



Opuntia ficus-indica (L.) Mill. (Cactaceae) in Climate Change Scenarios and Its Potential for Wastewater Bioremediation in Semi-Arid Regions: A Systematic Review and Meta-Analysis

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Authors' contributions

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ABSTRACT

Anthropogenic actions have caused climatic changes and contamination of water resources, generating negative consequences for plants and instigating the search for new alternatives for water treatment. The objective of this work was to use a systematic and narrative review in databases and meta-analysis to assess the state of the art on the implications of climate changes in forage palm crop and to highlight the potential of this cactus for wastewater bioremediation, as well as to verify if this form of water treatment is used in semi-arid regions, especially in the semi-arid region of Brazil. Systematic review, narrative and meta-analysis were used, searching the database. The articles obtained with a theme pertinent to the study were carefully analyzed. The data were submitted to descriptive analysis and meta-analysis using random effects model. It was verified that the forage palm is a strategic crop for cultivation in the semi-arid, mainly for its expressive adaptive capacity, through the activation of defense mechanisms against sudden variations in temperature, CO₂ atmospheric concentration, photosynthetic active radiation and soil water availability. In addition, forage palm has a high potential for wastewater bioremediation, reaching an average of 82.71% of water contaminants. In one study, the authors report that this cactus is abundant and can be used for bioremediation of wastewater in semi-arid regions such as northern Ethiopia. No studies were found with the use of palm for bioremediation of wastewater in the semi-arid region of Brazil.

Keywords: Opuntia ficus-indica; forage palm; environment; temperature; water quality; adsorption; flocculation.

1. INTRODUCTION

Since far afield, farmers have sought strategies to coexist with environmental adversities. Knowing the factors that influence rural man's decision making regarding the adoption of strategies to adapt to climate change is essential for increasing productivity in agroecosystems. These understanding guides public policies and shows a broad field of action for the scientific community [1].

It is important to note that different aspects related to climate change, such as the increase in temperature, the reduction of rainfall and the higher atmospheric concentration of CO₂, have different effects on crop yields. In this context, the use of crop yield prediction models is a promising strategy for estimating productivity in future scenarios of climate change [2].

It is a fact that the climatic changes affect the spatial and temporal distribution of the rains, being able to cause water deficit to the cultures. It should be noted that the increase in population and the consequent demand for larger quantities of food tend to increase the consumption of water resources [3]. This scenario has increased the pressure for alternative water sources, denoting the potential of wastewater for use in irrigation [4].

The increase in the volume of wastewater on the planet implies an environmental problem of

difficult solution, mainly due to the characteristics of these waters as their coloration, high turbidity, biochemical and chemical oxygen demand, hydrogenation potential and temperature, showing high complexity for the appropriate treatment and subsequent return to the environment [5,6].

It is estimated that the daily production of drinking water from natural waters is 250 liters, on average, with use of 2 liters by man and waste of 248 liters polluted [7]. Treating wastewater requires a comprehensive planning, design, construction, and management of treatment facilities to ensure that the treated water is safe for human consumption and for discharge to the environment. The potential treatments include primary, secondary, and tertiary treatment using mechanical, chemical, and biological processes. Nowadays wastewater treatment plays an important role in providing safe water to ease water scarcity in some areas [8,9].

Currently, several sources of adsorbents have been investigated for the purpose of being used for water treatment. However, some of the adsorbents are difficult to develop and high cost which makes their use on a large scale unfeasible. Thus, the use of polysaccharide adsorbents is considered a sustainable and potential alternative in the treatment of wastewater [10].

Forage palm (*Opuntia ficus-indica* (L.) Mill.) is an important source of proteins, minerals, fats, carbohydrates, fibers, energy and fatty acids, with high antioxidant capacity [11]. This plant can also be used for medicinal purposes [12], a raw material in the manufacture of cosmetics and pharmaceuticals, and is widely used for wastewater treatment [13,14].

The forage palm is a cactus adapted to the semi-arid climatic conditions, especially due to its morphophysiological mechanism CAM (Crassulacean Acid Metabolism), which gives it greater efficiency in the use of CO₂ and water [15]. Knowledge of soil water dynamics helps to make decisions about the water supply of the palm, justifying the development of forage palm research in climate change scenarios [16].

Based on this information, it is important to note that the cost of implantation and time demand with experimental tests has encouraged the scientists to use the technique of systematic review and meta-analysis to collect evidence to support their hypotheses, mainly because this technique statistical results of quantitative studies [17]. In this sense, the absence of meta-analytical studies on the use of forage palm to remove contaminants from water evidences the need to gather specialized literature that proves the evidence that this cactus can be used as an alternative for water purification.

The objective of this work was to use a systematic and narrative review in databases and meta-analysis to assess the state of the art on the implications of climate changes in forage palm crop and to highlight the potential of this cactus for wastewater bioremediation, as well as to verify if this form of water treatment is used in semi-arid regions, especially in the semi-arid region of Brazil.

2. MATERIALS AND METHODS

2.1 Characterization of Search Type

The research is classified as qualitative and quantitative [18]. The qualitative aspect is characterized by the narrative explanation of the effects of climatic changes, such as the increase in temperature, the reduction of the rainfall regime and the higher atmospheric concentration of CO₂ on the forage palm variables and the mechanisms involved in the tolerance responses of these plants. The quantitative aspect is

represented by the collection of data regarding the number of articles published in each database and the forage palm response variables expressed by means of sample size, mean and standard deviation, which will be used for meta-analysis.

Regarding nature, research is of an applied type, since it aims to generate knowledge for practical application, aimed at solving specific problems related to forage palm and its applicability to bioremediation. In relation to the objectives the research is classified as explanatory [19]. As for the procedures, the research is of the bibliographic type, complemented by systematic review and meta-analysis [20].

2.2 Systematic and Narrative Review

For the realization of this research, we used a systematic and narrative review [21]. To do so, a systematic search was made in the databases: Scholar Google, Scielo, Science Direct, Scopus, Springer Link and Wiley Online Library, on August 26, 2017. The search terms were: "*Opuntia ficus-indica*" AND "water deficit"; "*Opuntia ficus-indica*" AND "déficit hídrico"; "*Opuntia ficus-indica*" AND "climate changes"; "*Opuntia ficus-indica*" AND "mudanças climáticas"; "*Opuntia ficus*" AND "water treatment"; and "*Opuntia ficus*" AND "tratamento de água".

The Boolean operator "AND" was used to obtain articles that contained the two quoted terms simultaneously in the same article, considering title, abstract and keywords. The data obtained were arranged in electronic spreadsheet and submitted to descriptive statistical analysis. The articles with pertinent themes to explain the implications of climate change and water scarcity on forage palm, as well as the mechanisms involved in the responses of this plant, were carefully examined and described in the narrative review form.

2.3 Meta-analysis

The meta-analysis was used to show the potential of forage palm for wastewater bioremediation, according to the methodology described by [20]. We used the systematic search data from the Scopus database between 1999 (year of the first available record) and August 26, 2017, considering the search term: "*Opuntia ficus*" AND "water treatment".

The search resulted in 23 documents, which were thoroughly analyzed and submitted to the inclusion and exclusion criteria for subsequent meta-analytical data treatment. Eleven studies were included, with the use of forage palm for water purification, having as variable response the turbidity or percentage of removal of some contaminating metal or pesticide from the water. Due to the different nature of these variables, the responses were expressed in terms of percentage of contaminant bioremediation, obtained through the following relationship:

$$PCR = \frac{ICC - CCT}{ICC} * 100$$

Where: PCR - percentage of contaminant removal, ICC - initial concentration of contaminant and CCT - concentration of contaminant after treatment.

In the selected studies, after inclusion and exclusion criteria, data regarding sample size (S), mean response variable (M) and standard deviation (SD) were obtained in the experimental group treated with *Opuntia ficus-indica* (OFI) and in the group control without OFI treatment. The estimation of the variability between the studies (r^2) was done by the method described by DerSimonian and Laird [22] and the calculation of the weighting of each study was done using the inverse variance method. Due to the high heterogeneity, the random effects model was used [23]. The meta-analysis was conducted in software R, using the "metafor" package [24,25].

3. RESULTS AND DISCUSSION

3.1 Search Relevance

The results for relevance of the research, obtained from the combination of search terms in the databases are represented in Fig. 1. The significant number of published documents denotes the relevance of the proposed research. The relevant literature has an abundance of publications relating *Opuntia ficus-indica* to the water deficit (average of 112 and maximum of 491 documents) (Fig. 1A and B). For *Opuntia ficus-indica* relationship with climate change (average of 68 and maximum of 158 documents) (Fig. 1C and D). For the relation of *Opuntia ficus-indica* with the treatment of water (average of 235 and maximum of 689 documents) (Fig. 1E and F).

The results indicate that Scholar Google returns an expressive number of documents related to the search terms, both in English and Portuguese, possibly for retrieving the documents contained in the other databases. For efficient searches in the other databases, the terms must be inserted in English.

It is important to note that, in historically consolidated databases, publications undergo a rigorous selection process to be indexed, whereas in Scholar Google (SG) content filtering is less rigorous [26]. According to Noruzi [27], the scope of the SG consists of all information published on the Web, including all kinds of academic material, which may not always be considered in this way. In a complementary sense, [28] report that the coverage guaranteed by the SG does not cover all content related to the search, and there is a need to search the other databases.

3.2 Forage Palm and Climate Changes

The semi-arid regions are characterized by the type of climate with low humidity and low rainfall volume. In the world classification, the semi-arid climate is one that presents average rainfall between 200 mm and 400 mm. Fig. 2 shows the semi-arid climate regions in the world. In Brazil, the semi-arid region is located in the Northeast, covering the states of Bahia, Ceará, Alagoas, Piauí, Paraíba, Pernambuco, Sergipe and Rio Grande do Norte; and Southeast of the country, covering the north of the state of Minas Gerais.

The forage palm is native to Mexico, but has a wide geographic distribution, being cultivated in South America, Africa, and Europe [29]. In Brazil, cultivation occupies an area of more than 600 thousand hectares, predominantly in the Northeast region [30].

The negative impacts of climate change can influence the food security of the growing world population, mainly due to the increase in temperature and atmospheric concentration of CO₂. In this context, the cultivation of plants with crassulaceous acid metabolism (CAM), e.g. *Opuntia ficus-indica*, is a sustainable alternative for biomass production, mainly because they have high water use efficiency (WUE) and resilience to climatic changes [31].

Opuntia ficus-indica plants evolved to better adapt to arid and semi-arid ecosystems, with an emphasis on supporting the spatial and temporal

distribution of rainfall. These plants open the stomata and capture CO₂ at night when the temperature is low, reducing perspiration and increasing WUE. The parenchyma tissue of

forage palm water storage associated with the high hydraulic conductivity of its roots makes the plant efficient in absorbing and storing water during a period of low availability [32].

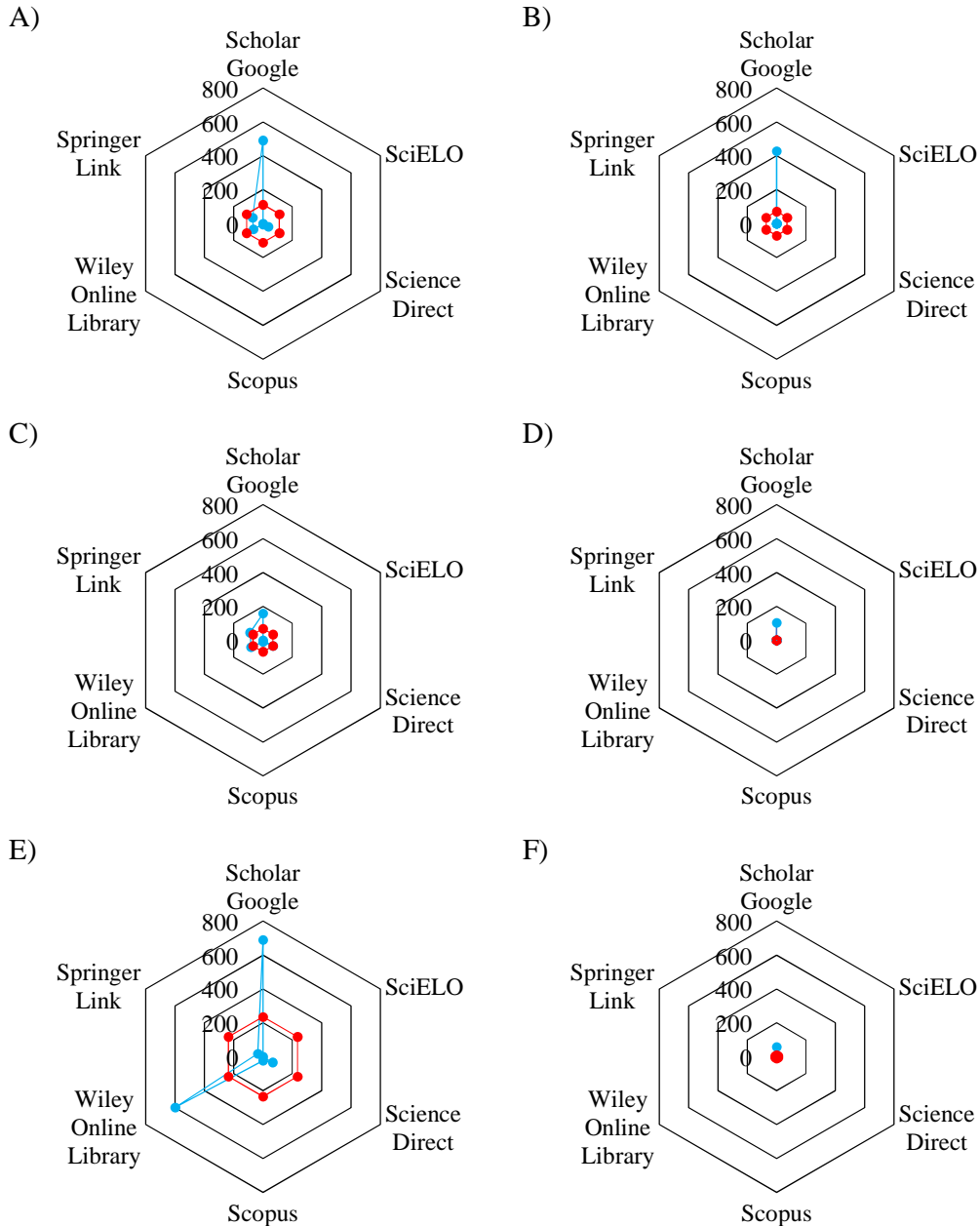


Fig. 1. Number of articles based on databases for search terms: "*Opuntia ficus-indica*" AND "water deficit" (A); "*Opuntia ficus-indica*" AND "déficit hídrico" (B); "*Opuntia ficus-indica*" AND "climate changes" (C); "*Opuntia ficus-indica*" AND "mudanças climáticas" (D); "*Opuntia ficus*" AND "water treatment" (E); and "*Opuntia ficus*" AND "tratamento de água" (F). Blue line (---) represents articles by database and red line (---) average articles in all databases

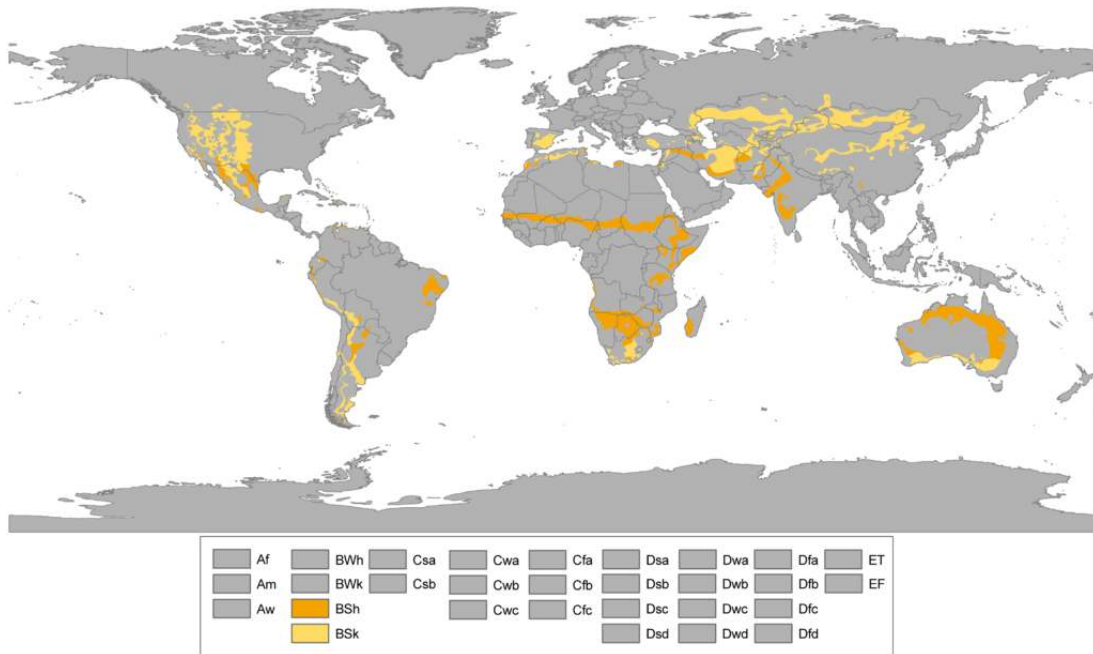


Fig. 2. Global distribution of regions with hot semiarid climate (BSh) and cold semiarid climate (BSk). Source: [33]

The forage palm prospects, obtained through climate simulations for the year 2070, indicate that the crop has a high potential to increase biomass yield, which is justified by the possibility of a 10% increase in CO₂ assimilation as a result of their ability to utilize small amounts of available water in the soil and to have low sensitivity to extreme temperature variations [31].

3.3 Forage Palm and Water Scarcity

The water deficit reduces the growth of forage palm. In regions with rainfall of less than 368 mm, irrigation is required for the crop to express greater productive potential [34]. Although *Opuntia ficus-indica* is adapted to the semi-arid conditions, significant reductions occur in its photochemical apparatus under soil water restriction. In fact, in chlorenchyma there are reductions of 42, 34 and 31% in total chlorophylls *a* and *b*, while in the parenchyma the reductions of these pigments are 39, 36 and 26%, respectively. The activity of the enzyme phosphoenolpyruvate carboxylase (PEP) is reduced by 19% in chlorenchyma and 60% in the parenchyma. The transport of photosynthetic electrons is reduced by 29% in chlorenchyma and increases by 150% in the parenchyma. The quantum efficiency of photosystem II is reduced

both in the parenchyma and in the chlorenchyma [35].

The activity of the antioxidant system of forage palm increases under conditions of soil water scarcity. This is due to increases in metabolites, such as phenolic acids and flavonoids, in addition to the activity of the enzyme phenylalanine ammonia-lyase [36]. It is important to emphasize that, under irrigation, the forage palm can modify its metabolism to CAM-optional. It is emphasized that the mechanisms by which this change in metabolism occurs are poorly understood. However, the efficiency of such a metabolic change is questioned because of this change occurring in a short period of time and little contribution to carbon accumulation, and there is a need for a resumption of CAM metabolism [37].

3.4 Efficiency of Forage Palm for Bioremediation

The results of the meta-analysis are presented in Table 1. It was verified that the general mean of the differences is positive, indicating that the group treated with *Opuntia ficus-indica* was effective in 82.71% in the removal of contaminants from the water, being able to

remove 75.22% in the scenario of lower removal and 90.21% in the scenario of greater removal. It should be emphasized that all studies considered converge to *Opuntia ficus-indica* efficiency for bioremediation. In fact, the overall effect, Z, was significant ($p < 0.001$), confirming the difference between the *Opuntia ficus-indica* treatment and the control group. However, the estimation of the variability among the studies was high ($\tau^2 = 159.9$) with high ($I^2 = 99.9\%$) heterogeneity significantly ($p < 0.001$), justifying the choice of the random effects model in this study [23].

The graphical representation of the meta-analysis is shown in Fig. 3, showing that all studies have positive averages (to the right of the graph) and that the confidence intervals do not cross the mean (0), evidencing unanimity of the OFI treatment for bioremediation contaminated water.

3.5 Mechanisms of Bioremediation

The mechanisms by which *Opuntia ficus-indica* promotes the removal of contaminants from water have not yet been fully elucidated, so much research is done with the application of components of this cactus to remove turbidity, heavy metals and pesticides. It is known that this plant is used in the form of mucilage, powder of dry cladodes and even portions or juice of fresh cladodes, acting on coagulation, flocculation and sedimentation [13,14].

Fig. 4 show the micrograph obtained by scanning electron microscopy showing the surface morphology of the polysaccharide isolated from *Opuntia ficus-indica*. Generally, the images showed a rough surface with large voids evincing an estimated average particle size of 255 nm (using ImageJ software). The rough surfaces are advantageous, as they could provide more sites (i.e., higher surface area) for the transfer (via diffusion) of the metal ions from the solution matrix onto the sorbent, thereby enhancing its adsorption efficiency [38].

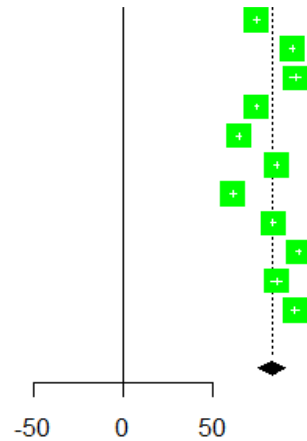


Fig. 3. Graphical representation, forest plot, of the individual effects of each study and of the combined effect of the use of *Opuntia ficus-indica* for wastewater bioremediation

Table 1. Meta-analysis summary for 11 studies to identify whether forage palm can be used for bioremediation of contaminated water

| Study | SO | MO | SDO | SC | MC | SDC | Weight | AD | [95% - CI] |
|----------------------------|-------|-------|------|-------|-------|------|--------|-------|----------------|
| Onditi et al. [38] | 3.00 | 87.00 | 1.00 | 3.00 | 13.00 | 1.00 | 9.10 | 74.00 | [72.40; 75.60] |
| Nharingo et al.[39] | 3.00 | 97.00 | 1.00 | 3.00 | 3.00 | 1.00 | 9.10 | 94.00 | [92.40; 95.60] |
| Belbahloul et al.[9] | 4.00 | 97.96 | 2.15 | 4.00 | 2.04 | 2.15 | 9.00 | 95.91 | [92.93; 98.89] |
| Nawel et al. [40] | 3.00 | 87.00 | 0.80 | 3.00 | 13.00 | 0.12 | 9.10 | 74.00 | [73.08; 74.92] |
| Fedala et al. [41] | 5.00 | 82.20 | 1.00 | 5.00 | 17.80 | 1.00 | 9.10 | 64.40 | [63.16; 65.64] |
| Betatache & Aouabed [42] | 3.00 | 92.66 | 1.00 | 3.00 | 7.34 | 1.00 | 9.10 | 85.32 | [83.72; 86.92] |
| Vishali & Karthikeyan [43] | 3.00 | 80.44 | 1.00 | 3.00 | 19.56 | 1.00 | 9.10 | 60.88 | [59.28; 62.48] |
| Bouatay & Mhenni [44] | 3.00 | 91.66 | 1.00 | 3.00 | 8.34 | 1.00 | 9.10 | 83.32 | [81.72; 84.94] |
| Asha et al. [45] | 3.00 | 98.75 | 1.00 | 3.00 | 1.25 | 1.00 | 9.10 | 97.50 | [95.90; 99.10] |
| Gebrekidan et al. [46] | 2.00 | 92.67 | 1.53 | 2.00 | 7.33 | 1.53 | 9.00 | 85.33 | [82.34; 88.33] |
| Buttice et al. [47] | 3.00 | 97.71 | 1.37 | 3.00 | 2.29 | 1.37 | 9.10 | 95.42 | [93.23; 97.61] |
| Total [95% - IC] | 35.00 | | | 35.00 | | | 100.00 | 82.71 | [75.22; 90.21] |

Heterogeneity: $\tau^2 = 159.9$; $X^2 = 2471.41$; $DF = 10$; ($p < 0.0001$); $I^2 = 99.9\%$
 Overall effect: $Z = 331.66$; ($p < 0.0001$)

SO: size of the sample treated with *Opuntia ficus-indica* (OFI); MO: response variable means after treatment;
 SDO: standard deviation of treated samples; SC: size of the sample not treated with OFI; MC: mean of response variable without treatment with OFI; SDC: standard deviation of untreated samples; AD: average of the differences; CI: confidence interval; τ^2 : estimation of variability between studies. X^2 : chi-square test; DF: degree of freedom; p: probability of significance; I^2 : heterogeneity; and Z: Z test

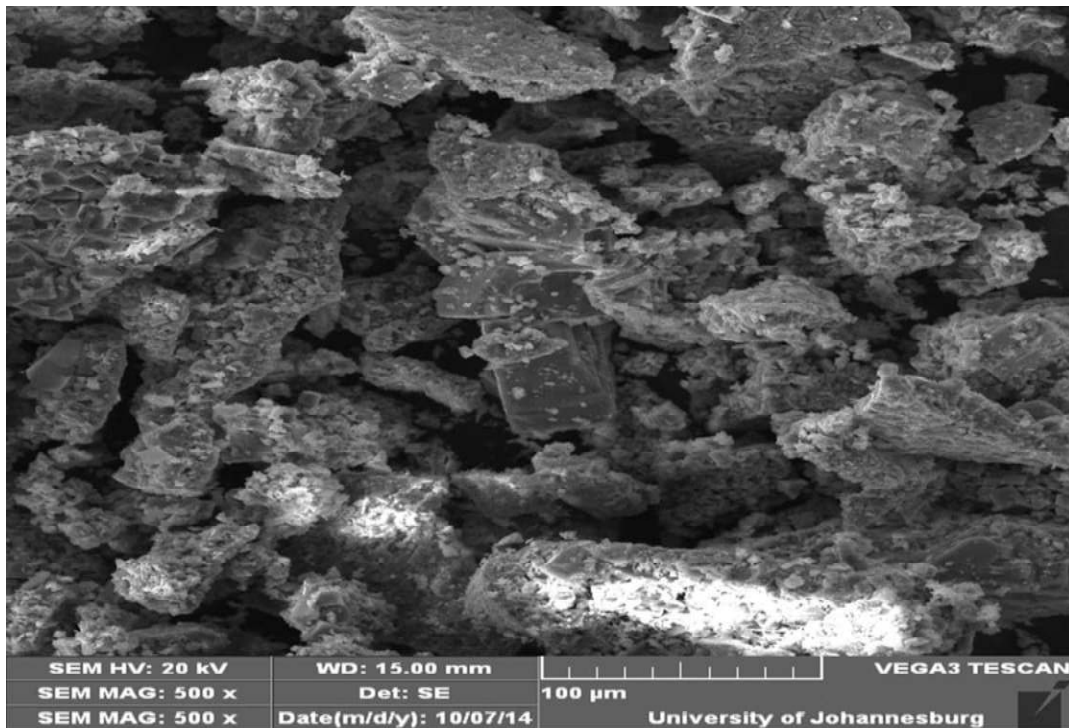


Fig. 4. Micrograph obtained by scanning electron microscopy (SEM) evidencing the surface morphology of the isolated polysaccharide. Source: [38]

The efficiency of *Opuntia ficus-indica* for coagulation is related to the colloidal destabilization and the formation of larger agglomerates, which will later be separated from the liquid fraction. Four mechanisms are responsible for the destabilization of colloids, namely: double-layer compression, adsorption-destabilization, scanning, and formation of chemical bridges [39]. The measurement of zeta potential and conductivity suggests that the most likely mechanisms are the adsorption and the formation of chemical bridges, notably because, despite the increase of *Opuntia ficus-indica* added to the solutions, the zeta potential of the filtrate is still negative, which excludes the thesis adsorption and scanning [42].

3.6 Successful Cases in Bioremediation

Using polysaccharides extracted from *Opuntia ficus-indica*, Onditi et al. [38] found a high removal capacity of heavy metals such as lead ion (Pb^{2+}) and cadmium (Cd^{2+}), reaching 256 and 151 mg L⁻¹, respectively, being considered high when compared with other natural biosorbents. Nharingo et al. [39] report that *Opuntia ficus-indica* is an effective bioflocculant for the removal of Pb^{2+} ions and that the extract of this plant in

other studies has proved to be efficient for the removal of Zn, Cd and Cu from the waters of the Mukuvisi River.

Belbahloul and Anouar [48] obtained water turbidity removal efficiency greater than 99% using *Opuntia ficus-indica* mucilage pectin. Nawel et al. [40] verified that the addition of juice of this vegetable in wastewater promotes the removal of the turbid, attributing this effect to the concentration of *Opuntia ficus-indica*, pH and conductivity. For Fedala et al. [41], *Opuntia ficus-indica* is a good flocculating agent to reduce turbidity, highlighting its low cost and sustainability.

It is important to emphasize that in the studies of Betatache and Aouabed [42] and Vishali and Karthikeyan [43], the results obtained with *Opuntia ficus-indica* juice are also compared with those of commercial polyelectrolytes such as Chimfloc C4346, a cationic polymer, Sedipur NF 400, a non-ionic polymer, and Sedipur AF 102, an anionic polymer, and inorganic conditioners such as $FeCl_3$ and $Al_2(SO_4)_3$. *Opuntia ficus-indica* juice proved to be the most efficient because the optimum dosage was found to be 0.4 gkg⁻¹ of dry matter for *Opuntia ficus-indica* juice whereas for

Chimfloc C4346, FeCl₃ and Al₂(SO₄)₃ the optimum doses were be found to be 0.8, 80 and 60 gkg⁻¹. Based on the obtained results, *Opuntia ficus-indica* juice could be used as a natural conditioner in sewage sludge treatment.

4. CONCLUSION

The development of research related to forage palm in scenarios of climatic changes and water scarcity is pertinent, given that the literature has gathered an expressive number of publications on the subject, where are evidenced innumerable gaps to be studied.

Forage palm is a strategic crop for semi-arid cultivation, mainly because of its expressive adaptive capacity, through the activation of defense mechanisms against sudden variations in temperature, atmospheric CO₂ concentration, photosynthetic active radiation and soil water availability.

Forage palm has a high potential for bioremediation of contaminated water, reaching an average of 82.71% of water contaminants. In only one of the 11 papers studied, the authors report that *Opuntia ficus-indica* is abundant and can be used for bioremediation of wastewater in semi-arid regions such as Northern Ethiopia. No studies were found using *Opuntia ficus-indica* for bioremediation of contaminated water in the Brazilian semi-arid region.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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