

# Assessing the capacity of *Salicornia bigelovii* Torr. to grow and remove enrofloxacin and oxytetracycline in aquaculture wastewater

Evaluando la capacidad de *Salicornia bigelovii* Torr. para crecer y remover enrofloxacin y oxitetraciclina en aguas residuales de la acuicultura

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## ABSTRACT

To improve shrimp production, chemicals, such as antibiotics, are added to the system, which results in a series of adverse effects on the environment. Phytoremediation by wetlands built with halophytes has been a possible solution to eliminate antibiotics, among other micropollutants; *Salicornia bigelovii* could be a viable alternative to eliminate them. The present study investigated *S. bigelovii* capacity to grow on saline aquaculture effluents and remove the antibiotics enrofloxacin and oxytetracycline. Seven concentrations of each antibiotic (1 - 1000 µg/L) were used; plant growth was higher than the control without antibiotics and showed a high potential for root accumulation and a low translocation rate from root to stem. The plants in enrofloxacin presence kept the translocation factor at the same level, but the bioconcentration factor decreased with three higher antibiotic (50, 100, and 1000 µg/L) concentrations. When enrofloxacin was used, growth improved at the 100 and 1000 µg/L concentrations, whereas with oxytetracycline, growth improved at seven concentrations. The present study demonstrated that *S. bigelovii* can grow in water with enrofloxacin and oxytetracycline presence. Therefore, plants can be used to exploit wastewater nutrients in the shrimp industry, besides producing biomass to generate biofuels and avoid pollutants reaching the sea.

## RESUMEN

Para aumentar la producción en las granjas camaronícolas se agregan sustancias, como los antibióticos, que generan efectos adversos sobre el ambiente. La fitorremediación es una posible solución para eliminar antibióticos de las aguas residuales; la planta *Salicornia bigelovii* podría ser una alternativa viable para eliminarlos. En el presente estudio se investigó la capacidad de *S. bigelovii* para crecer en efluentes salinos de la acuicultura y remover los antibióticos enrofloxacin y oxitetraciclina. Se usaron siete concentraciones de cada antibiótico (desde 1 hasta 1000 µg/L); el crecimiento de las plantas fue mayor que los controles y mostraron un alto potencial para la acumulación radicular y baja tasa de translocación al tallo. Con enrofloxacin las plantas mantuvieron el factor de translocación en el mismo nivel; el factor de bioconcentración disminuyó en las tres concentraciones más altas (50, 100 y 1000 µg/L). Con enrofloxacin el crecimiento mejoró en 100

y 1000 µg/L mientras que con oxitetraciclina lo hizo en las siete concentraciones. El presente estudio demostró que *S. bigelovii* puede crecer en agua con enrofloxacin y oxitetraciclina, y pueden ser usadas para explotar los nutrientes de las aguas residuales camaronícolas, producir biomasa para biocombustibles y evitar que los contaminantes lleguen al mar.

**Keywords:** Wastewaters, shrimp industry, wetlands, removal, micropollutants, remediation.

## INTRODUCTION

Shrimp production represents 34 % of Mexican aquaculture, making this product of great commercial importance (Espinoza *et al.*, 2012). Consequently, to intensify and improve its production, chemicals, such as nutrients, growth promoters, and antibiotics, are added to the system (Graslund *et al.*, 2003). This practice generates several adverse effects on the environment when wastewater is discharged into water bodies; due to the previous, the practice has been addressed by scientists and environmentalists (García-Galindo *et al.*, 2021; Iber and Kazan, 2021). Among the impacts of shrimp farming that have been reported, water eutrophication is one of them since 60 - 90 % of the nutrients added to feed are released in effluents in nitrogen and organic phosphorus (Troell *et al.*, 2003). Likewise, notable amounts of antibiotic residuals discharged in coastal zones have been reported as ecotoxic agents. Compounds may bioaccumulate and bio-magnify in marine organisms, generating endocrine, reproductive disorders, and microbial resistance to antibiotics; such resistance could be transferred to terrestrial animals and affect human and animal health, causing a high ecological risk (Adenaya *et al.*, 2023). The concentration of antibiotics in wastewaters shows a wide range from ng/L to µg/L (Li *et al.*, 2020).

When aquaculture wastewater is discharged into the ocean, it becomes an important source of pollutants (Zhang *et al.*, 2013), where physical processes, such as filtration and sedimentation, may disseminate the content of antibiotics and nutrients in effluents. Nonetheless, such processes are inadequate to treat significant volumes of wastewater produced in shrimp farming (Silvanir *et al.*, 2024).

Phytoremediation by wetlands built with halophytes has been a possible solution to eliminate antibiotics from wastewater. These green systems are based on plant, mi-

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croorganisms, and contaminant interactions (Carvalho *et al.*, 2012) with several physical, chemical, and biological processes that are co-occurring, such as absorption, accumulation in plants, microbial degradation, and others (Vymazal, 2010; García *et al.*, 2014).

The selection of plant species is critical to eliminate antibiotics from wastewater efficiently. However, knowledge of the relationship among physiological, morphological, and biochemical characteristics is limited in using saline wetlands. On the other hand, these species should be salt-tolerant. Halophytes have developed a variety of tolerance mechanisms to cope with salinity stress, which also helps them tackle stress from other contaminants (Manousaki *et al.*, 2011; Liang *et al.*, 2016). The genus *Salicornia* has been reported for removing salt, heavy metals, and xenobiotics in diverse types of wastewaters (Delgadillo *et al.*, 2011; Webb *et al.*, 2012; Liang *et al.*, 2016). Thus, *S. bigelovii* could be a viable alternative for the removal of this type of microcontaminants compared with other methods currently used.

The use of *Salicornia* for phytoremediation has more than one side because wastewater contains nutrients, such as nitrogen and phosphorus. These nutrients can be exploited for plant growth and eliminated from water to avoid reaching the sea, besides favoring cultivation and gaining ground as fresh food. Furthermore, the plant (seeds) could also be used as a source of oil for biodiesel (Al Yammahi *et al.*, 2024) or to eliminate microcontaminants, such as antibiotics in wastewater. Considering the previous information, the objective of the present study was to assess the capability of *S. bigelovii* to grow in aquaculture wastewater and remove oxytetracycline and enrofloxacin antibiotics.

## MATERIALS AND METHODS

*Salicornia bigelovii* plants of the same cohort (15 cm in height), apparently healthy (turgent and intense green color), were collected from Miramar Estuary in Guaymas, Sonora, Mexico (27° 55' 48.81" N and 110° 56' 54.25" W) from October to December 2017. The plants were extracted with their root systems, transferred to the laboratory in pots with natural substrate (sand) as support, and irrigated with seawater from the same site where they were extracted until they arrived at the laboratory.

The residual water from shrimp farming was obtained from the aquaculture shrimp farm "Revolución Cardenista" (Leased by: SRY Promotora Acuicola, S.A. de C.V.) north of Bahía del Tóbari (27° 08' 08.3" N and 110° 02' 10.3" W). Sampling was performed based on the Mexican norm for wastewater sampling (NMX-AA-003-SCFI-1980), that establishes general guidelines and recommendations for sampling wastewater dischargers, to determine their physical and chemical characteristics. In the laboratory, the plants were separated from the substrate, washed with distilled water, and maintained in a 15-day acclimation period in environmental conditions and marine water, adding nutritional Hoagland solution at 20% with respect to the composition reported by Leyva and Bashan (2008). Subsequently, the plants were transferred

to a hydroponic growth system by lots, which consisted of circular opaque plastic recipients with an operation volume of 65 mL of filtered wastewater.

Seven treatments of enrofloxacin and oxytetracycline (independent experiments) were performed with concentrations of 1, 5, 10, 20, 50, 100, and 1000 µg/L (C1, C2, C3, C4, C5, C6, and C7, respectively), and adjusted in wastewater from shrimp farming. Each treatment consisted of 10 plants and two types of control groups. The first control (biotic) consisted of 10 plants/treatment (hydroponic plant system in a shrimp farming water medium without antibiotics) and the second one (abiotic), which consisted of a hydroponic system with concentrations C1-C7 but with no plant. A total of 80 plants/antibiotics were assessed in their removal capacity at the end of a 4-week experimental period.

### Limitations: the experiments were carried out separately because of the small working area.

#### Antibiotic extraction

Two extraction buffers (also used as a mobile phase in the chromatographic system) were prepared; buffer A (Intorre *et al.*, 2000) contained phosphoric acid at 0.1% in water plus acetonitrile (70:30), and buffer B (Reed *et al.*, 2004) contained oxalic acid 0.01 M in water plus methanol (50:50). Then, 2 mL of water from the hydroponic system were mixed, adding 2 mL of extraction buffer (buffer A for enrofloxacin and B for oxytetracycline) and left to settle for 30 min. After that, the mixture was agitated in vortex for one minute and subsequently centrifuged at 3000 and 5500 rpm, respectively for 15 min (Centrifuge 5810 R Eppendorf®, Hamburg, Germany). The necessary dilutions were performed, and 1 mL was taken to filter it through a 0.2 µm porous membrane (Millipore®, Billerica, and MS, USA) for its subsequent injection into the equipment (modified from Martínez, 2013 adapted from papers published by Intorre *et al.*, 2000 and Reed *et al.*, 2004).

#### Plant samples

At the end of the experiment, fresh plants were washed with distilled water and separated into aerial parts (stems) and roots. After that, 2 g of aerial tissue and 0.6 g of root were ground in a mortar, adding 5 mL of extraction buffer (buffer A for enrofloxacin and buffer B for oxytetracycline) and, subsequently, homogenized until the medium was uniform. Then, in the case of the enrofloxacin samples, they were left to settle for 15 min and centrifuged at 13000 rpm at 4°C; as for oxytetracycline, the procedure was similar but centrifuged at 13 400 rpm. Finally, 1 mL of each sample was taken and subsequently filtered into a vial through a 0.2 µm porous membrane (Millipore®), Billerica, MS, USA) and injected into high-performance liquid chromatography (HPLC) (Modified from Martínez, 2013, adapted from previous papers published by Della Rocca *et al.*, 2004 and Reed *et al.*, 2004).

#### Chromatographic system

Antibiotics were HPLC grade and obtained from Sigma (San Louis, MO, USA). Calibration standard curves with a detection

limit inferior to 1 µg/L were performed to identify and quantify antibiotics with high-performance liquid chromatography (HPLC) (Agilent®, 1260, Santa Clara, USA). The HPLC system was equipped with a quaternary pump (1260 HiP ALS), an auto-injector with a capacity of 0.1 - 100 µL (1260 HiP ALS) and a diode detector (1290 DAD). A ZORBAX Eclipse Plus-C18 (4.6 x 150 mm, 3.5 µm) column and OpenLAB CDS software (Version A.01.04) data processor were used. The chromatographic conditions for enrofloxacin were: buffer A used as mobile phase, an injection volume of 10 µL (for samples deriving from plants) and 20 µL (for samples coming from water), a flux of 1 mL/min at 30 °C and a wavelength (λ) of 280 nm. For oxytetracycline: buffer B used as the mobile phase, the conditions were a 1 mL/min flux at 30 °C and a wavelength (λ) of 264 besides 10 and 20 µL injection for samples deriving from plants and water, respectively. The run time for both antibiotics was 10 min. Wavelengths, retention times, and flows were modified because more response area was obtained with those modifications (Modified from Martínez, 2013, adapted from previous papers published by Della Rocca *et al.*, 2004 and Reed *et al.*, 2004).

### Calculation of antibiotic removal

To calculate the global removal percentage of each antibiotic in each treatment, the following equation was used:

$$\% \text{ Removal} = \frac{\text{initial liquid concentration} - \text{final liquid concentration}}{\text{initial liquid concentration}} [100]$$

### Effect on physiological development

Weekly growth monitoring (cm) in plant height and length of the root system was performed with a Vernier. Moreover, the number of shoots and biomass quantity were counted at the beginning and end of the experiment.

### Calculation of accumulation index

The bioconcentration factor (BCF) of antibiotics in plant tissues was calculated as the relationship of the chemical antibiotic concentration in the plant tissue with the enriched (or nominal) concentration in the growth medium, according to the equation proposed by Wu *et al.* (2013).

$$BCF = \frac{\text{plant concentration} \left( \frac{\mu\text{g}}{\text{kg}} \right)}{\text{solution concentration} \left( \frac{\mu\text{g}}{\text{L}} \right)}$$

### Calculation of the translocation factor

Antibiotic translocation from the roots to the aerial part was expressed as translocation factor (TF) and calculated simply as the concentration ratio in the aerial part from the roots according to the equation proposed by Hurtado *et al.* (2016).

$$TF = \frac{\text{concentration in aerial tissue} \left( \frac{\mu\text{g}}{\text{kg}} \right)}{\text{concentration in radicle tissue} \left( \frac{\mu\text{g}}{\text{kg}} \right)}$$

### Statistical analysis

The results obtained were subjected to an analysis of variance (ANOVA) and Tukey's range test for multiple comparison at 95 % confidence by the statistical package Statgraphics Plus 5.1. A difference was defined at the moment that the

statistical analysis (ANOVA) showed a *p-value* equal to or less than 0.05 when the means of the variables were compared.

## RESULTS

The present study investigated the capacity of *S. bigelovii* to treat saline aquaculture effluents and remove enrofloxacin and oxytetracycline in higher concentrations than those found in this type of effluents.

The first step for a successful phytoremediation is that the plant should be tolerant to relevant concentrations of the pollutant of concern (Gerhardt *et al.*, 2016). Figures 1 and 2 show the response in growth indicators for *Salicornia* exposed to antibiotics concentrations of 1, 5, 10, 20, 50, 100, and 1000 µg/L. In the case of enrofloxacin and oxytetracycline, the concentrations studied did not represent apparent toxi-

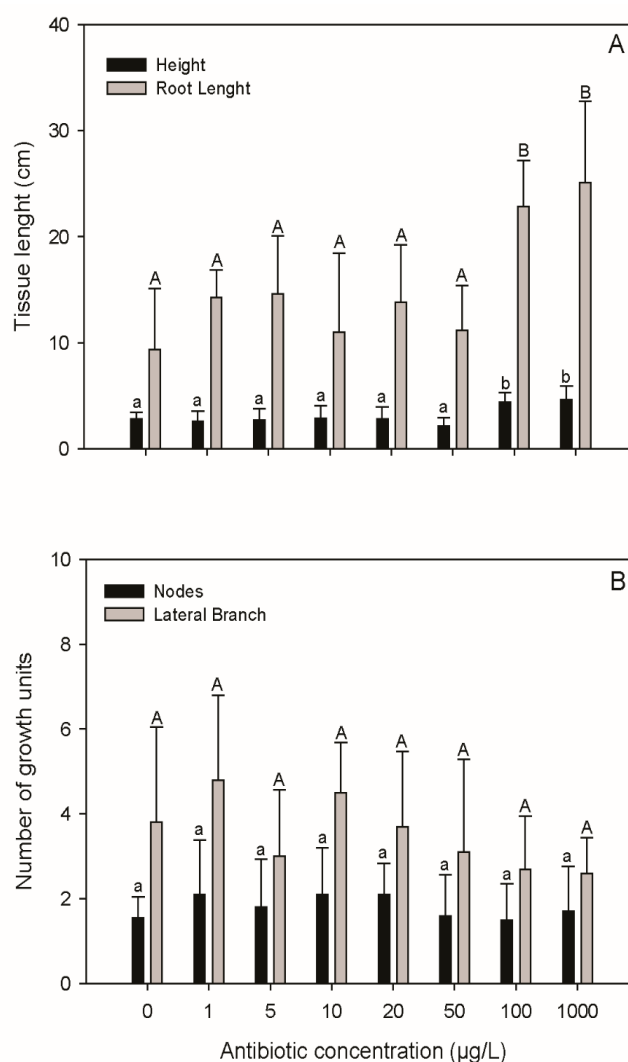


**Figure 1.** Growth increase indicators of *Salicornia bigelovii* exposed to concentrations of enrofloxacin. (A) Aerial part and roots (B) Nodes and lateral branch.

\*For the same variable, different letters show significant statistical differences in the multiple range comparison (Tukey) for 95 % confidence ( $p \leq 0.05$ ).

**Figura 1.** Indicadores de aumento del crecimiento de *Salicornia bigelovii* expuesta a concentraciones de enrofloxacin. (A) Parte aérea y raíces (B) Nodos y ramas laterales.

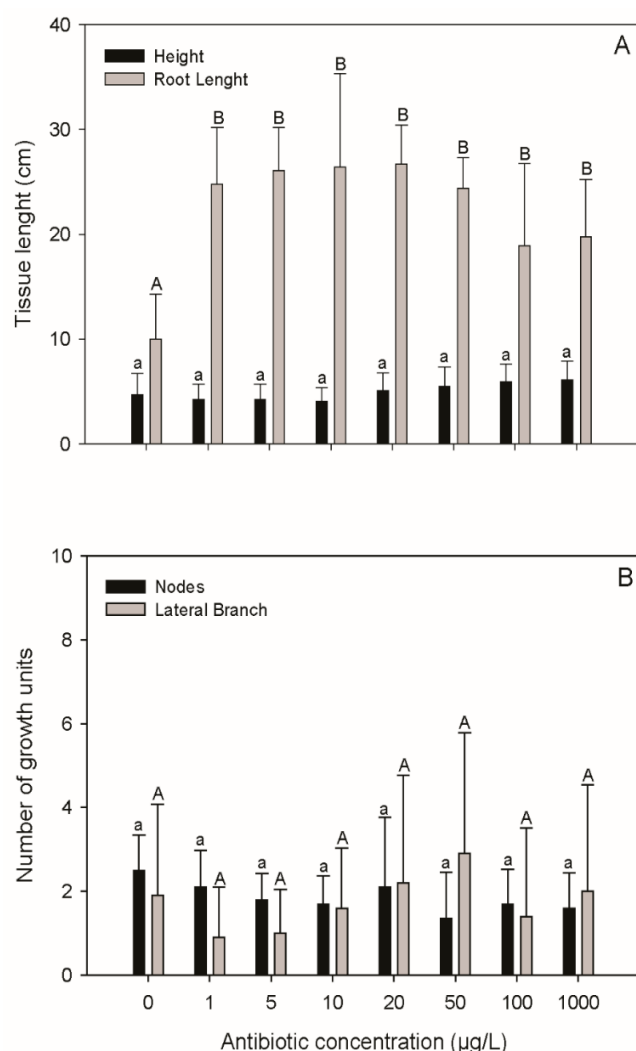


**Figure 2.** Growth increase indicators of *Salicornia bigelovii* exposed to different oxytetracycline concentrations. (A) aerial part and roots (B) nodes and lateral branches.

\*Different letters for the same variable show significant statistical differences in Tukey's multiple comparison range test for 95 % confidence ( $p \leq 0.05$ ).

**Figura 2.** Indicadores de crecimiento de *Salicornia bigelovii* expuesta a diferentes concentraciones de oxitetraciclina. (A) Parte aérea y raíces (B) Nodos y ramas laterales.

city for *Salicornia*; its growth and physiological development were not affected.

### Plant length

Both the aerial part and roots showed differences with respect to control in length (for the concentrations corresponding to 100 and 1000 µg/L) when the plants were grown in the presence of enrofloxacin (Fig. 1A). In the case of plants grown in the presence of oxytetracycline, they showed differences with respect to control for all the concentrations for the root variable, contrary to the aerial part that did not show differences at any of the concentrations (Fig. 2A).

### Number of nodes and lateral branches

In the variable nodes and lateral branches, no differences were observed with respect to control of the plants exposed to enrofloxacin in any of its concentrations (Fig. 1B). The same behavior was observed for the plants grown in the presence of oxytetracycline (Fig. 2B).

Table 1 shows the accumulation distribution of enrofloxacin in the plant, which could only be detected with the analytical method used for concentrations 50, 100, and 1000 µg/L. No difference was found among the BCF (bioconcentration factors) aerial and roots obtained for each treatment at 95 % confidence.

In the case of TF (Table 1), no statistical evidence was found among treatments with a 95 % confidence; furthermore, approximately  $42.63 \pm 2.27$  % of the antibiotic absorbed by the plant root was translocated by *S. bigelovii* to the aerial part in the same ratio for each one of the treatments.

## DISCUSSION

According to the results with respect to plant growth parameters, no toxicity effect of the antibiotics was found in the plant. For enrofloxacin, the two concentrations (100 and 1000 µg/L) showed a bigger response in length, both in roots and the aerial part; on the other hand, the plants exposed to oxytetracycline showed an increase in length only in the root, but with all the concentrations. This phenomenon can occur since such concentrations could have changed or activated phytohormone production (auxins, gibberellic acid,

**Table 1.** Distribution and accumulation factors in tissues of *Salicornia* exposed to different enrofloxacin concentrations.

**Tabla 1.** Factores de distribución y acumulación en tejidos de *Salicornia* expuestos a diferentes concentraciones de enrofloxacina.

| Antibiotic concentration (µg/L) | Root (µg/g)       | Aerial part (µg/g) | Plant (µg/g)      | TF                 | BCF plant             |
|---------------------------------|-------------------|--------------------|-------------------|--------------------|-----------------------|
| 50                              | $0.65 \pm 0.15^a$ | $0.46 \pm 0.04^a$  | $1.12 \pm 0.14^a$ | $0.71 \pm 0.21^a$  | $0.022 \pm 0.002^a$   |
| 100                             | $0.77 \pm 0.07^a$ | $0.52 \pm 0.86^a$  | $1.30 \pm 0.08^a$ | $0.630 \pm 0.16^a$ | $0.013 \pm 0.0008^b$  |
| 1000                            | $0.51 \pm 0.22^a$ | $0.42 \pm 0.22^a$  | $0.93 \pm 0.32^a$ | $0.96 \pm 0.16^a$  | $0.0009 \pm 0.0003^c$ |

BCF = bioconcentration factor; TF = translocation factor. Different letters in the same line show significant statistical differences in Tukey's multiple comparison range test (Tukey) for 95% of confidence ( $p \leq 0.05$ ).

and cytokinins), which are responsible for cell division and elongation, allowing aerial and roots growth (Li *et al.*, 2022; Wu *et al.*, 2024; Wang *et al.*, 2025). Many of such phytohormones are exogenous and determined by the presence of rhizobacteria that are capable of promoting plant growth through a variety of mechanisms; these mechanisms include plant nutrition improvement and phytohormone production and regulation, as well as the possible use of the antibiotic as the substrate because of a partial degradation or mineralization in association with the plant (Kristanti *et al.*, 2023).

Contrary to the results in the present study, common receptors in plants have been reported before the presence of fluoroquinolones that affect chloroplast replication; tetracyclines have an effect on transcription and translation, as well as sulfonamides that affect metabolic pathways, as folate biosynthesis (Frade *et al.*, 2014). Folate and its byproducts are involved in the adaptation and plasticity of the root system (Reyes-Hernández *et al.*, 2014).

Moreover, sulfonamides, tetracyclines, and quinolones have been reported to have a bacteriostatic effect on the microorganisms associated with plant roots in the wetlands (Thiele-Bruhn and Beck, 2005). For example, Conkle and White (2012) reported that concentrations from 1-50 µg/L of ciprofloxacin caused damage in the microbial community, resulting in negative implications in plant productivity, physiological development, and a reduction in system treatment efficiency.

Several authors have pointed out lipid content as an indicator of hydrophobic compound absorption potential in the roots of different plants (Huang *et al.*, 2009). Moreover, a positive correlation between lipid content and antibiotic concentration in roots has been recorded. The amount of lipids in plants of the genus *Salicornia* is around 8 % and 5 % of dry matter in its shoots and roots, respectively (Tikhomirova *et al.*, 2008). However, this behavior does not apply to all the pollutants, highlighting that it is not the only influencing variable (Wu *et al.*, 2013). This high catchment or translocation trend of antibiotics could also be due to the detoxification system of the enzymatic metabolic type, transpiration rates, growth, and others (Hu *et al.*, 2010; Biczak *et al.*, 2025; Wang *et al.*, 2025).

Some xenobiotics, as antibiotics, could be transported in plants through specific proteins of putative drugs. These drug transporters have a broad specificity by the substrate, but they can transport structurally diverse compounds, such as auxins, flavonoids, glutathione conjugates, and metal chelators (Conte *et al.*, 2011).

Another essential variable involved in the acceptance and accumulation of compounds by plant roots is hydrophobicity (Liu *et al.*, 2021), which is governed by the partition coefficients octanol/water (Kow); however, it also makes translocation to the aerial part more difficult. In general, the absorption of some antibiotics is produced when hydrophobicity degree is 1 to 4; when they have a much lower hydrophobicity, they are detected in the external root surface, which could have been the case that no oxytetracycline re-

moval (-0.9 Kow) existed in this experiment (Bui *et al.*, 2018). In the case of soil-based experiments, biotransformation of antibiotics and other pharmaceutical and personal care products has been reported to occur through plants once the roots absorb them. However, no reports have shown a total removal of antibiotics by this route (Franklin *et al.*, 2018). The organic compounds are transported through the symplasm, apoplast, and transmembrane routes (Wang *et al.*, 2020). When Kow values are higher than 1.8, they are not adequate for catchment and translocation in plant tissues via the apoplast. Enrofloxacin has a Kow value of 0.7, which is why its accumulation can be present in the root and the aerial part of *Salicornia* tissue (Bui *et al.*, 2018; Hoang *et al.*, 2013).

The pharmaceutical products of acid nature disassociate from anions since plants do not easily capture them because they cross the membranes more slowly than the neutral molecule, and the cells have a negative electric potential in the cellular membrane (Carter *et al.*, 2014). The dissociation of acid pharmaceutical products increases when pKa decreases. Because enrofloxacin has a pKa value of 6.27, it could be a catchment mechanism. On the other hand, the hydrophobic compounds tend to be absorbed on the external epidermis instead of the partition of the internal root, which favors a more significant accumulation in root tissue (Riaz *et al.*, 2018).

In the current study, the removal percentages of the enrofloxacin obtained were  $23.95 \pm 0.20$ ,  $21.82 \pm 0.23$  and  $6.15 \pm 2.45$  for the treatments C5, C6, and C7, respectively. A statistical difference exists among the removals obtained in the three treatments with a 95 % confidence ( $p < 0.05$ ). Moreover, as enrofloxacin concentration increased in the hydroponic medium, *S. bigelovii* decreased its removal capacity, which was consistent with that reported by Lillenberg *et al.* (2010), mentioning that the intake of antibiotics depends on working concentration, plant species, environmental conditions, and exposure time. Given that the concentrations used in the present study were up to 500 times less than those used by Lillenberg *et al.* (2010) and that exposure time was similar, the difference should be due to the plant and working conditions. According to the results shown in Table 1 (Column 4), the saturation concentration for *S. bigelovii* is assumed to be about 1.0 - 1.30 µg/g.

In the present study, *Salicornia* showed low removal percentages for enrofloxacin and a null removal in oxytetracycline compared to those reported in available studies for other halophyte species. Such is the case of *Phragmites australis*, which was capable of removing 99 % of oxytetracycline and enrofloxacin from wastewater of the aquaculture industry supplemented with 100 µg/L of each antibiotic (Bôto *et al.*, 2016). The system used by Bôto *et al.* (2016) was a constructed wetland capable of removing 95 % of total and antibiotic-resistant bacteria. Furthermore, removal percentages of organic matter, nutrients, and metals were not affected by the presence of the antibiotic; however, in this case, contact time was more significant within 9 weeks. The removal of 94 and 75 % of enrofloxacin and tetracycline was reported in an aqueous system by *Phragmites australis*

doped with concentrations of 10 and 1000 µg/L during seven days (Carvalho *et al.*, 2012). Moreover, Christofilopoulos *et al.* (2016) reported removal with the halophyte *Juncus acutus* for a quinolone (ciprofloxacin) of 95 % to an initial concentration of 0.1 mg/L in 28 days. Hoang *et al.* (2013) reported a removal of 60 % of ciprofloxacin and norfloxacin using the halophytes *Rhizophora apiculata* and *Acrostichum aureum* during a 21-d experiment in sediments of aquaculture farms.

The accumulation and removal differences between one antibiotic and another one, were related to the type of molecule and a parameter named complexity; in the current study, enrofloxacin showed better removal than oxytetracycline, exhibiting a complexity degree of 613 (oxytetracycline molecular complexity degree is 1000) (Böttcher, 2018). Thus, oxytetracycline was more difficult to be absorbed by the plant due to its molecular complexity, and that same factor also prevented the rhizosphere microorganisms from being able to transform it in simpler molecules (Böttcher, 2018, PubChem database, 2018). The bioconcentration factors in the aerial part and root were < 1 for all the cases, indicating a trend with accumulation potential in the root and translocation from root to stem at a low rate. This result agreed with Hoang *et al.* (2013), who reported fewer values than those in the present study for both factors in removing ciprofloxacin and norfloxacin with *R. apiculata* and *A. aureum*, which were < 0.5.

The constructed wetlands may remove other contaminants independently of antibiotics presence, which provides the possibility of reusing or recirculating aquaculture wastewater (Bôto *et al.*, 2016). No nutrient analysis was performed, but in every single antibiotic analysis, original farm wastewater (as negative control) was included to assure that only the added antibiotics were present. According to Iber and Kazan (2021), a typical wastewater from a shrimp farm has the following composition (in mg/L): ammonium ( $0.6 \pm 0.37$ ), ammonia ( $0.81 \pm 0.012$ ), nitrite ( $0.446 \pm 0.376$ ), nitrate ( $1.963 \pm 1.693$ ) and phosphate ( $0.72 \pm 0.07$ ). Production systems that allow performing aquaculture are being established, treating wastewater generated, irrigating cultivation of halophytes, such as *S. bigelovii*, and its biomass-producing bioenergy, including biofuels (Iaccarino *et al.*, 2021).

On the other hand, *Salicornia* could be a source of fatty acids for the production of biodiesel besides being used to remove nutrients. Pourhoseini *et al.* (2024) found that biodiesel from *S. persica* has a large amount of unsaturated fatty acids and a low amount of saturated fatty acids. The fatty acids of *S. persica* show a high oxidation stability and the lowest dynamic viscosity compared to biodiesel from other conventional sources, such as palm, sunflower and soy. Cárdenas-Pérez *et al.* (2021) had previously published that *Salicornia* oil was suitable for the production of biodiesel and bioethanol. Another study by El-Araby *et al.* (2020) mentions that *S. bigelovii* is rich in linoleic acid (approximately 70%) with a fatty acid profile and percentage of total lipids similar to sunflower (26-33 % of total lipids).

Finally, is important to mention that the use and management of antibiotics is complicated due the lack of uniformity among producers. The dosages, the periodicity and the specific antibiotic used vary widely. Therefore, the antibiotics used in farms could be present in the consumed shrimp. The same paper mentions that the antibiotics used in shrimp farms can generate environmental and human health adverse reactions (Estrada-San Agustín *et al.*, 2023). According to Farías *et al.* (2024) 80 % of antibiotics administered to fish in farms are lost through dispersal in the water. Also, the authors argue that its excessive use increase the pollution problems.

## CONCLUSIONS

The present study demonstrated that *S. bigelovii* may grow without problems in water with the presence of enrofloxacin and oxytetracycline. Although antibiotic absorption was low (enrofloxacin) or null (oxytetracycline), the plants can be used to exploit wastewater nutrients in the shrimp industry. Finally, because of their significant quantity of fatty acids, *S. bigelovii* can also be used to obtain raw matter for biofuels, mainly biodiesel. In this manner, the problem of contamination by wastewater rich in nitrogen and phosphorus can be solved, preventing them from reaching the sea, estuaries, or coastal lagoons and obtaining a benefit in terms of biodiesel.

## DECLARATION OF INTERESTS

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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