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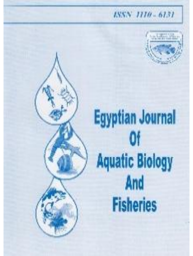

The Role of *Procambarus clarkii* in Achieving Sustainable Development Goal-6

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ABSTRACT

Pollution's cumulative negative repercussions are a key interconnected component of many worldwide challenges (as, incidence of diseases, malnutrition, poverty, etc.) that can make achieving sustainability difficult. Consequently, the current research aims, for the first time, to throw the light on the possibility of investment of *Procambarus clarkii* exoskeleton waste, not only in reducing metal pollution but also in paving the way for tackling some of these challenges.

The study was divided into two parts; (1) conducting experiments in batches to determine the optimal operating parameters (contact duration "minutes", pH, and initial metal concentration "mg/L") required to reduce copper (Cu^{2+}) or zinc (Zn^{2+}) ion concentrations in aqueous solutions using 0.5 g Chitosan (CS) extracted from *P. clarkii* (to meet the values set by WHO and Egyptian Governmental Law No. 48, 1982); and (2) elucidating the synergistic relationship between achieving SDG-6.3.1 with other SDGs. Our results showed that the adsorption process, for both ions on CS, attained equilibrium at 20 minutes, pH 5.0 (for Cu^{2+}) and 7.0 (for Zn^{2+}), and initial concentrations of 4.49 mg/L (for Cu^{2+}) and 5.15 mg/L (for Zn^{2+}). The removal efficiency of the metal ions by CS decreased in the order of Cu^{2+} (99.11%) followed by Zn^{2+} (88.35%). Moreover, the investigated dose of CS (0.5 g) proved its potential to meet both the Egyptian and WHO guideline values for the optimal concentrations of Cu^{2+} and Zn^{2+} ions within the 15-minute period.

The very fast adsorption kinetics (20 min) observed for the studied metals showed an advantage for using CS in the purification system for the industrial sector. As a result, the percentage of untreated industrial wastewater will decrease, clearing the path for Egypt to make significant progress toward achieving SDG-12.4, SDG-2.1, SDG-3.3, SDG-11.5, SDG-6.4, SDG-1.5, SDG-11.6, and SDG-13.1 by 2030.

INTRODUCTION

Copper (Cu) and zinc (Zn) are essential trace elements for living organisms, however, they become toxic at high concentrations. Industrial wastewaters contain considerable quantities of these heavy metals. Cu^{2+} ions in wastewater are primarily produced by mining, printing, dyes, electroplating, and electrical combustion (**Kadirvelu *et al.*, 2001**; **Razo *et al.*, 2004**), whereas

Zn^{2+} ions are produced by battery and tire manufacturing as well as galvanic industries (**Ennigrou *et al*., 2014**).

These metallic ions would endanger public health and the environment if discharged without adequate treatment (**Narain *et al*., 2020; Emam and Soliman, 2021a & b**). Copper, in particular, binds to enzymes and other metabolic agents that are involved in respiration, rendering them inert. Copper in high concentrations causes damage to the kidneys and liver, as well as irritation of the central nervous system, which leads to depression (**WHO, 1984**). Zinc in high concentrations can cause nausea, anemia, and pancreas loss (**Bhowmik *et al*., 2010**). Hence, the concentrations of Cu^{2+} and Zn^{2+} discharged in the water from industrial production must be reduced to the maximum permissible limits allowed for drinking (2.0 and 3.0 mg/L according to **WHO, 2003a** and **WHO, 2003b**, respectively) before being discharged into the environment. Accordingly, there is a considerable interest in the recovery of heavy metals from industrial wastewaters (**Banat *et al*., 2002**).

Various methods have been proposed to remove heavy metal ions from wastewaters, such as precipitation (**Huisman *et al*., 2006**), solvent extraction, membrane processes (**Sahebjamee *et al*., 2019**), ion exchange (**Zhao *et al*., 2019**), and adsorption (**Eltaweil *et al*., 2021**). The later technique is regarded as an excellent cost-effective choice for treating wastewater from heavy metals because of its rapid kinetics and high efficiency (**Omer *et al*., 2022**).

Different adsorbent materials have been widely utilized for adsorbing toxic metals from wastewater. With respect to the cost, biodegradability, and natural abundance, chitosan (CS) has received a significant consideration over the last two decades as an efficient low-cost adsorbent (**Omer *et al*., 2022**). CS can be prepared from the exoskeleton of aquatic invertebrates including sponges, mollusks, shrimps, crabs, lobsters, and crayfish (**Fadlaoui *et al*., 2019**). **Zheng *et al*. (2010)** found that the carapace of crayfish has all the properties required to attain optimum biosorption performance. **Morris *et al*. (2012)** and **Park *et al*. (2018)** used crushed crayfish shells and crayfish-shell biochar successfully in removing heavy metal ions from contaminated waters.

Globally, of the 500 known species of crayfish, the red swamp crayfish *Procambarus clarkii* is the most important commercial one (**Hamdi and Abd El-Monem, 2006**). This species was unintentionally introduced into the River Nile in the 1980s by an Egyptian investor who brought it from South America to be farmed, believing it was a freshwater shrimp. But, when the crayfish grew up with front legs similar to claws that could cut fishing nets, he threw them in the River Nile. Shortly thereafter, the crayfish succeeded to infiltrate all types of freshwater environments, independent of quality (**Ibrahim *et al*., 1995**). At first, everyone assumed that it is a dangerous invasive species, and fishermen complained that it attacks stream banks, fishing nets, and ate fish eggs (**Ibrahim *et al*., 1995**), and they asked researchers to find a way to get rid of them. With increasing awareness and academic studies, it was found that it can help in controlling crop pests as *Eobania vermiculata* snails (**Ibrahim *et al*., 2022**). Its feeding behaviour on the intermediate hosts of blood and liver flukes has helped to overcome the spread of their diseases. Also, it can be used as a source of high protein (**Huner *et al*., 1988**).

Egypt is one of the highest 25 inland fish-producers in the world (**Mohamed *et al*., 2022**). Recently, it has witnessed an increase in crayfish's industry. In 2013, a $3 million crayfish farm was opened in Obour City via a joint Spanish-Chinese investment to export crayfish to China, United States, and some European countries. The crayfish's exoskeleton represents about 70% of its total body weight (**Ibrahim and Khalil, 2009**). The processing of crayfish generates annually 100,000 tons of wastes **(Peng *et al*., 2016)**. Discarding these wastes randomly in nature will lead to environmental pollution (**Arvanitoyannis and Kassaveti, 2008**). Moreover, proper disposal of such waste is expensive, for instance, in Australia it costs 150 $/ton (**Hamed *et al*., 2016**). Therefore, it is crucial to turn these wastes into useful products.

In light of the UN 2030 Agenda for Sustainable Development's sixth sustainable development goal (SDG-6), reducing metal pollution and investing in industrial wastewater treatments to halve the percentage of untreated wastewater by 2030 became crucial to ensure the availability of safe water for all. Egypt's progress in this goal, particularly in the 3rd target (SDG-6.3) concerning the percentage of treated wastewater, is still facing challenges according to the latest available sustainability reports (**SDR, 2021**).

Accordingly, to address the issue of crayfish waste and enhance the progress towards achieving SDG-6, the current study set the following objectives: (i) determining the optimal operating conditions (contact time, pH, and initial metal concentration) required to treat aqueous solutions contaminated with Cu^{2+} or Zn^{2+} ions using 0.5 g chitosan extracted from *Procambarus clarkii* exoskeleton waste; (ii) investigating the time required for 0.5 g chitosan to adsorb different concentrations of Cu^{2+} or Zn^{2+} from contaminated water in order to meet the guidelines set by WHO for drinking water (**WHO, 2003 a & b**) as well as those stipulated in the Executive Regulations for protecting the River Nile from pollution (**Egyptian Governmental Law No. 48, 1982**); (3) elucidating the synergistic relationship between achieving the sixth SDG with other SDGs.

MATERIALS AND METHODS

1. Chitosan (CS) preparation "Adsorbent"

Procambarus clarkii was used for the preparation of chitosan. The study collected 50 fresh samples from fishermen on the River Nile near Giza, Egypt. The cephalothorax was decapitated from each specimen, and its exoskeleton was removed, washed in distilled water, and dried. Dehydration in the sun for 72 hours was followed by oven drying for 48 hours at 60 °C. Finally, the dried exoskeleton was pulverised. The process of CS extraction was described in **Darweesh *et al*. (2020)**.

2. Preparing synthetic aqueous solution “Adsorbate”

In the laboratory, stock synthetic aqueous solution of 1000 mg/L Cu^{2+} ion was prepared through dissolving 3928 mg of highly purified solid $CuSO_4 \cdot 5H_2O$ into 1000 ml deionized water. Similarly, stock solution of 1000 mg/L Zn^{2+} ion was prepared using 4396 mg of solid $ZnSO_4 \cdot 7H_2O$. The working solution used by dilution of standard solution. pH readings were measured using a pH meter (MODEL818 type, American Orion Company) and adjusted by using 1 M HCl.

3. Batch adsorption experiments

The adsorption capacity of CS to remove Cu^{2+} and Zn^{2+} ions from the synthetic solutions was examined in batches to understand the effect of contact time, different pH values, and initial metal concentrations on the adsorption process.

The effect of contact time was examined at 5, 10, 15, 20, 25, and 30 minutes, by adding 0.5g CS to ١٠٠ ml synthetic solution, containing Cu^{2+} or Zn^{2+} ions, in a 300 ml Pyrex Erlenmeyer flask. The mixtures were then stirred at a speed of 250 rpm, pH (5.0 for Cu^{2+} and 7.0 for Zn^{2+}), and initial concentrations (C_o) of 4.49 mg/L (for Cu^{2+}) and 5.15 mg/L (for Zn^{2+}) at room temperature for the defined time. The metal contents in the supernatants were then filtered using Whatman N$^{\underline{o}}$ 42-filter paper and kept at 4 °C until analysis. Heavy metal analysis was conducted using a flame atomic absorption spectrophotometer (AAS, GBC Scientific Equipment Pty Ltd, Australia).

Before using the batch experiment, three pH levels (3.0, 5.0, and 7.0) were adjusted using 1 M HCl solution to examine the effect of solution pH on the adsorption of Cu^{2+} and Zn^{2+} ions onto 0.5 g CS for 20 minutes at room temperature using initial concentrations of 4.49 mg/L (for Cu^{2+}) and 5.15 mg/L (for Zn^{2+}).

Cu^{2+} solutions with concentrations of 4.49, 9.5, and 14.6 mg/L and Zn^{2+} solutions with concentrations of 5.15, 10.4, and 15.6 mg/L were prepared to examine the effect of their initial concentrations using 0.5 g CS for 20 minutes at pH 5.0 (for Cu^{2+}) and 7.0 (for Zn^{2+}) at room temperature.

4. Adsorption capacity (q) and removal efficiency (X) of Cu^{2+} and Zn^{2+} ions

Each type of batch experiment was conducted in triplicate and the mean values were reported in this study. Flame atomic absorption spectrophotometer was used for heavy metal analysis.

The quantity of heavy metals adsorbed (q; mg/g) per weight unit of CS was calculated using the equation given below:

$$\mathbf{q} = \frac{\mathbf{V(C_o - C_e)}}{\mathbf{W}}$$

where,

- $\mathbf{C_o}$ and $\mathbf{C_e}$ are the initial and final heavy metal concentrations (mg/L),
- **V** is the volume of the synthetic aqueous solution (L), and
- **W** is the dry weight of the CS (g).

The removal efficiency (X; %) of metal ions was calculated using the following formula:

$$\mathbf{X}\,(\%) = \frac{\mathbf{(C_o - C_e)}}{\mathbf{C_o}} \times \mathbf{100}$$

RESULTS & DISCUSSION

1. Chitosan (CS) yield (%)

100g of ground shell was obtained after grinding. After demineralizing ground crayfish shell, a yield of 64 percent was obtained, whereas 52 percent of raw chitin was recovered after the deproteinization process, and the ultimate amount of CS retrieved from the crayfish waste was roughly 25 percent. In comparison with other crustaceans, the highest CS yield was achieved from *P. clarkii*, as shown in **Table (1)**.

Table 1: The amount of chitin and CS retrieved from other crustaceans in comparison with *P. clarkii*

Animal	Habitat	Chitin (%)	CS yield (%)	Author
Red swamp crayfish (*Procambarus clarkii*)	River Nile	52	25	**Present study**
Crab	Nigeria	NA	15.40	**Sumaila *et al.* (2020)**.
Indian white shrimp (*Penaeus indicus*).	Iran	NA	19.47	**Nouri *et al.* (2016)**
Grooved Tiger Prawn (*Penaeus semisulcatus*)	Arabian Gulf (Kuwait)	19.13	NA	**Sagheer *et al.* (2009)**
Jinga Shrimp (*Metapenaeus affinis*)	Arabian Gulf (Kuwait)	16.75	NA	**Sagheer *et al.* (2009)**
Blue Swimming Crab-Male (*Portunus pelagicus*)	Arabian Gulf (Kuwait)	20.80	NA	**Sagheer *et al.* (2009)**
Blue Swimming Crab-Female (*Portunus pelagicus*)	Arabian Gulf (Kuwait)	20.14	NA	**Sagheer *et al.* (2009)**
Scyllarid Lobster (*Thenus orientalis*)	Arabian Gulf (Kuwait)	21.26	NA	**Sagheer *et al.* (2009)**

NA: not available

2. Effect of contact time (Adsorption Kinetics)

It is worth mentioning that CS adsorption effectiveness for Cu removal is higher than that of Zn in the single solution containing both ions (**Jaros *et al.*, 2005**). Thus, the current study examined the optimal conditions for each metal ion alone.

Figure 1 displays the effect of contact time on Cu^{2+} and Zn^{2+} adsorption onto CS (0.5 g) at 5, 10, 15, 20, 25, and 30 minutes using the initial concentration (C_o) for Cu^{2+} as 4.49 mg/L, whereas for Zn^{2+} as 5.15 mg/L. Moreover, pH values used for Cu^{2+} and Zn^{2+} were adjusted at 5.0 and 7.0, respectively.

Results of the present study showed that the adsorption efficiencies of both ions on CS increased rapidly with time, till attaining the equilibrium (optimum contact time) after 20 minutes. The removal efficiencies of Cu^{2+} (at pH 5.0 and C_o= 4.49 mg/L) and Zn^{2+} ions (at pH 7.0 and C_o= 5.15 mg/L) increased from 79.96% to 99.11% (**Table 2**) and from 65.05 % to 88.35% (**Table 3**), respectively with an increase in time from 5 to 20 minutes. The initial adsorption phase (after 5 min) was rapid because of the large number of unoccupied sites **(Rao and Kashifuddin, 2014)** on the surface of CS. However, as time proceeds, most of the sites become filled with Cu^{2+} (or Zn^{2+}) ions, consequently, the quantity of adsorbed ions decreases.

In general, the uptake of Cu^{2+} ions by CS was higher than for Zn^{2+} ions (**Figure 1**). This can be attributed to the fact that Cu^{2+} ions have a smaller ionic radius than Zn^{2+} ions, accordingly, Cu^{2+} ions can reach the surface of certain sites easier than Zn^{2+} ions (**Ferro-Garcia *et al.*, 1988**).

In conclusion, the optimum contact time for both ions was found to be 20 minutes.

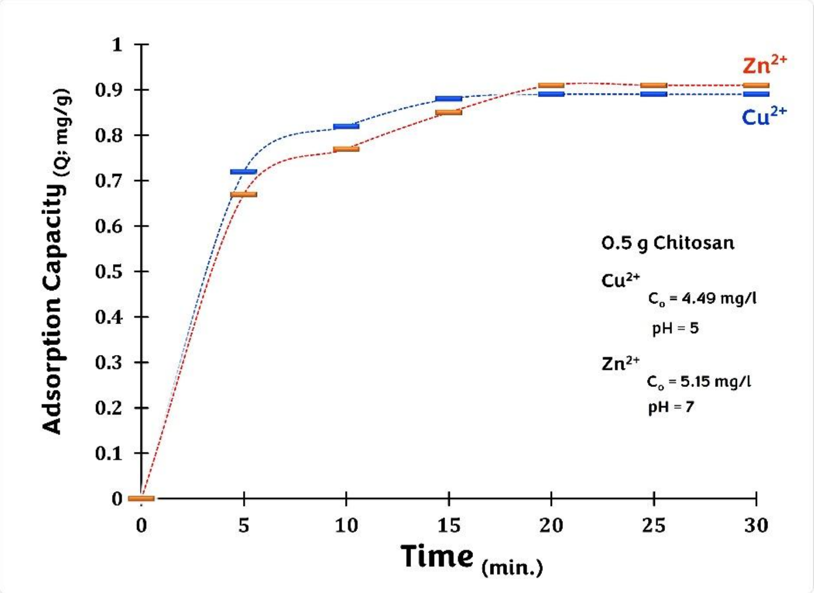

Figure 1. Effect of time on adsorption of Cu^{2+} and Zn^{2+} ions onto 0.5 g CS at room temperature using initial Cu^{2+} and Zn^{2+} concentrations as 4.49 and 5.15 mg/L at pH 5.0 and 7.0, respectively.

Table 2: Adsorption capacity and removal efficiency of Cu^{2+} using 0.5 g chitosan from synthetic aqueous solution at different pH levels and different initial concentrations

Time (min)	C_o = 4.49 mg/L			C_o = 9.5 mg/L			C_o = 14.6 mg/L		
	pH=3			pH=3			pH=3		
	C_e (mg/L)	Q (mg/g)	X (%)	C_e (mg/L)	Q (mg/g)	X (%)	C_e (mg/L)	Q (mg/g)	X (%)
0	4.49	0	0	9.5	0	0	14.6	0	0
5	1.5	0.598	66.59	3.2	1.26	66.32	5.5	1.82	62.33
10	0.75	0.748	83.30	1.7	1.56	82.11	3	2.32	79.45
15	0.2	0.858	95.55	0.6	1.78	93.68	1.3	2.66	91.10
20	0.1	0.878	97.77	0.3	1.84	96.84	0.6	2.80	95.89
25	0.1	0.878	97.77	0.3	1.84	96.84	0.6	2.80	95.89
30	0.1	0.878	97.77	0.3	1.84	96.84	0.6	2.80	95.89
	pH=5			pH=5			pH=5		
0	4.49	0	0	9.5	0	0	14.6	0	0
5	0.9	0.72	79.96	2.5	1.4	73.68	4.3	2.06	70.55
10	0.4	0.82	91.09	1.1	1.68	88.42	2	2.52	86.30
15	0.07	0.88	98.44	0.2	1.86	97.89	0.7	2.78	95.21
20	0.04	0.89	99.11	0.13	1.87	98.63	0.3	2.86	97.95
25	0.04	0.89	99.11	0.13	1.87	98.63	0.3	2.86	97.95
30	0.04	0.89	99.11	0.13	1.87	98.63	0.3	2.86	97.95
	pH=7			pH=7			pH=7		
0	4.49	0	0	9.5	0	0	14.6	0	0
5	1.1	0.678	75.50	2.8	1.34	70.53	4.7	1.98	67.81
10	0.5	0.798	88.86	1.3	1.64	86.32	2.2	2.48	84.93
15	0.1	0.878	97.77	0.4	1.82	95.79	0.9	2.74	93.84
20	0.05	0.888	98.89	0.2	1.86	97.89	0.4	2.84	97.26
25	0.05	0.888	98.89	0.2	1.86	97.89	0.4	2.84	97.26
30	0.05	0.888	98.89	0.2	1.86	97.89	0.4	2.84	97.26

C_o = initial Cu^{2+} concentration before adsorption (mg/L); **C_e** = Cu^{2+} concentration after adsorption (mg/L); **Q** = quantity of adsorbed Cu^{2+} ions (mg/g); **X** = efficiency of Cu^{2+} removal (%)

3. Effect of initial pH

pH is one of the principal factors controlling the adsorption process of metal ions in aqueous solutions (**Benefield *et al.*, 1982**), as it determines the magnitude and sign of the charge on ions. On dissolving CS in an acidic medium, the acid donates H^+ to the NH_2 group of the CS turning it into NH_3^+ thus, minimizing its efficacy to react with the metal ion **(Zia *et al.*, 2019)**. To restore the efficiency of the NH_2 group, the pH should be less acidic **(El-Naggar *et al.*, 2022).**

Consequently, the present study used three pH levels (3.0, 5.0, and 7.0) in examining the effect of pH on Cu^{2+} and Zn^{2+} adsorption (using 0.5 g CS, initial Cu^{2+} and Zn^{2+} ion concentrations as 4.49 and 5.15 mg/L, respectively, and a contact period of 20 minutes) (**Figure 2**).

Results of the present study showed that the adsorption capacity of Cu^{2+} ions onto CS was low at pH 3.0 and attained its optimal initial pH value at pH 5.0 with 99.1% removal efficiency (**Table 2**). Our result agrees with **Benavente *et al.* (2011)** who found that the maximum adsorption capacity for Cu^{2+} onto CS occurred at pH values between 4.0 and 6.0. Also, **Zheng *et al.* (2010)** found that as the pH increased from 2.5 to 3.5, the adsorption capacity for Cu^{2+} onto crayfish carapace micro-powder (CCM) increased slowly and reached its equilibrium in the pH range from 4.5 to 6.5.

Table 3: Adsorption capacity and removal efficiency of Zn^{2+} using 0.5 g chitosan from synthetic aqueous solution at different pH levels and different initial concentrations

Time (min)	C_o = 5.15 mg/L			C_o = 10.4 mg/L			C_o = 15.6 mg/L		
	pH=3			**pH=3**			**pH=3**		
	C_e (mg/L)	Q (mg/g)	X (%)	C_e (mg/L)	Q (mg/g)	X (%)	C_e (mg/L)	Q (mg/g)	X (%)
0	5.15	0	0	10.4	0	0	15.6	0	0
5	2.1	0.61	59.22	4.5	1.18	56.73	7	1.72	55.13
10	1.5	0.73	70.87	3.2	1.44	69.23	5	2.12	67.95
15	1.1	0.81	78.64	2.7	1.54	74.04	4.1	2.30	73.72
20	1	0.83	80.58	2.1	1.66	79.81	3.5	2.42	77.56
25	1	0.83	80.58	2.1	1.66	79.81	3.5	2.42	77.56
30	1	0.83	80.58	2.1	1.66	79.81	3.5	2.42	77.56
	pH=5			**pH=5**			**pH=5**		
0	5.15	0	0	10.4	0	0	15.6	0	0
5	1.8	0.67	65.05	3.9	1.3	62.50	6	1.92	61.54
10	1.2	0.79	76.70	2.6	1.56	75.00	4.5	2.22	71.15
15	0.9	0.85	82.52	2.1	1.66	79.81	4	2.32	74.36
20	0.7	0.89	86.41	2	1.68	80.77	3.3	2.46	78.85
25	0.7	0.89	86.41	2	1.68	80.77	3.3	2.46	78.85
30	0.7	0.89	86.41	2	1.68	80.77	3.3	2.46	78.85
	pH=7			**pH=7**			**pH=7**		
0	5.15	0	0	10.4	0	0	15.6	0	0
5	1.8	0.67	65.05	3.8	1.32	63.46	5.9	1.94	62.18
10	1.3	0.77	74.76	2.8	1.52	73.08	4.6	2.20	70.51
15	0.9	0.85	82.52	2	1.68	80.77	3.1	2.50	80.13
20	0.6	0.91	88.35	1.5	1.78	85.58	2.5	2.62	83.97
25	0.6	0.91	88.35	1.5	1.78	85.58	2.5	2.62	83.97
30	0.6	0.91	88.35	1.5	1.78	85.58	2.5	2.62	83.97

C_o = initial Zn^{2+} concentration before adsorption (mg/L); **C_e** = Zn^{2+} concentration after adsorption (mg/L); **Q** = quantity of adsorbed Zn^{2+} ions (mg/g); **X** = efficiency of Zn^{2+} removal (%)

On the other hand, the adsorption capacity of Zn^{2+} ions onto CS was low at pH 3.0 and 5.0 but increased at pH 7.0 with 88.35% removal efficiency (**Figure 2, Table 3**). Our result agrees with **Lu *et al.* (2007)** who found that the optimal initial pH of Zn^{2+} solution for adsorption by crayfish carapace micro-powder was near neutral.

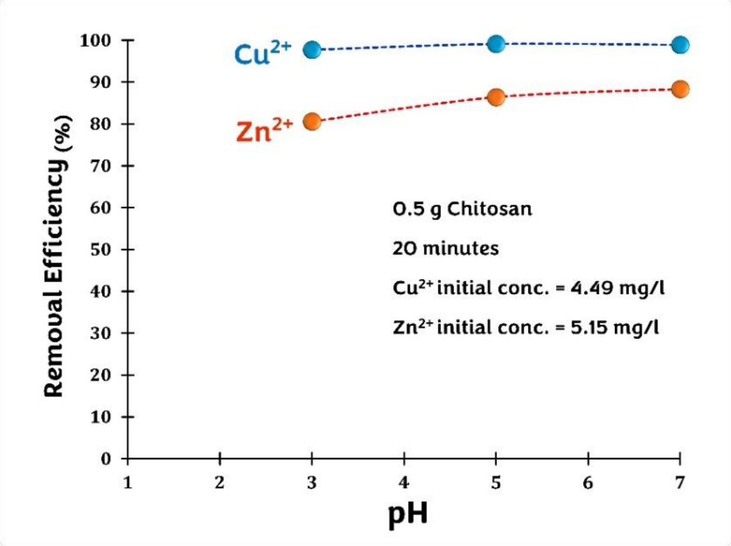

Figure 2. Comparison between the effect of the initial pH values on the uptake of Cu^{2+} and Zn^{2+} ions by 0.5 g CS at 20 min. Initial Cu^{2+} and Zn^{2+} ion concentrations are 4.49 and 5.15 mg/L, respectively.

4. Effect of initial ion concentrations (C_o)

Taking into consideration using the optimal time for adsorption (at 20 minutes), it was clear that as the initial concentrations of Cu^{2+} and Zn^{2+} ions increase, the removal percentage decreases (**Figure 3**).

Figure 4 displays the potential of implementing the examined chitosan dose (0.5 g) —on different concentrations of Cu^{2+} and Zn^{2+} ions prevailing in industrial wastewater— to meet the guideline values set by WHO for drinking water (**WHO, 2003 a & b**) and the Egyptian Environmental Law No. 48 (1982) for protecting the River Nile from pollution (**Egyptian Governmental Law No. 48, 1982**). Both ion concentrations must be less than “1.0 mg/L”, according to Egyptian rules, although WHO recommends Cu^{2+} and Zn^{2+} values of less than “2.0 mg/L” and “3.0 mg/L”, respectively.

The time taken by CS to attain the guideline values increases as the initial concentrations of Cu^{2+} and Zn^{2+} ions increase, as shown in **Figure (4).** For Cu^{2+}, the time it took to adsorb each of the three examined concentrations - to fulfil WHO and Egyptian law's guideline levels - was in the 15-minute range, which was faster than optimal. For Zn^{2+} (at C_o = 5.15 mg/L), CS required 5 and 15 minutes to satisfy WHO and Egyptian legislation guideline values, respectively. CS, on the other hand, took 10 and 20 minutes to obtain Zn^{2+} concentrations below 3 mg/L (WHO criteria) at C_o = 10.4 and 15.6 mg/L, respectively, however the Egyptian guideline limit (<1 mg/L) was not met. Still, if the period is extended, the Egyptian limit can be obtained.

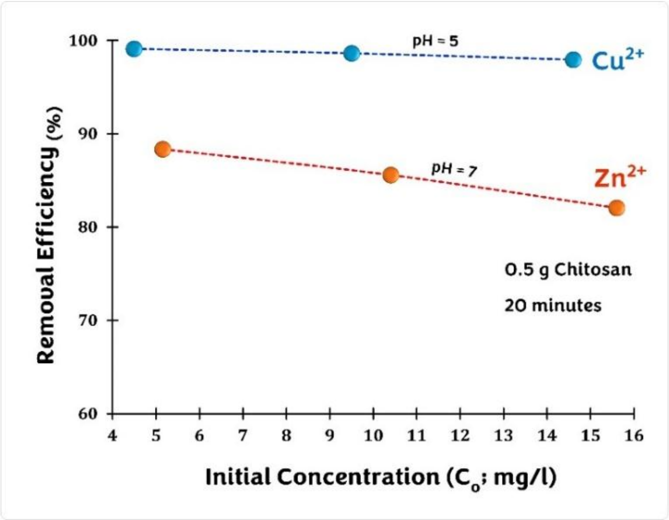

Figure 3. Comparison between the effect of different initial concentration (mg/L) of Cu^{2+} and Zn^{2+} ions on the adsorption process using 0.5 g CS for 20 min (at pH 5.0 for Cu^{2+} and pH 7.0 for Zn^{2+})

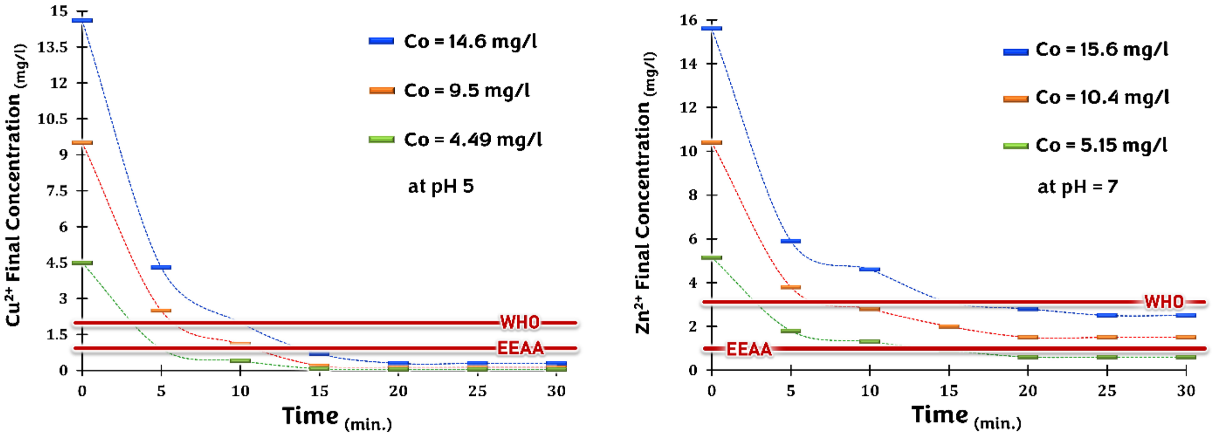

Figure 4. Effect of using 0.5 g CS on different concentrations (mg/L) for Cu^{2+} and Zn^{2+} ions, at room temperature, in comparison with EEAA permissible guidelines.

5. Elucidating the synergistic relationship between achieving the sixth SDG with other SDGs:

SDGs are interconnected and interwoven, which means that actions taken in one will have an impact on outcomes in others (**UNGA, 2015**). SDG-6 aims to ensure universal access to “safe drinking water and sanitation”, with an emphasis on the long-term management of water and wastewater resources and ecosystems. SDG-6 includes 8 targets, of which wastewater treatment and improving water quality are represented in target 6.3 with two indicators, viz, 6.3.1 and 6.3.2, respectively. Globally, 56% of the world's domestic wastewater is safely treated (SDG-6.3.1) **(https://www.sdg6data.org/**).

Unfortunately, there are not enough data available to make an estimate about the percentage of industrial wastewater that receives at least some treatment —from mining and quarrying, manufacturing, electricity, gas, steam and air conditioning supply, and construction activities— in Egypt throughout the period from 2015−2020 (**https://www.sdg6data.org/indicator/6.3.1**). Nevertheless, **Emam and Khalil (1995)** estimated the average annual yield of *P. clarkii* at Ismailia canal in the River Nile to be about 4.6 tonnes/year. Together with the increase in crayfish industry, the adoption of CS as a heavy metal absorber would undoubtedly help Egypt reduce its untreated industrial wastewater percentage by 2030 (SDG-6.3.1). **El-Naggar *et al*. (2022)** employed CS to adsorb heavy metals from *Oreochromis niloticus*, demonstrating that its use in adsorbing heavy metals is not limited to wastewater.

Figure 5 highlights the synergistic interactions that can occur with other SDGs, once target 6.3.1 is met. Increasing the percentage of treated wastewater, will ensure the proper management of chemicals and waste flow (**SDG-12.4**). Moreover, it will not only reduce the risk of malnutrition (**SDG-2.1**) but also the incidence of waterborne diseases (**SDG-3.3**) and the associated number of deaths (**SDG-11.5**). Over and above, the reuse of treated wastewater across all sectors (**SDG-6.4**) will reduce the high demand for freshwater required for economic growth, thereby reducing poverty (**SDG-1.5**), improving the environmental performance of cities (**SDG-11.6**), and strengthening resilience against climatic risks related to water scarcity (**SDG-13.1**).

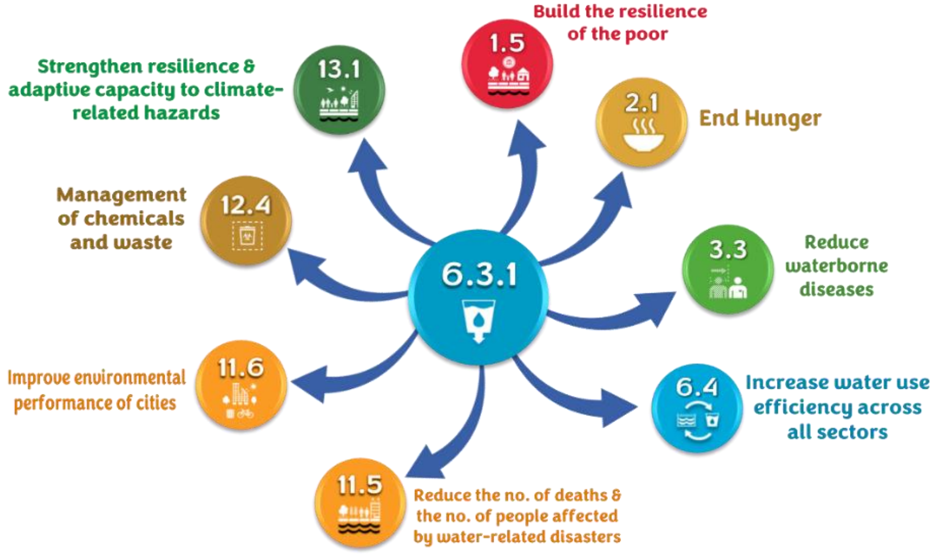

Fig. 5. A schematic diagram showing SDG-6.3.1 synergistic relationship with other SDGs.

CONCLUSION

In conclusion, when compared to other crustaceans, the exoskeleton wastes of *Procambarus clarkii* produced the highest amount of chitosan. The adsorption process for Cu^{2+} and Zn^{2+} ions on CS attained equilibrium at 20 minutes, pH 5.0 (for Cu^{2+}) and 7.0 (for Zn^{2+}), and initial concentrations of 4.49 mg/L (for Cu^{2+}) and 5.15 mg/L (for Zn^{2+}). The removal efficiency of the metal ions by CS decreased in the order of Cu^{2+} (99.11%) followed by Zn^{2+} (88.35%). Moreover, the investigated dose of CS (0.5 g) proved its potential to meet both the Egyptian and WHO guideline values for the optimal concentrations of Cu^{2+} and Zn^{2+} within the 15-minute period. The very fast adsorption kinetics (20 min) observed for the studied metals showed an advantage for using CS in the purification system for the industrial sector. Increasing the percentage of treated industrial wastewater (SDG-6.3.1) will clear the path for Egypt to make a significant progress toward achieving SDG-12.4, SDG-2.1, SDG-3.3, SDG-11.5, SDG-6.4, SDG-1.5, SDG-11.6, and SDG-13.1 by 2030.

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