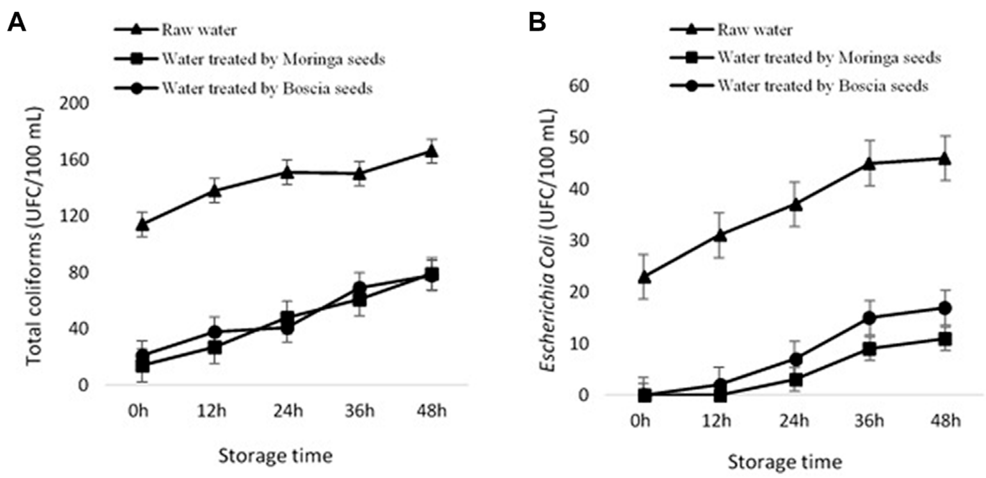

FIGURE 13
Evolution of total coliforms **(A)** and *Escherichia coli* **(B)** in water samples treated with *Moringa oleifera* (Mo) and *Boscia senegalensis* (Bs) as a function of storage time.

3.6 Results of microbiological parameters

A total absence of Enterococci in the raw water and treated water was observed. Moreover, the total coliforms that were present in the raw water (144 CFU/100 mL) have clearly decreased in the water treated with *Moringa Oleifera* seeds (about 90.27%) and *Boscia Senegalensis* seeds (about 85.41%)

Escherichia Coli was present in the raw water (21 CFU/100 mL). With the *Moringa oleifera* and the *Boscia senegalensis* seeds, the treatment reduced *E. coli* to 1 CFU/100 mL (about an abatement of 95.23%) and 3 CFU/100 mL (about abatement of 85%), respectively (Figure 12).

However, it should be noted that even if these treatments were allowed to obtain good yields in terms of elimination of microorganisms, these last ones nevertheless experienced a slow proliferation as the treated water remained stored at room temperature (Figures 13A, B).

4 Discussion

The reduction of turbidity by the different plant extracts identified was partially successful. Indeed, among the nine extracts prepared in solution, five showed almost no coagulant activity in the reduction of the turbidity of raw water. These are solutions based on *Acacia nilotica*, *Adansonia digitata*, *Balanites aegyptiaca*, *Capparis corymbosa*, and *Tamarindus indica*. This implies that these extracts do not have properties that promote coagulation/flocculation of colloids in raw water. To this effect, the people interviewed during the survey indicated that these extracts were very little effective compared to other extracts such as Moringa seeds. In contrast, *Tamarindus indica* and *Adansonia digitata* have been studied by some authors such as Edogbanya (Hoa and Hue, 2018; Edogbanya and Obaje, 2020) and found to be relatively effective in treating a type of raw water synthesized with clay in the laboratory.

Solutions based on *Aloe vera* and cactus (*Opuntia ficus indica*) sap, showed a low coagulant activity. Indeed, this activity was 20.7% for *Aloe vera*, and 32.25% for cactus. These rates are thus low compared to those of other studies conducted on the purifying potential of cactus (Pichler et al., 2012; Choudhary et al., 2019) and *Aloe vera* (Benalia et al., 2021; Katubi et al., 2021).

According to some studies, the active principle of cactus sap, i.e. the component of its mucilage mainly responsible for its coagulant activity is galacturonic acid (Othmani et al., 2020). However, this hypothesis was challenged by Choudhary et al. (2019), who reported in their study that none of the mucilage compounds such as neutral sugar and galacturonic acid had specific coagulation/flocculation activity. On the other hand, the combined action of the whole mucilage, i.e., pectic polysaccharides, non-pectic polysaccharides and natural electrolyte components, could be responsible for the coagulation/flocculation behavior (Othmani et al., 2020). Bouaouine et al. (2018), on the other hand suggests that the coagulant activity of the cactus is due to the presence of phenol groups, which could be attributed to lignin and tannins.

During the coagulation-flocculation process with *Aloe vera*, its functional groups (the carboxyl group) act as adsorption sites for colloidal particles in suspension (Katubi et al., 2021). In other words, the amide groups in *Aloe vera* form intermolecular bonds between the suspended solids and the coagulant, thus increasing the efficiency of the coagulation process (Benalia et al., 2021; Katubi et al., 2021).

For the treatment based on *Moringa oleifera* seeds, it was indeed demonstrated that these seeds constitute a coagulant of first order (Suhartini et al., 2013; Adelodun et al., 2020). This coagulant property is due to their richness in active cationic polyelectrolytes (Poumaye et al., 2012), that neutralize colloidal materials and cause sedimentation of mineral and organic particles (Iwuozor, 2019).

In 1995, Gassenschmidt and his collaborators were able to isolate a molecule among many others from *Moringa oleifera* seeds that had flocculent properties (Ng and Elshikh, 2021). This molecule involved in the coagulation and purification mechanism of raw water is a protein that has been named *Moringa oleifera* 2.1 (MO2.1) (Broin et al., 2002; Bodlund et al., 2014).

The MO2.1 protein also called MOCP (*Moringa oleifera* cationic protein) (Saini et al., 2016; Moulin et al., 2019), is a polymer of 13 kDa with subunits of about 6.5 kDa MO2.1 proteins once in raw water attach to surfaces of negatively charged mineral and organic particles such as silt, clay, bacteria, etc., where they will be removed by adsorption due to electrostatic interactions (Kwaambwa et al., 2015; Hoa and Hue, 2018). Due to the collision of particles and neutralization, flocs are produced which are deposited by sedimentation under the effect of gravity, leaving the water more or less clear (Moulin et al., 2019; Adeleke et al., 2022).

The seeds of *Boscia senegalensis*, like the seeds of *Moringa oleifera* were traditionally used for the clarification of turbid waters, but also as a remedy against some diseases such as stomach aches, swellings, colds etc. Salih (2015) has indeed demonstrated through potabilization tests that water treated with *Boscia senegalensis* seeds shows a significant reduction in turbidity. However, until now, no study had been able to determine for this extract, the active compound responsible for the destabilization of colloids and the reduction of turbidity.

Regarding the different physicochemical parameters other than turbidity, a slight increase in the concentration of calcium, and carbonate ions in the water after treatment was noted. This increase is not significant, and can be justified by a contribution of ions from the different plant extracts some of which contributed to the complexation of colloids present in turbid waters (Hermeline et al., 2020). This justifies the effectiveness of *Moringa oleifera* and *Boscia senegalensis* extracts in the efficient treatment of raw water.

Regarding the microbiological quality, the waters treated with *Moringa oleifera* and *Boscia senegalensis* showed a good reduction. Indeed, according to some studies, the MO2.1 protein of *Moringa oleifera* seeds has a very interesting antibacterial activity (Santos et al., 2013; Nhut et al., 2021). The activity of this peptide against pathogens, including *Pseudomonas* and *Streptococcus*, has been well studied by Suarez et al. (2005).

5 Conclusion

The quality of the water consumed is essential to human development and wellbeing. Unfortunately, raw water, whether underground or surface, does not always meet the required criteria in terms of chemical and microbiological quality. This is why water must be treated before it is consumed. Coagulation-flocculation is one of the most widely used processes for the treatment of raw water, as it is efficient and simple to implement. Its implementation requires coagulants generally of chemical origin such as aluminum sulfate, which however presents a danger for humans and the environment; hence the need to find an alternative.

Thus, this experimental study demonstrated the capacity of extracts of certain plants such as *Moringa oleifera* seeds and *Boscia senegalensis* seeds to make surface water drinkable. These two biocoagulants are just as effective as aluminum sulfate and could even replace it. We also obtained interesting results with cactus and *Aloe vera* sap, which proved to be less effective as coagulants, but showed possible and good capacities as flocculation aids. Finally, this study brings on one hand an interesting contribution in the field of the valorization of the organic natural resources, and on the other hand possibilities of resolution of the problem of the access to drinking water by the use of biocoagulants.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

The study protocol was written by AK, PS, and MHD. The field and laboratory research was conducted by AK. The manuscript was written by AK, PS, MD, and MHD. Statistical analyses were performed by AK, RD, and MD. Scientific supervision of the study was provided by PS and MHD. All authors contributed to the article and approved the submitted version.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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