Journal of Cleaner Production 297 (2021) 126746

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Cleaner production of salt-tolerance vegetable in coastal saline soils using reclaimed water irrigation: Observations from alleviated accumulation of endocrine disrupting chemicals and environmental burden

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ARTICLE INFO

Article history:
Received 9 December 2020
Received in revised form
28 February 2021
Accepted 12 March 2021
Available online 17 March 2021

Handling editor: Cecilia Maria Villas Bôas de Almeida

Keywords:
Saline soil utilization
M. crystallinum
Endocrine disrupting chemicals
Reclaimed water irrigation
Coastal zone

ABSTRACT

It is important to investigate the feasibility of reclaimed water irrigation for fulfilling cleaner production of salt-tolerant vegetables in coastal saline soils which widely distribute in the world. Reclaimed water irrigation might cause the accumulation of endocrine disrupting chemicals in crops although it is a good approach for alleviating water resource shortage. This study firstly investigated the possible cleaner production and benefits of cultivating *Mesembryanthemum crystallinum* (*M. crystallinum*) in coastal saline soil irrigated by simulated reclaimed water. Concentrations of target pollutants including bisphenol A (BPA) and nonylphenol (NP) in root of *M. crystallinum* were higher than those in stem and leaf while soil salinity could increase the concentrations of BPA/NP in root and decrease those in leaf and stem. The highest concentration of BPA/NP in root of *M. crystallinum* growing in soil with salt content of 7.2‰ reached 29.28/243.47 μg/kg. BPA mainly accumulated in leaf of *M. crystallinum* with the highest amount of 621.93 ng under non-saline conditions while NP mainly accumulated in root with the highest amount of 1114.57 ng under saline conditions. The hazard quotients sharply decreased by >50% when the soil salinity increased from 1.1‰ to 7.2‰. Non-cancer health risks of BPA and NP in *M. crystallinum* were acceptable for all human groups while the daily intake of BPA/NP was much lower than the corresponding tolerant daily intake. Life cycle assessment illustrated that *M. crystallinum* cultivation in soil with salt content of 1.1‰ posed the lowest environmental burden. Salt-tolerant vegetables such as *M. crystallinum* would be recommended to be cultivated in low-salinity saline soils using reclaimed water irrigation due to lower pollutant accumulation and environmental burden to achieve the goals of cleaner vegetable production. These findings provide new insight on the promising potential of reclaimed water irrigation and crop cultivation in saline soils in coastal regions.

1. Introduction

Cleaner production has become an important strategy for sustainable development of various fields such as biodiesel production (Athar and Zaidi, 2020), plastic granule production (Cascone et al., 2020), and food production (Santos et al., 2018). Humans have faced a series of problems including extensive exploration of resources, release of massive wastes, and environmental pollution so that cleaner production has become an inevitable alternative for the traditional production activities to support the sustainable human society. Many techniques including green engineering (Van Loy et al., 2018), waste reuse/recycle (Guerra et al., 2020), and pollutant reduction (Ahmadisharaf and Benham, 2020) have been established to achieve the goals of cleaner production. Efforts on cleaner agricultural production are still needed due to the current limited studies.

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https://doi.org/10.1016/j.jclepro.2021.126746
0959-6526/

Saline soils have widely distributed in global arid and semi-arid areas (Wang et al., 2020) to cause waste of land resource due to low productivity. Current utilization of saline soils includes land application after amelioration and cultivation of salt-tolerance plants (Chiconato et al., 2019). Salt-tolerance plant cultivation is perfect for salt-affected soil usage due to both economic benefit and soil amelioration effect (Chiconato et al., 2019). Study on cultivation of salt-tolerance economic plants in salt-affected soils is not enough yet to obtain comprehensive information on its cleaner production. It is feasible to cultivate the salt-tolerance vegetables and crops in salt-affected soils using reclaimed water which contains enough nutrients for plant growth to reach goals of both saving water resource and utilizing the saline lands. Vegetable cultivation in salt-affected soils might be an effective approach for cleaner food production.

The *Mesembryanthemum crystallinum* (*M. crystallinum*), also called ice plant, is a halophyte originating from Africa (Atzori et al., 2017) to be introduced into China as a kind of popular leafy vegetables for years. Current research work on *M. crystallinum* still mainly focuses on its growth conditions and physiological-biochemical properties although *M. crystallinum* has shown good tolerance to stress caused by salt and some heavy metals (Atzori et al., 2017). *M. crystallinum* might be a perfect candidate for testing feasibility of reclaimed water irrigation in salt-affected soils. The reclaimed water is an essential water resource that was widely used for irrigation due to the shortage of freshwater resources in coastal regions (Lu et al., 2020a). Reclaimed water could also be an important pollution source of emerging contaminants such as endocrine disrupting chemicals (EDCs) for crops (Lu et al., 2015) and water (Lu et al., 2020a). Current investigations on reclaimed water exert efforts on discussing the potential effect of its application including irrigation and recharge (Lu et al., 2020b). Rare information is currently available on accumulation of EDCs in salt-tolerance plant such as *M. crystallinum* growing in saline soils irrigated by reclaimed water as well as the potential environmental assessment of this process.

EDCs widely exist in different matrices to pose potential risks to ecosystem and human health (Lu et al., 2020b). As a kind of emerging contaminants, EDCs have attracted more attention due to its adverse effect with low concentration and pseudo-persistence (Giulivo et al., 2016). Many substances including natural hormones and artificial chemicals such as heavy metals, phenolic chemicals, pesticides, and persistent organic pollutants (Futran Fuhrman et al., 2015) have exhibited endocrine-disrupting features. Among artificial EDCs, bisphenol A (BPA) and nonylphenol (NP) deserve more attention since they generally exist in environments with relatively high concentrations and wide existence (Hermabessiere et al., 2017). BPA and NP have been frequently detected in different matrices (Santonicola et al., 2020) to exert potential threat to humans. They have been observed to accumulate in vegetables under reclaimed water irrigation which is generally regarded as a good way for solving problem of water resource shortage (Dodgen et al., 2013). It is necessary to discuss the food safety with reclaimed water irrigation, especially the possible accumulation of pollutants including EDCs during salt-tolerance plant cultivation in salt-affected soils using reclaimed water owing to the scarce relevant information. Reduction on accumulation of EDCs in plants also needs further investigation to meet requirements of cleaner agricultural production.

Anthropogenic activities will cause environmental burden to the ecosystem and health risks to humans so that many methods have been developed to evaluate the environmental impact of these activities (Wen et al., 2019) as well as to establish novel techniques to reduce various pollutants. Health risk evaluation is useful to quantify the potential risks of pollutants to humans (Lu et al., 2020b). Life cycle assessment (LCA) is a good approach for environmental impact evaluation by considering the whole processes “from cradle to grave” (Gunady et al., 2012). LCA is also a good tool for assessing the potential impact of cultivation of *M. crystallinum* in saline soils under the conditions of reclaimed water irrigation. LCA results will provide useful information on cleaner agricultural production in saline soils.

This study will investigate the effect of soil salinity on accumulation of typical phenolic EDCs in *M. crystallinum* irrigated by simulated reclaimed water. The LCA of *M. crystallinum* cultivated in coastal saline soils was also conducted. The final goal is to provide initial information on risk alleviation of reclaimed water irrigation in coastal zone by considering the potential environmental impact on saline soil utilization. This study firstly reported the possibility and feasibility of reclaimed water irrigation in saline soils for *M. crystallinum* cleaner production. The findings of this work will provide useful information on utilization of saline soils, reclaimed water application, and vegetable cleaner production.

2. Materials and methods

2.1. Standards, reagents, and chemicals

Standards including BPA (purity>99%), NP (4-n-NP, purity>98%), and surrogate (β-estradiol 17-acetate with purity≥99%) were purchased from Sigma-Aldrich (St. Louis MO, USA). Bisphenol A-D16 (BPA-D16, 98 atom% D) was used as isotope dilution standard (IDS) and obtained from Sigma-Aldrich (St. Louis MO, USA). Trimethylchlorosilane (TMCS, purity> 98%) and N,O-bis(trimethylsilyl) trifluoroacetamide (BSTFA, purity>98%) were obtained from Alfa Aesar (Ward Hill, MA). Solvents including acetonitrile, acetone, and methylene chloride with HPLC grade were purchased from Merck (Germany). Standards were individually dissolved in acetonitrile to make stock solution with concentrations of 1 g/L which was stored at 4 °C before use. The simulated reclaimed water was made by diluting BPA/NP stock solution using deionized water to reach irrigation concentration of 20 μg/L which was consistent with previous reports (Lu et al., 2020a).

2.2. Plant materials, coastal saline soils, and experiments

The experiment was performed by following the flowchart (Fig. 1). *M. crystallinum* and soils were carefully prepared. The cultivation experiments were conducted by using simulated reclaimed water containing BPA/NP. Different tissue parts were weighed and analyzed. Health risk evaluation and life cycle assessment were also conducted to determine the various effects of soil salinity.

The *M. crystallinum* seeds were purchased from a seed company (Weifang, China). Seeds were washed and sown on organic substrate at 25 °C with relative humidity of 60%−70% in the dark for 7 days. *M. crystallinum* seedlings after 2-week germination were transplanted in experimental pots with different soils. Simulated reclaimed water was daily irrigated for these seedlings. Coastal soils were collected from the Yellow River Delta. Soil with salinity of 1.1‰/2.4‰/7.2‰ was used as the representative soils and denoted as SAS1/SAS2/SAS3. Control soil samples were collected from a garden of Yantai and denoted as SCK. The analysis methods of soil physio-chemical properties referred to Wang et al. (2020). The detailed physio-chemical properties of target soils were listed in Table 1. BPA and NP were not detected in all soils.

Base fertilizer was firstly added into different soils at addition amount of 6 mg/cm^2 to provide enough nutrient for growth of *M. crystallinum*. Real reclaimed water contains different components to possibly exert complex effect on accumulation of EDCs in

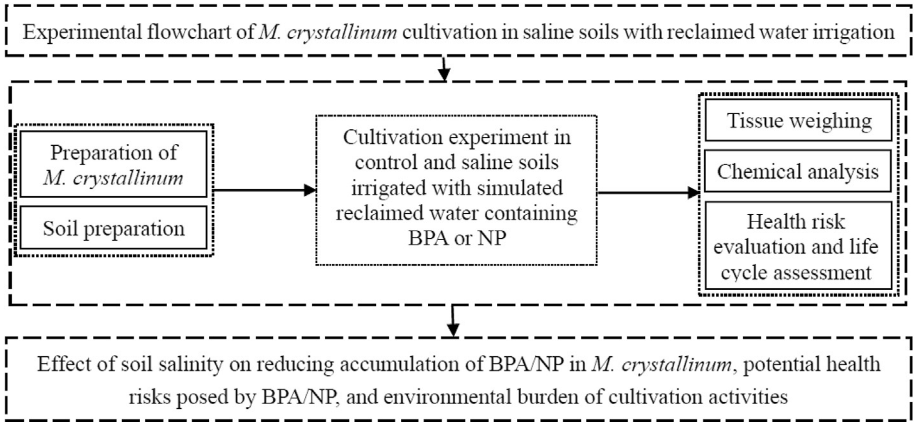

Fig. 1. Flowchart of the experimental design for this study.

Table 1
Basic properties of the common soil and salt-affected soils.

Soil	Soil salinity	Salt content (‰)	pH	EC (dS/m)	Organic matter (g/kg)	CEC (cmol/kg)	Sand	Silt	Clay
							———(%)———		
SCK	Non-saline	0.5	7.50	0.08	22.13	8.27	20.49	37.73	41.78
SAS1	Very slightly saline	1.1	7.62	0.43	20.21	8.98	22.72	32.89	44.39
SAS2	Slightly saline	2.4	7.55	0.86	13.02	16.12	12.78	38.65	48.57
SAS3	Moderately saline	7.2	7.52	3.01	19.78	6.08	21.49	39.26	39.25

Note: ions content was determined at the liquid-soil ratio of 5:1, and same to EC (electrical conductivity) and pH. The organic matter was determined by the method of potassium dichromate heating.

M. crystallinum. The simulated reclaimed water was used in this study to simplify the experiment and eliminate the impact of the other interference factors. Simulated reclaimed water containing BPA or NP was daily added to experimental pots by root irrigation. Pots were placed in a chamber for growth at 25 ± 1 °C with relative humidity of 60%–70%. Light condition was set with 16-h photoperiod and 8-h night. Treated plants were harvested after 30-day irrigation and ready for analysis. Each plant after harvest was rinsed by deionized water and dissected into root, stem, and leaf parts. Fresh weight of root/stem/leaf for each plant was recorded. All plant samples were stored at −20 °C until extraction. Each assay was performed in triplicate.

2.3. Sample preparation and instrumental analysis

The plant extraction procedure referred to the previous report (Lu et al., 2015). In brief, 5 g of plant samples mixed by 100 mL acetone were added by IDS and surrogate at spiking amount of 50 μg/kg. The plant samples were homogenized by a blender, ultrasonically extracted for 5 min, filtered, and evaporated to dryness. The dried samples were re-dissolved in acetonitrile and ready for acid hydrolysis. The hydrolyzed samples were extracted by methylene chloride. The extracts were dried and derivatization using BSTFA (99%)-TMCS (1%). The derivatized extracts were dried by high-pure nitrogen and dissolved in 100 μL of hexane for instrumental analysis.

The instrumental analysis referred to Lu et al. (2020b). In summary, the target EDCs were analyzed by GC-MS (Agilent 7820A GC system with M7 single quadrupole MS system) equipped with a 30 m DB-5MS column. The carrier gas was helium (purity>99.999%) at 1.0 mL/min and the injection volume was 1 μL at splitless mode. Temperature program was set as the followings: column oven (50 °C) kept for 1 min, increased to 120 °C at 20 °C/min and hold for 3 min, and increased to 280 °C at 8 °C/min to keep for 8 min. Retention time and selective ions were together used to confirm BPA and NP (Lu et al., 2020b). The limit of detection (LOD) for BPA/NP was 0.13/0.21 μg/kg.

Two spiked plant samples (*M. crystallinum* bought from the local market without detected BPA and NP) with spiking concentration of 20 μg/kg were analyzed for every 10 samples. Recoveries of spiking plant samples were in the range of (93%–99%)/(91%–102%) for BPA/NP with relative standard deviation (RSD) less than 6% to guarantee quality control of analysis.

2.4. Health risks assessment and LCA

Principal component analysis (PCA) was performed on OriginPro 2019 (OriginLab, USA). Interaction network analysis was conducted on Cytoscape 3.7.2 (The Cytoscape Consoritum, USA) with absolute value of Spearman coefficient greater than 0.6 and $p < 0.05$. Correlation analysis with significance at $p < 0.05$ was performed by SPSS 19 (IBM, USA).

Health risks posed by target EDCs were evaluated by hazard quotients (*HQ*). The detailed calculation referred to Wen et al. (2019) with some modifications.

$$HQ = \frac{C \times IR \times EF \times ED}{BW \times AT \times RfD} \quad (1)$$

where *RfD* represents the reference dose through oral exposure route which is $6.00\times10^{-3}/6.48\times10^{-2}$ mg/(kg·day) for BPA/NP; *AT* stands for average lifespan; *BW* means body weight; *C* refers to concentration of BPA/NP in *M. crystallinum*; *IR* represents vegetable consumption rate; *ED* refers to ingestion exposure duration; *EF* refers to ingestion exposure frequency (EF = 365 days/yr). Vegetable consumption rate (*IR*) of different groups referred to previous reports of China (Li et al., 2017; Zheng et al., 2007) and other country (Rosário et al., 2018) with value of 231.5/292/245.5/344.3/

356.7 g/d for children/female teenagers/male teenagers/female adults/male adults. *AT* value is set as 2190/6570/25550 days and *ED* value is set as 6/18/70 years for children/teenagers/adults; *BW* value is set as 19.73/47.64/51.24/55.18/63.29 kg for children/female teenagers/male teenagers/female adults/male adults. Threshold of *HQ* was set as 1 (Wen et al., 2019).

The LCA on *M. crystallinum* cultivation activities was performed by Simapro 7.1 (PRé Consultants, Netherland). The function unit was set as 1 kg of *M. crystallinum*. The life cycle inventories (LCI) mainly included irrigation and transportation. The LCI data were linked to the corresponding library of Simapro 7.1. Eco-indicator 99 (H) V2.06/Europe EI 99 H/A was employed to evaluate the potential impacts of *M. crystallinum* cultivation activities. Impact categories including climate change, ecotoxicity, acidification/eutrophication, fossil fuels, and land use were assessed. The detailed input/output/method information referred to "Database manual" and "Introduction into LCA" of Simapro 7.1. LCA results on ice plant cultivation in saline soils using reclaimed water irrigation might be partially affected by site conditions which would influence some LCA inputs so that LCA of different regions is needed in the future.

3. Results and discussion

3.1. Distribution and accumulation of BPA and NP in M. crystallinum

The yield of *M. crystallinum* in SAS1/SAS2/SAS3 was 97.1%/90.2%/73.6% of that in SCK for BPA treatment while the plant yield in SAS1/SAS2/SAS3 was 93.8%/87.4%/71.6% of that in SCK for NP treatment. Soil salinity of 1.1‰ or 2.4‰ did not significantly decrease the yield of *M. crystallinum.* Distribution of BPA and NP in *M. crystallinum* showed significant difference (Fig. 2). Concentrations of BPA and NP in root were higher than those in other parts of *M. crystallinum* growing in different soils, especially for NP. Soil salt could enhance the concentration of BPA and NP in root of *M. crystallinum*. Concentration of BPA in root of *M. crystallinum* growing in SAS3 with salt content of 7.2‰ reached 29.28 μg/kg, almost 1.37 times that growing in SCK and 1.29/1.16 times that growing in SAS1/SAS2 (Fig. 2a). It was interesting that concentrations of NP in root of *M. crystallinum* were significantly higher than those of BPA, all higher than 200 μg/kg (Fig. 2b). Similarly, soil salt enhanced the concentration of NP in root of *M. crystallinum*. Concentration of NP in root of *M. crystallinum* growing in SAS3 reached 243.47 μg/kg, almost 1.16 times that growing in SCK and 1.07/1.03 times that growing in SAS1/SAS2 (Fig. 2b). Different from root, concentration of BPA and NP in stem and leaf decreased with the salt content (Fig. 2). Concentrations of BPA and NP in stem were much lower than those in root and leaf. Concentrations of BPA and NP in different parts of *M. crystallinum* followed the order of root>leaf>stem. Concentrations of BPA in leaf/stem were averagely 57.3%/33.4% those in root while concentrations of NP in leaf/stem were averagely 4.1%/1.2% those in root, illustrating significant distribution difference caused by chemical properties of target EDCs. Considering leaf and stem are the main edible tissues of vegetables, relatively low concentrations of target EDCs in stem and leaf might be good news for consumers and producers. Concentration of BPA and NP in stem or leaf of *M. crystallinum* growing in SAS3 was less than 50% of that growing in control soil. Salt stress showed the similar negative effect on distribution of BPA and NP in stem and leaf (Fig. 2). Higher salinity significantly decreased the concentrations of BPA and NP in stem and leaf of *M. crystallinum*. Similar trends of other pollutants such as heavy metals in plants under salt stress were also reported (Fritiof et al., 2005). Concentration and accumulation amount of copper and cadmium in both *Elodea* and *Potamogeton* decreased with increased salinity (Fritiof et al., 2005).

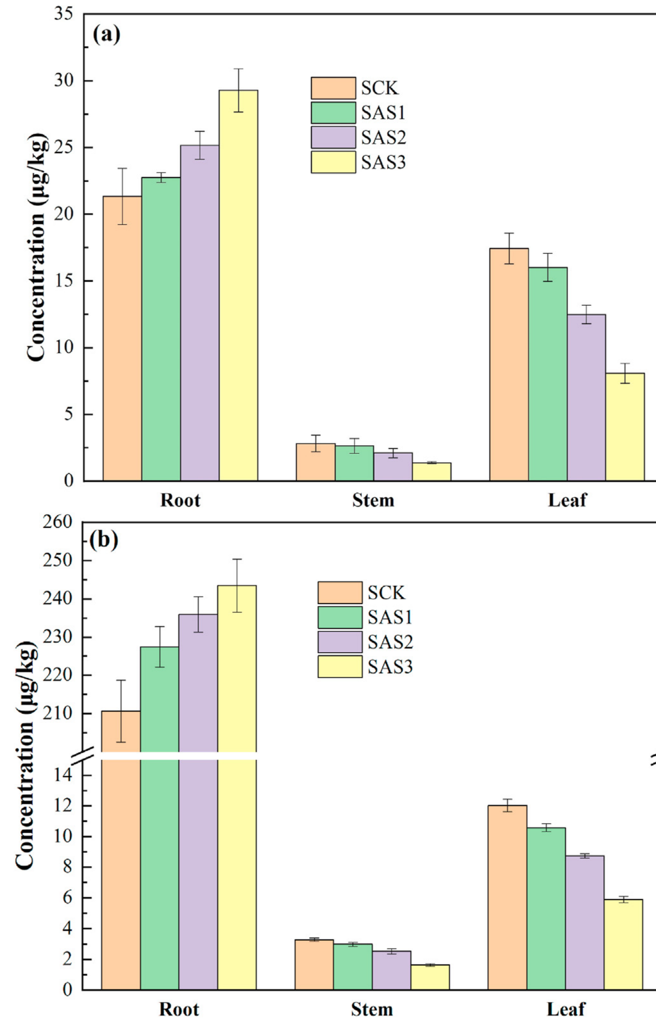

Fig. 2. Distribution of BPA (a) and NP in different parts of *M. crystallinum*. SCK refers to control soil; SAS1/SAS2/SAS3 refers to salt-affected soil with salinity of 1.1‰/2.4‰/7.2‰.

It was interesting that increased salinity could only decrease the concentration of zinc in cucumber while the other metals such as lead and copper showed the opposite variations (Taghipour and Jalali, 2019). Effects of soil salinity on accumulation of pollutants in the plants might be related to various factors such as physiochemical properties of pollutants and binding pathways of pollutants in the plants. Reclaimed water irrigation has been widely used for agriculture in many areas such as coastal zone (Lu et al., 2020a) and urban parks (Zalacáin et al., 2019). Reclaimed water irrigation can be an important trial for cleaner production of crops in saline soils due to rich nutrients in reclaimed water. However, accumulation of salt and pollutants in plants was frequently observed (Zalacáin et al., 2019), which negatively affected the further application of reclaimed water irrigation to some extent. Soil salt could inhibit the accumulation of BPA and NP in leaf and stem of *M. crystallinum*, which provided good news on possible cleaner production of salt-tolerant vegetables in saline soils.

The BPA and NP in *M. crystallinum* were mainly influenced by factor 1 which was the salinity of the soil according to the PCA analysis (Fig. 3). The control group was quite different from the groups under different salinity treatments. The SAS1 group was closer to SCK group than the other saline groups, illustrating that salinity exposure significantly influenced the uptake of EDCs in

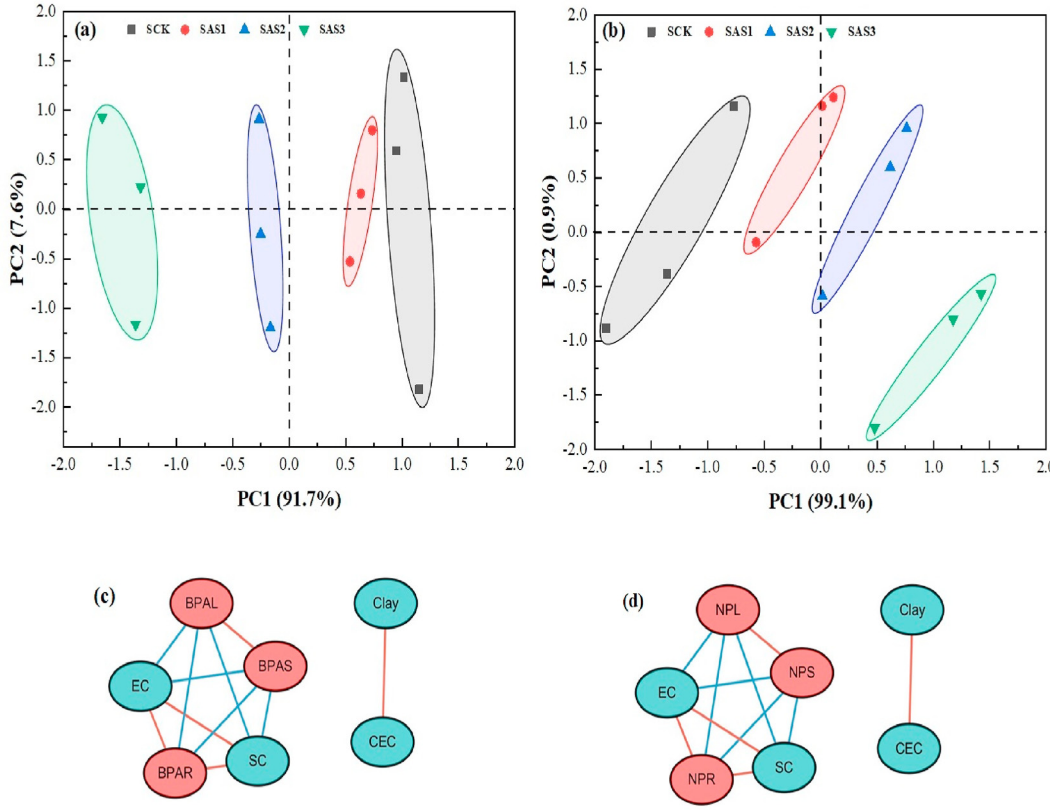

Fig. 3. Principal component analysis (PCA) and interaction network analysis of BPA (a and c) and NP (b and d) in the *M. crystallinum*. Soil property included soil salinity (SC), electrical conductivity (EC), cation exchange capacity (CEC), and clay. EDCs in crops included BPA in root (BPAR), leaf (BPAL), and stem (BPAS) as well as NP in root (NPR), leaf (NPL), and stem (NPS). The red and blue lines indicated the positive and negative correlation between the soil property and EDCs in crop. SAS1/SAS2/SAS3 refers to salt-affected soil with salinity of 1.1‰/2.4‰/7.2‰.

crops. The distance between the control group and salinity treatment group increased with the soil salinity (Fig. 3a and b). Additionally, the concentration of BPA and NP in root had strong positive relationship with the soil EC and salinity while those in the shoot had strong negative relationship with the soil EC and salinity (Fig. 3c and d), confirming that the uptake of the EDCs in shoot could be inhibited by the soil salinity. Relatively lower concentrations of target EDCs in shoot could decrease the potential health risk of consuming *M. crystallinum*. Relatively high levels of soluble salt in soils could increase osmotic stress to affect the water uptake and imbalanced accumulation of ions in the plants (Minhas et al., 2020), which did harm to the plant growth but possibly had good effect on controlling accumulation of pollutants. Ions in reclaimed water with soil soluble salts together might participate in the competition of NP and BPA in the plant to further inhibit the transport of target EDCs from root to shoot. Reclaimed water irrigation in coastal saline soils showed good effect not only on water resource conservation but also on controlling the accumulation of pollutants, exhibiting prospective potential in cleaner vegetable production.

The BPA mainly accumulated in leaf of *M. crystallinum* while NP mainly accumulated in root (Fig. 4). Accumulation amount of BPA in root reached the highest with 115.74 ng for *M. crystallinum* growing in SAS2 with salt content of 2.4‰ while accumulation amount of NP in root reached the highest (1114.57 ng) for the plant growing in SAS1 with salt content of 1.1‰ (Fig. 4). Accumulation of BPA and NP in leaf and stem decreased with salt content of soils. Accumulation amount of BPA in stem of plant growing in SAS1/SAS2/SAS3 was 86.0%/49.9%/23.4% that of plant growing in control soil while accumulation amount of BPA in leaf of plant growing in SAS1/SAS2/SAS3 was 85.5%/50.0%/24.5% that of plant growing in SCK (Fig. 4a). Accumulation amount of NP in stem of plant growing in SAS1/SAS2/SAS3 was 82.9%/49.5%/23.8% that of plant growing in control soil while accumulation amount of NP in leaf of plant growing in SAS1/SAS2/SAS3 was 81.5%/53.1%/25.2% that of plant growing in SCK (Fig. 4b). Accumulation amount of BPA in leaf/stem reached the highest with 621.93/60.04 ng for *M. crystallinum* growing in control soil while that of NP in leaf/stem reached the highest with 429.63/71.12 ng in leaf/stem of plant growing in SCK. Accumulation amount of BPA in leaf accounted for 59.4%–78.6% of total accumulated BPA in whole plant while that of NP in root covered 68.5%–85.1% of total accumulated NP in whole plant. Significant difference in accumulated amount of BPA and NP in different parts of *M. crystallinum* might be caused by chemical properties of target EDCs and features of the plant. Higher salinity significantly decreased the accumulation amount of the target EDCs in *M. crystallinum* as well as the plant yield. Therefore, selection of suitable saline soil might directly affect the cleaner production of using reclaimed water irrigation. Soils like SAS1 with low salinity might be more suitable for cultivating *M. crystallinum* using reclaimed water irrigation by considering the accumulation of pollutant and plant yield. Reclaimed water irrigation in low-salinity soil might be an effective pathway for cleaner production of vegetables and other crops. Mechanisms such as the development and effect of plant bladder cells on BPA/NP accumulation in *M. crystallinum* under different soil salinities with reclaimed water irrigation might be needed for the future study.

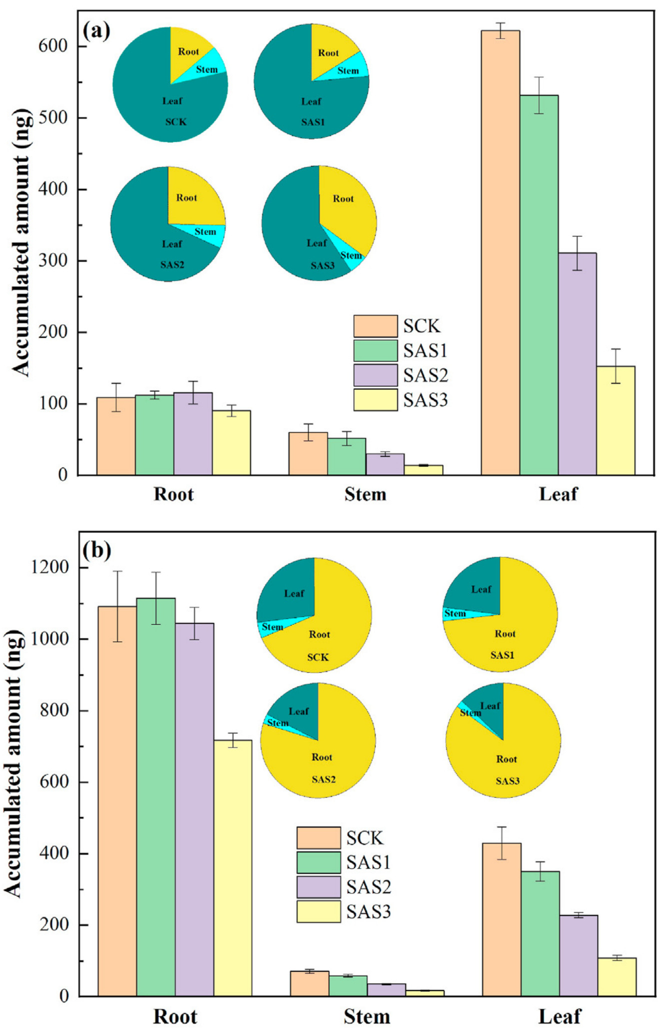

Fig. 4. Accumulation of BPA (a) and NP (b) in different parts of *M. crystallinum*. SCK refers to control soil; SAS1/SAS2/SAS3 refers to salt-affected soil with salinity of 1.1‰/2.4‰/7.2‰.

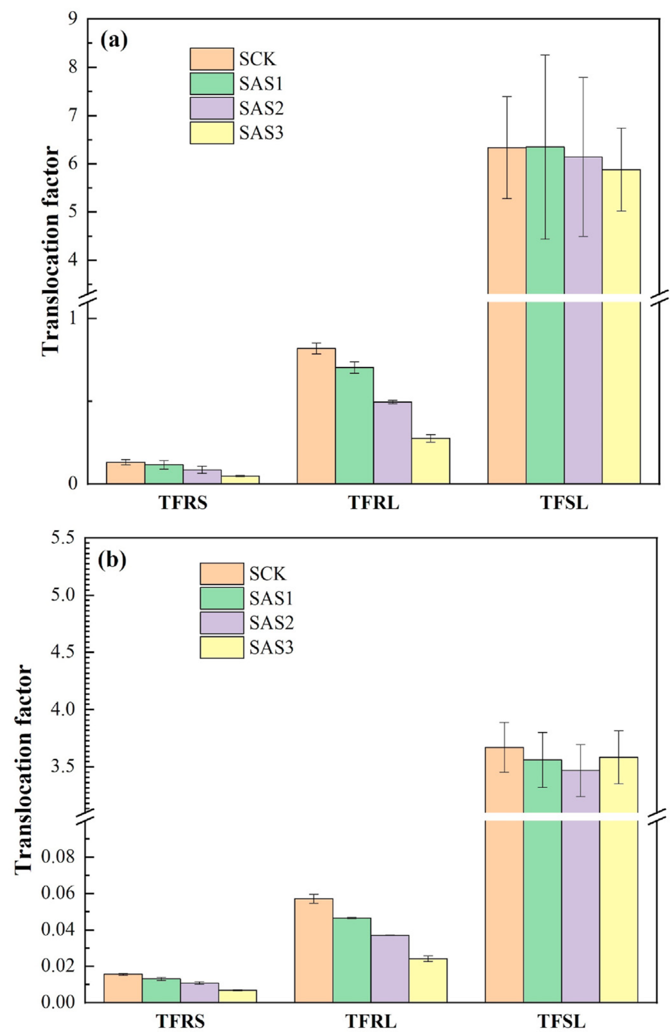

Fig. 5. Translocation factor of BPA (a) and NP (b) in *M. crystallinum*. SCK refers to control soil; SAS1/SAS2/SAS3 refers to salt-affected soil with salinity of 1.1‰/2.4‰/7.2‰; TFRS represents translocation from root to stem; TFRL represents translocation from root to leaf; TFSL represents translocation from stem to leaf.

3.2. Translocation of BPA and NP in M. crystallinum as well as the tolerance of plant

The translocation of BPA and NP in *M. crystallinum* showed difference (Fig. 5). Translocation factors from root to stem were the lowest while those from stem to leaf were the highest for BPA and NP. Translocation factors from stem to leaf reached 6.35 for BPA and 3.67 for NP (Fig. 5a), exhibiting that BPA and NP were more readily to transport to leaf. Translocation factors of BPA decreased with increased salt content in soils while those from root to stem or leaf decreased to higher extent, which might be ascribed to the increased concentration of BPA in root. Compared with BPA, very low translocation factors from root to stem or leaf of NP caused more accumulated amount of NP in root of *M. crystallinum* (Fig. 5b). Pollutants generally move in the root by following the order of root hairs → intracellular spaces → cortical cell walls → endodermis → xylem and organic pollutants with log-based octanol-water partition coefficient (K_{ow}) greater than 3.5 can be easily absorbed in soil granule and root surface of the plants (Kvesitadze et al., 2015). The log K_{ow} value of BPA/NP was 3.40/4.48 (Lu et al., 2015) to suggest that the target EDCs could be easily accumulated in the root part. K_{ow} also has significant effect on transport of non-ionized organic pollutants from root to shoot and K_{ow} of 1.8 or less is optimal for pollutant to move across the membranes (Kvesitadze et al., 2015). It is obvious that translocation from root to shoot is not easy for BPA and NP in the plants due to their high K_{ow} values.

Tolerance of *M. crystallinum* to BPA and NP was similar (Fig. 6). Interestingly, *M. crystallinum* showed good tolerance to target EDCs with all tolerance indices greater than 1, illustrating that addition of EDCs might serve as the hormone which could be helpful to alleviate the salt stress on the plant growth. Previous investigations have proved that EDCs could promote the growth of crops (Pan et al., 2013).

3.3. Health risk assessment of BPA and NP in M. crystallinum

Non-cancer health risks of BPA and NP in *M. crystallinum* were caused by oral ingestion (Fig. 7). The evaluation was performed by concentrations of BPA and NP in leaf of *M. crystallinum*. *HQs* of BPA and NP in *M. crystallinum* in different soils for all human groups followed the order of SCK>SAS1>SAS2>SAS3. The *HQs* sharply decreased by more than 50% when the soil salinity increased from 1.1‰ to 7.2‰. Concentrations of BPA and NP in leaf of *M. crystallinum* growing in soils decreased with the soil salt content, which could be helpful to decrease the health risks. It should

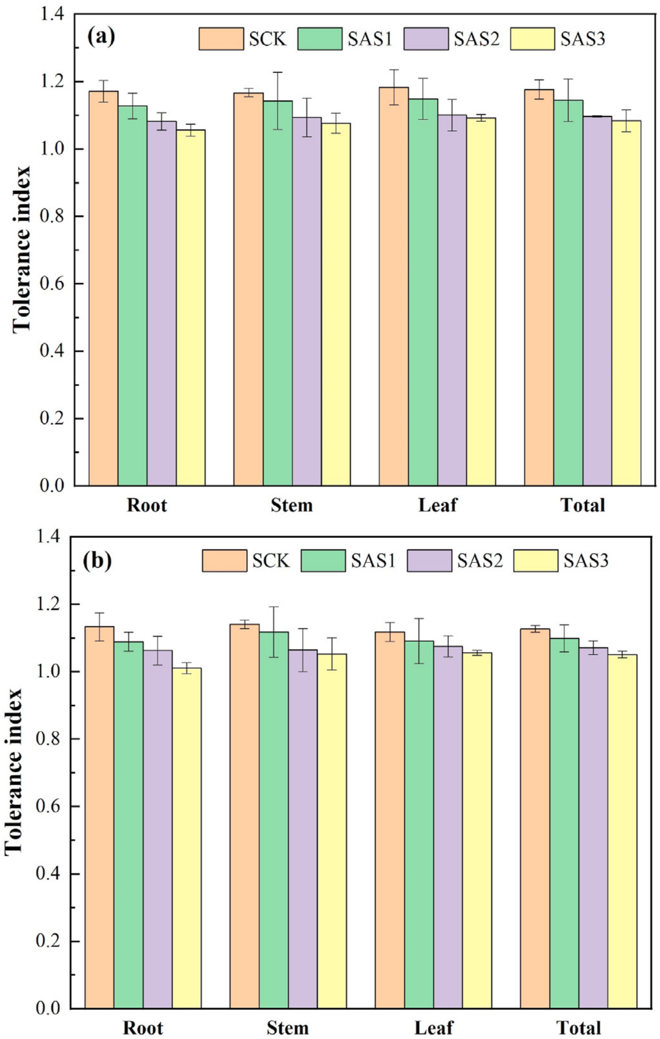

Fig. 6. Tolerance index of BPA (a) and NP (b) in different parts of *M. crystallinum*. SCK refers to control soil; SAS1/SAS2/SAS3 refers to salt-affected soil with salinity of 1.1‰/2.4‰/7.2‰.

be paid attention to that the health risk of BPA/NP for children was almost 1.9–2.4 times that for teenagers and adults. Hazard quotients of BPA and NP for females were higher than those for males of the same age group, which might be influenced relatively high daily intake amount of *M. crystallinum* and lower weight of female groups. Compared with BPA, *HQs* posed by NP in *M. crystallinum* were much lower due to higher *RfD* value. All *HQs* posed by BPA and NP for different human groups were much lower than 1.0 to show acceptable risk, illustrating that it might be safe to daily consume *M. crystallinum*.

Daily intake of BPA through eating *M. crystallinum* was in the range of (1.87–4.04)/(2.36–5.09)/(1.99–4.28)/(2.79–6.00)/(2.89–6.22) μg/d for children/female teenagers/male teenagers/female adults/male adults while daily intake of NP was in the range of (1.36–2.78)/(1.72–3.51)/(1.45–2.95)/(2.03–4.14)/(2.10–4.29) μg/d for the corresponding group. The tolerance daily intake (TDI) of BPA and NP was calculated based on the recommended threshold by the European Commission Scientific Committee on Food and the Danish Institute of Safety and Toxicology, respectively (Lu et al., 2015). The TDI of BPA/NP for children, female teenagers, male teenagers, female adults, and male adults were 19.7/9.9, 47.6/23.8, 51.2/25.6, 55.2/27.6, and 63.3/31.6 μg/d, respectively. All daily intake amounts of BPA/NP were much lower than the corresponding TDIs, also illustrating that consumption of *M. crystallinum* was safe. Higher soil salinity decreased the concentration and accumulation amount of BPA and NP in *M. crystallinum* to further reduce the health risks of these harmful chemicals under the conditions of reclaimed water irrigation. Li et al. (2010) also remarked that soil salinity might be useful to reduce the health risk of heavy metals in fruits to further support the results of this study. Consumption of *M. crystallinum* growing in saline soils and cultivated by reclaimed water would decrease daily intake of target EDCs, exhibiting that plant cultivation in saline soils coupled with reclaimed water irrigation might be a promising approach for utilization of coastal saline soils.

Cleaner production means less pollutant accumulation and lower health risks for vegetable cultivation. Salinity decreased concentration and accumulation of BPA and NP in *M. crystallinum* to further alleviate the potential health risks posed by these pollutants, illustrating that vegetable cultivation in saline soils with reclaimed water irrigation could be a useful trial for crop cleaner production.

3.4. Life cycle assessment of *M. crystallinum* cultivation in salt-affected soils irrigated by reclaimed water

LCA using five indices was performed to explore whether *M. crystallinum* cultivation in coastal saline soils irrigated by reclaimed water would cause significantly increased environmental burden (Fig. 8). Acidification/eutrophication of *M. crystallinum* growing in SAS2 and SAS3 was only 9.3% and 11.1% higher than that in SCK soil. The remaining indices including climate change, ecotoxicity, fossil fuels, and land use of *M. crystallinum* cultivation in SAS2 and SAS3 were only 9.0%–9.4% and 11.0%–12.1% higher than those of the plant growing in control soil. It was interesting that all indices except land use of *M. crystallinum* growing in SAS1 with salt content of 1.1‰ were significantly lower than those of the plant growing in other soils. Climate change, ecotoxicity, fossil fuels, and acidification/eutrophication of *M. crystallinum* growing in SAS1were only 3.3%, 11.4%, 23.8%, and 2.2% of that of the plant growing in control soil. Land use of the ice plant (*M. crystallinum*) growing in SAS1 were 1.9/1.7/1.7 times that of the plant growing in SCK/SAS2/SAS3.

The yield of *M. crystallinum* growing in SAS1 and SAS2 was comparable with that in control soils. Low concentration and accumulation amount of the target EDCs in *M. crystallinum* growing in SAS1 and SAS2 showed the potential of cultivation of vegetables in saline soils. Low environmental burden of *M. crystallinum* cultivation in SAS1 approved that reclaimed water irrigation in coastal saline soils with low salt content could be a perspective method for coastal saline soil utilization. Coastal areas possess wide saline soils, a large population, and fast-developing economy (Wang et al., 2020). Water scarcity has become an important problem in the world (UN, 2019), especially the coastal areas. Reclaimed water usage will become an important strategy for humans to alleviate the water scarcity. LCA results of this study further confirmed the feasibility and effectiveness of cultivating *M. crystallinum* in slight saline soil irrigated by reclaimed water, which also showed that reclaimed water irrigation could be useful for the cleaner crop production in coastal saline soils.

4. Conclusions

It is necessary to discuss the effect of reclaimed water irrigation on cleaner vegetable production in saline soils since the previous studies seldom mentioned that. This study firstly reported that soil salinity decreased the accumulation of BPA and NP in

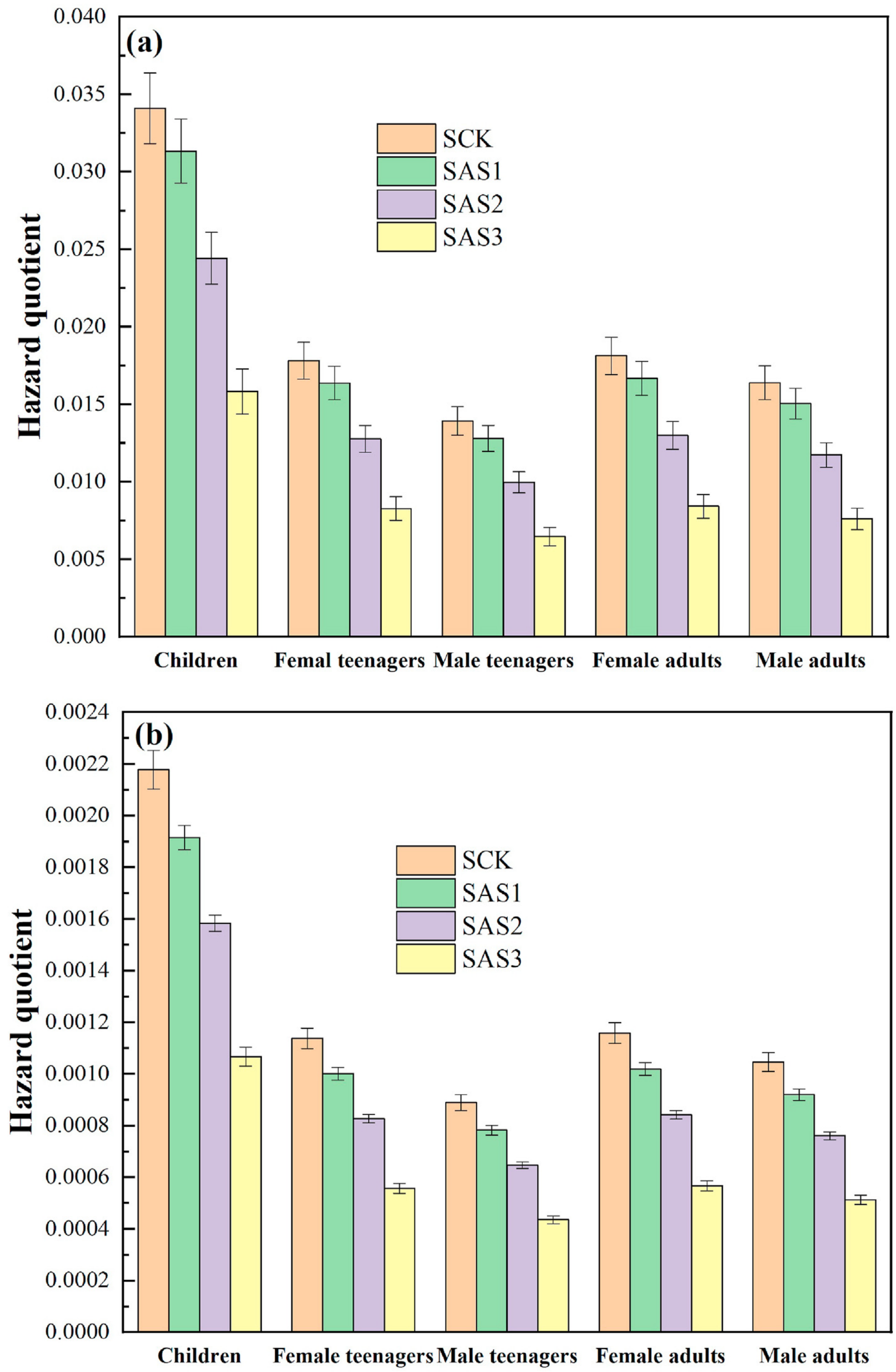

Fig. 7. Hazard quotient of BPA (a) and NP (b) in *M. crystallinum* for different groups. SCK refers to control soil; SAS1/SAS2/SAS3 refers to salt-affected soil with salinity of 1.1‰/2.4‰/7.2‰.

M. crystallinum to alleviate the potential health risks by 8.1%–53.6% for BPA and 12.1%–51.0% for NP. Concentrations of BPA and NP in root were higher than those in stem and leaf while accumulated amount of BPA/NP in leaf/root covered (59.4%–78.6%)/(68.5%–85.1%) of total accumulated target EDC in *M. crystallinum*. It was safe to daily consume *M. crystallinum* due to acceptable health risks posed by target EDCs in it. The *M. crystallinum* cultivation in slight saline soil irrigated by reclaimed water posed low environmental burden and low accumulation of EDCs. These results suggested that cultivating crops in the coastal saline soils with reclaimed water irrigation might be a good trial for the cleaner crop production in terms of saving water resource, utilizing saline soils, and alleviating the potential risks. These findings provide useful evidence that crop production irrigated with reclaimed water will be the promising practice for the coastal saline soil utilization. Cultivation strategies and optimal operation conditions of salt-tolerance plants in saline soils are recommended for future works.

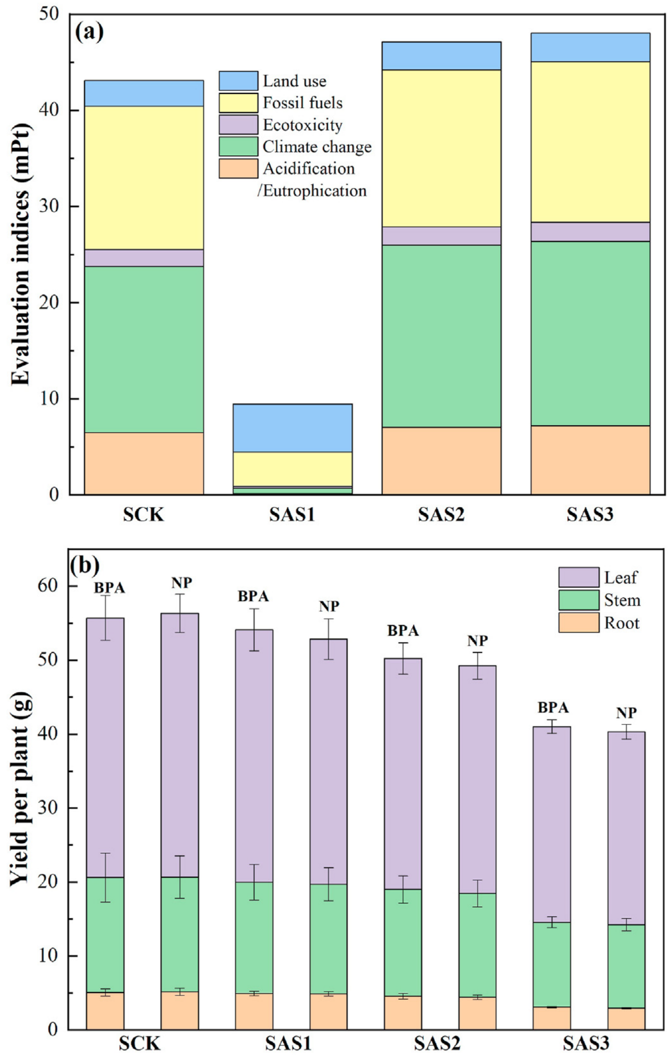

Fig. 8. Life cycle assessment results for crop cultivation in common soil and saline soils. SCK refers to control soil; SAS1/SAS2/SAS3 refers to salt-affected soil with salinity of 1.1‰/2.4‰/7.2‰.

CRediT authorship contribution statement

Jian Lu: Conceptualization, Funding acquisition, Investigation, Methodology, Project administration, Writing – original draft, Writing – review & editing. **Jun Wu:** Conceptualization, Methodology, Investigation, Software, Supervision, Writing – original draft, Writing – review & editing. **Cui Zhang:** Formal analysis, Investigation, Methodology.

Declaration of competing interest

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.

Acknowledgements

This work was financially supported by National Natural Science Foundation of China (41671319), Taishan Scholars Program of Shandong Province (tsqn201812116), Science and Technology Service Network Initiative of the Chinese Academy of Sciences (KFJ-STS-QYZX-114), and Two-Hundred Talents Plan of Yantai (No. Y739011021). We also would like to thank the reviewers for their valuable comments and suggestions on the manuscript.

Abbreviations in this paper

BPA	bisphenol A
NP	nonylphenol
M. crystallinum	Mesembryanthemum crystallinum
EDCs	endocrine disrupting chemicals
LCA	Life cycle assessment
LCI	life cycle inventories
TMCS	trimethylchlorosilane
BSTFA	(N,O-bis(trimethylsilyl) trifluoroacetamide)
IDS	isotope dilution standard
SAS1/SAS2/SAS3	soil with salinity of 1.1‰/2.4‰/7.2‰
SCK	control soil sample
PCA	principal component analysis
HQ	hazard quotients
RfD	the reference dose through oral exposure route
AT	average lifespan
BW	body weight
IR	vegetable consumption rate
ED	ingestion exposure duration
EF	ingestion exposure frequency
K_{ow}	octanol-water partition coefficient
TDI	tolerance daily intake
TFRS	translocation from root to stem
TFRL	translocation from root to leaf
TFSL	translocation from stem to leaf
SC	soil salinity
EC	electrical conductivity
CEC	cation exchange capacity
BPAR	BPA in root
BPAL	BPA in leaf
BPAS	BPA in stem
NPR	NP in root
NPL	NP in leaf
NPS	NP in stem

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