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Utilizing Seawater as a Foliar Spray Under Freshwater Irrigation: How Can Harness the Inexpensive Resource of Beneficial Elements *via* Converting it to Nanoscale for Pepper Cultivation?

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ABSTRACT

Seawater, the most abundant water resource on Earth, presents a potential solution for sustainable agriculture. However, its high salinity challenges plant growth and soil health, necessitating innovative approaches. This study evaluates the feasibility of using seawater as a foliar spray under freshwater irrigation for pepper plants. Treatments involved seawater from the Mediterranean and Red Seas, both as normal and algae-based nanoparticle forms, combined with a salt solution (vanadium, zirconium, titanium). Seawater from Gamasa and Safaga, applied at 1% and 5% concentrations, was tested in its normal and nanoparticle forms, with and without the salt solution through a completely randomized experimental design. Results indicated that normal seawater from Gamasa and Safaga, even at higher concentrations, showed limited improvement over the control. Algae-based nanoparticles demonstrated enhanced plant growth and productivity, particularly from Safaga. The combination of nanoparticle seawater with the salt solution significantly outperformed other treatments; with Safaga's combination, showing the highest increase in growth performance, photosynthetic pigments, fruit yield, and quality traits of pepper plants. This study highlights the potential of seawater for agricultural use, suggesting that algae-based nanoparticle treatment, especially when combined with a salt solution, can effectively enhance crop productivity. Future research should focus on optimizing these techniques to maximize benefits and minimize adverse effects, paving the way for seawater as a viable resource in sustainable agriculture.

Keywords: Algae-based nanoparticles, Seawater, Salt-solution

INTRODUCTION

Seawater, as the most abundant water resource on Earth, presents a promising solution for sustainable agricultural practices. However, the high salinity of seawater poses significant challenges to plant growth and soil health, necessitating innovative approaches to make its use viable in the agricultural sector. It is considered the most abundant and cost-effective source of beneficial and essential elements needed for plant growth. (Martínez-Alvarez *et al.* 2016).

One promising approach is the foliar application of seawater, which involves spraying diluted seawater directly onto the leaves of plants. This method can help to supply essential nutrients and minerals found in seawater while minimizing the negative impacts of soil salinity. Recent advancements in nanotechnology have introduced the concept of converting seawater into nanoscale form, which may significantly enhance its usefulness for plant growth. Algae-based nanoparticles of seawater has shown potential in reducing salinity stress on plants and improving the efficiency of nutrient uptake (Ayaz *et al.* 2022).

One innovative approach to harnessing seawater benefits involves converting seawater into nanoparticles through the use of algae. Algae, known for their remarkable ability to perform photosynthesis and absorb nutrients from their environment, play a crucial role in this process. Through a series of biochemical reactions, algae metabolize and break down the components of seawater into nano-sized particles, facilitating their absorption and uptake by plants. This conversion process not only increases the bioavailability of nutrients but also enhances their efficiency in promoting plant growth and development. By harnessing the natural capabilities of algae, scientists are exploring sustainable methods to optimize resource utilization and mitigate water scarcity in agriculture (Fawcett *et al.* 2017; Mukherjee *et al.* 2021). Converting seawater from its normal state to a nanoscale form can offer several advantages for agricultural use, particularly for pepper cultivation. One key benefit is the enhanced nutrient availability due to the increased surface area of nanoscale particles, which improves solubility and absorption by plants. This increased efficiency allows for targeted nutrient delivery, ensuring plants receive a steady supply over time and reducing wastage. Additionally, nanoscale nutrients can promote better plant growth and health by enhancing root development, photosynthesis, and stress tolerance, leading to more robust plants. Environmentally, the use of nanoscale nutrients can reduce pollution by minimizing fertilizer runoff and support sustainable agricultural practices by reducing dependence on synthetic fertilizers and freshwater resources. Economically, utilizing seawater, an abundant and inexpensive resource, combined with the efficiency of nanoscale nutrients, can lower agricultural costs and make resource utilization more effective. Finally, the ability to customize nanoscale formulations to meet the specific needs of different crops, such as peppers, enhances productivity and quality, making this approach a cutting-edge solution for modern agriculture (Abideen *et al.* 2022).

Vanadium is not considered an essential nutrient for plants but can play a beneficial role in certain physiological processes. It can act as a substitute for molybdenum in nitrate reductase, an enzyme involved in nitrogen assimilation,

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especially under molybdenum-deficient conditions. Vanadium can enhance plant growth by promoting chlorophyll synthesis and improving nitrogen fixation in some plants (Taha *et al.* 2017; Hanus-Fajerska *et al.* 2021).

Zirconium is not recognized as an essential element for plant growth, but it can contribute to plant health and development. It can stimulate the uptake of other essential nutrients, such as phosphorus, enhancing root growth and overall plant vigor. Zirconium has been observed to improve the structural integrity of cell walls and enhance the plant's resistance to stress (El-Ghamry *et al.* 2024).

Titanium is considered a beneficial element for plants. It is known to enhance photosynthesis and stimulate growth. Titanium can increase chlorophyll content, thereby improving the efficiency of photosynthesis. It enhances enzyme activities related to plant metabolism and promotes the uptake of essential nutrients (Ghazi *et al.* 2022).

The cultivation of pepper (*Capsicum annuum*) is of significant economic importance globally, making it crucial to explore innovative nutrition practices to ensure sustainable production (Shedeed *et al.* 2023; Mostafa *et al.* 2024).

By utilizing seawater, especially in its nano-treated form, as a foliar spray, the agricultural sector can tap into a sustainable water source, potentially transforming pepper cultivation practices in regions facing freshwater scarcity. This approach not only optimizes water use but also contributes to the resilience and productivity of pepper plants, supporting sustainable agricultural development. Therefore, the primary objective of this study is to evaluate the feasibility of using seawater, particularly in its nanoscale form, in conjunction with salt solution (vanadium, zirconium and titanium) in pepper cultivation and to determine the optimal treatment combinations that maximize plant performance and fruit quality. By addressing the potential of algae-based nanoparticles of seawater as a sustainable foliar application, this research contributes to the broader goal of enhancing water use efficiency and promoting sustainable agricultural practices in water-scarce regions

MATERIALS AND METHODS

Experimental site

A field trial was conducted during the season of 2024 (from January 1st) at the experimental farm of Mansoura University, Dakahlia governorate, Egypt. The experiment followed a completely randomized design with three replicates. Each treatment plot, along with its three replicates, measured 9.0 m^2 (3.0m x 3.0m). The variety of pepper used was California Wonder.

Treatments

Fig 1 shows the flowcharts of the studied treatments. The experimental treatments consisted of various seawater applications:

T_1: Control (Tap Water), having EC value of 0.4 dSm^{-1}

T_2: Gamasa City seawater (Mediterranean Sea), normal seawater at 10 ml L^{-1} (equal to 1%), having EC value of 1.4 dSm^{-1}

T_3: Gamasa City seawater (Mediterranean Sea), normal seawater at 50 ml L^{-1} (equal to 5%), having EC value of 2.34 dSm^{-1}

T_4: Gamasa City seawater (Mediterranean Sea), algae-based nanoparticles of seawater at 10 ml L^{-1} (equal to 1%), having EC value of 1.40 dSm^{-1}

T_5: Gamasa City seawater (Mediterranean Sea), algae-based nanoparticles of seawater at 50 ml L^{-1} (equal to 5%), having EC value of 2.33 dSm^{-1}

T_6: Gamasa City seawater (Mediterranean Sea), algae-based nanoparticles of seawater + Salt solution at 10 ml L^{-1} (equal to 1%), having EC value of 1.468 dSm^{-1}

T_7: Gamasa City seawater (Mediterranean Sea), algae-based nanoparticles of seawater + Salt solution at 50 ml L^{-1} (equal to 5%), having EC value of 2.76 dSm^{-1}

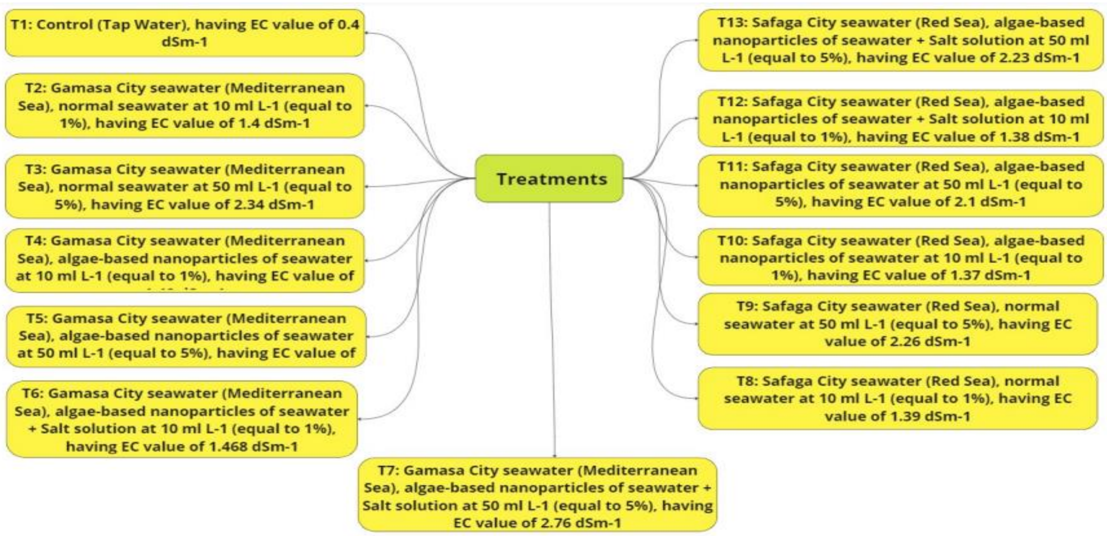

Fig. 1. Flowchart of the studied treatments

T_8: Safaga City seawater (Red Sea), normal seawater at 10 ml L^{-1} (equal to 1%), having EC value of 1.39 dSm^{-1}

T_9: Safaga City seawater (Red Sea), normal seawater at 50 ml L^{-1} (equal to 5%), having EC value of 2.26 dSm^{-1}

T_{10}: Safaga City seawater (Red Sea), algae-based nanoparticles of seawater at 10 ml L^{-1} (equal to 1%), having EC value of 1.37 dSm^{-1}

T_{11}: Safaga City seawater (Red Sea), algae-based nanoparticles of seawater at 50 ml L^{-1} (equal to 5%), having EC value of 2.1 dSm^{-1}

T_{12}: Safaga City seawater (Red Sea), algae-based nanoparticles of seawater + Salt solution at 10 ml L^{-1} (equal to 1%), having EC value of 1.38 dSm^{-1}

T_{13}: Safaga City seawater (Red Sea), algae-based nanoparticles of seawater + Salt solution at 50 ml L^{-1} (equal to 5%), having EC value of 2.23 dSm^{-1}

Preparation of algae-based nanoparticles from seawater

The collected seawater samples were diluted with distilled water to match the concentrations specified for the experimental treatments. A biological method, specifically biosynthesis using active algae, was utilized to produce algae-based nanoparticles. This method involves leveraging the natural properties of algae to encapsulate and transform salts, sediments, and other beneficial particles into a nano-sized form suitable for plant absorption.

Collection and preparation of algae for nanoparticle synthesis

Algae of the species *Sargassum latifolium* were collected from the Red Sea through collaboration with the National Institute of Oceanography and Fisheries in Hurghada (NIOF). This species is known for its robust bioactive properties and suitability for nanoparticle synthesis. The collected raw algae were thoroughly washed with distilled water to remove any adherent salt, sand, and other impurities. This step is crucial to ensure that the algae used for nanoparticle synthesis are free from contaminants that could interfere with the biosynthesis process. After washing, the algae were dried in the shade to prevent degradation of heat-sensitive bioactive compounds. The drying was conducted away from direct sunlight to maintain the integrity of the algae's phenolic compounds and other valuable components. The drying process continued until the algae reached a final moisture content of 8.5 ± 0.5%. This specific moisture level is optimal for ensuring the algae's stability and effectiveness in subsequent nanoparticle synthesis. The controlled drying process helps to preserve the functional properties of the algae, making them suitable for the production of bio-synthesized nanoparticles. This detailed process of collection and preparation ensures that the algae retain their bioactivity and are in the best condition for use in the synthesis of algae-based nanoparticles for agricultural applications.

Seawater collection and transportation

Seawater samples were gathered in glass bottles from both the Mediterranean Sea and the Red Sea and subsequently transported to the laboratory at Mansoura University. A portion of these samples underwent a biosynthesis process using a specialized apparatus developed by El-Ghamry and El-Khateeb (2021), herein referred to as the "El-Ghamry and El-Khateeb Bio-Nano Apparatus".

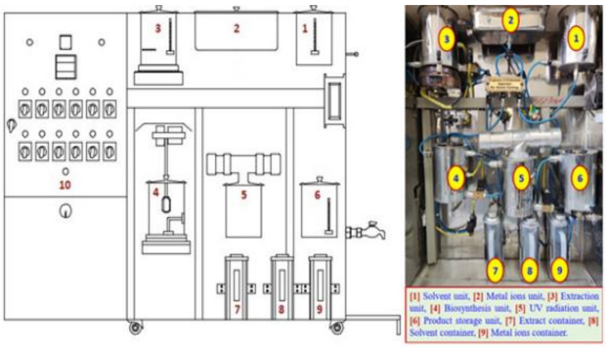

Photo: El-Ghamry and El-Khateeb Bio-Nano Apparatus (El-Ghamry *et al.* 2021)

Nanoparticle Preparation Process

When marine algae are added to seawater, the phenolic compounds present in the algae facilitate the isolation of salts and the formation of insulating layers around nanoparticles derived from these salts. This transformation renders the salts more accessible for plant uptake (El-Ghamry *et al.* 2021). The preparation of algae-based nanoparticles was conducted at the Agricultural Chemistry Department, Faculty of Agriculture, Mansoura University, following the methodology described by Devasenan *et al.* (2016). The following photo shows the apparatus used.

Steps of the biosynthesis process

Dilution and initial processing

The seawater samples, after being diluted according to the treatment specifications, were introduced into the first unit of the Bio-Nano Apparatus. This initial stage involved gradual heating and continuous stirring to activate the necessary reactions.

Algae extract preparation

In the second unit, water served as the solvent for preparing the algae extract. The algae's active compounds, particularly phenols, were extracted with controlled heating to optimize the extraction process.

Extraction unit

The third unit facilitated the extraction of active compounds from the algae, focusing on the phenolic content. Controlled temperature and extraction time ensured the efficiency of this process. Upon completion, an automatic electrical valve allowed the process to proceed to the next stage.

Biosynthesis unit

The fourth unit, known as the reducing unit, employed electronic oscillation (Resonance Hybrid) to reduce the salt ions to neutral, nano-sized particles. These particles were then encapsulated by polyphenols, creating the desired algae-based nanoparticles at the nanoscale.

By converting the salts and nutrients in seawater into nanoparticles through this biogenic synthesis, the resulting solution becomes highly effective for agricultural use, particularly in enhancing the nutrient uptake efficiency of plants while mitigating potential toxic effects associated with high salinity.

In addition to the algae preparation, a specific salt solution was formulated for this study. The salt solution contained vanadium sulfate (VSO_4), zirconium sulfate ($ZrSO_4$), and titanium dioxide (TiO_2), each at a concentration of 5.0 mg/L. they were put in the same apparatus according to the studied treatments. These compounds were selected for their potential to form nanoparticles (nano-V, nano-Zr, and nano-Ti, respectively) and their beneficial roles in plant nutrition.

Soil analysis

An initial soil sample was collected and analyzed according to Tandon, (2005). The soil properties are presented in Table 1.

Table 1. Soil properties (before implementing the experiment)

Characteristics	Values
Clay,%	50
Silt,%	30
Sand,%	20
Textural class	Clayey
Nitrogen, mg N Kg^{-1}soil	38.9
Phosphorus, mg P Kg^{-1} soil	7.89
Potassium, mg K Kg^{-1} soil	225
Organic matter, %	1.32
EC dSm^{-1} (suspension 1: 5)	0.95
pH (suspension 1:2.5)	8.00

Seawater analysis

The characteristics of seawater of both seas in as normal and algae-based nanoparticles of seawater were shown in Tables from 2 to 5.

Scanning electron microscopic (SEM) of seawater

The properties of seawater from both the Mediterranean Sea and the Red Sea, in both normal and nanoparticle forms, were analyzed using Scanning Electron Microscopy (SEM). Figures 2 to 5 display the results of this characterization, providing insights into the morphology and structure of the seawater particles at the nanoscale level.

Table 2. The characteristics of normal Gamasa City seawater (Mediterranean Sea)

Concentration average(Gamasa Citye normal)	
Al 396.152 {85} (Radial)	23.213 ppm
Se 196.090 {472} (Radial)	*ND
V 290.882 {116} (Radial)	0.042 ppm
Hg 184.950 {482} (Radial)	2.213 ppm
Ag 328.068 {103} (Radial)	0.501 ppm
B 249.773 {135} (Radial)	2.984 ppm
Ba 455.403 {74} (Radial)	0.627 ppm
Ca 393.366 {86} (Radial)	483.631 ppm
Cd 226.502 {449} (Radial)	0.071 ppm
Co 228.616 {447} (Radial)	0.173 ppm
Cr 283.563 {119} (Radial)	21.359 ppm
Cu 324.754 {104} (Radial)	1.534 ppm
Fe 259.940 {130} (Radial)	6.565 ppm
Ga 294.364 {114} (Radial)	*ND
In 325.609 {103} (Radial)	*ND
Li 670.784 {50} (Radial)	*ND
Mg 279.553 {121} (Radial)	664.929 ppm
Mn 257.610 {131} (Radial)	0.143 ppm
Ni 216.556 {456} (Radial)	0.022 ppm
Pb 220.353 {453} (Radial)	*ND
K 766.490 {44} (Radial)	154.292 ppm
Sr 407.771 {83} (Radial)	5.270 ppm
Zn 213.856 {458} (Radial)	5.565 ppm
As 189.042 {478} (Radial)	*ND
Na 589.592 {57} (Radial)	*ND
Bi 223.061 {451} (Radial)	*ND
Se 206.279 {463} (Radial)	*ND

***ND= not detected**

Table 3. The characteristics of algae-based nanoparticles of seawater of Gamasa city (Mediterranean Sea)

Concentration average	
Al 396.152 {85} (Radial)	*ND
Se 196.090 {472} (Radial)	*ND
V 290.882 {116} (Radial)	*ND
Hg 184.950 {482} (Radial)	0.140 ppm
Ag 328.068 {103} (Radial)	*ND
B 249.773 {135} (Radial)	4.079 ppm
Ba 455.403 {74} (Radial)	0.438 ppm
Ca 393.366 {86} (Radial)	555.441 ppm
Cd 226.502 {449} (Radial)	0.283 ppm
Co 228.616 {447} (Radial)	2.562 ppm
Cr 283.563 {119} (Radial)	0.729 ppm
Cu 324.754 {104} (Radial)	8.877 ppm
Fe 259.940 {130} (Radial)	22.329 ppm
Ga 294.364 {114} (Radial)	*ND
In 325.609 {103} (Radial)	6.047 ppm
Li 670.784 {50} (Radial)	0.012 ppm
Mg 279.553 {121} (Radial)	735.839 ppm
Mn 257.610 {131} (Radial)	7.066 ppm
Ni 216.556 {456} (Radial)	2.438 ppm
Pb 220.353 {453} (Radial)	0.274 ppm
K 766.490 {44} (Radial)	2,147.082 ppm
Sr 407.771 {83} (Radial)	8.396 ppm
Zn 213.856 {458} (Radial)	172.009 ppm
As 189.042 {478} (Radial)	*ND
Na 589.592 {57} (Radial)	5,628.391 ppm
Bi 223.061 {451} (Radial)	*ND
Se 206.279 {463} (Radial)	3.975 ppm

***ND= not detected**

Table 4. The characteristics of normal Safaga City seawater (Red Sea)

Concentration average	
Al 396.152 {85} (Radial)	*ND
Se 196.090 {472} (Radial)	*ND
V 290.882 {116} (Radial)	*ND
Hg 184.950 {482} (Radial)	0.451 ppm
Ag 328.068 {103} (Radial)	0.102 ppm
B 249.773 {135} (Radial)	1.998 ppm
Ba 455.403 {74} (Radial)	0.161 ppm
Ca 393.366 {86} (Radial)	367.899 ppm
Cd 226.502 {449} (Radial)	0.119 ppm
Co 228.616 {447} (Radial)	0.319 ppm
Cr 283.563 {119} (Radial)	0.304 ppm
Cu 324.754 {104} (Radial)	2.217 ppm
Fe 259.940 {130} (Radial)	*ND
Ga 294.364 {114} (Radial)	1.348 ppm
In 325.609 {103} (Radial)	*ND
Li 670.784 {50} (Radial)	*ND
Mg 279.553 {121} (Radial)	690.580 ppm
Mn 257.610 {131} (Radial)	*ND
Ni 216.556 {456} (Radial)	*ND
Pb 220.353 {453} (Radial)	*ND
K 766.490 {44} (Radial)	99.478 ppm
Sr 407.771 {83} (Radial)	3.836 ppm
Zn 213.856 {458} (Radial)	3.763 ppm
As 189.042 {478} (Radial)	*ND
Na 589.592 {57} (Radial)	5,251.737 ppm
Bi 223.061 {451} (Radial)	0.685 ppm
Se 206.279 {463} (Radial)	*ND

***ND= not detected**

Table 5. The characteristics of algae-based nanoparticles of seawater of Safaga city (Red Sea)

Concentration average	
Al 396.152 {85} (Radial)	*ND
Se 196.090 {472} (Radial)	*ND
V 290.882 {116} (Radial)	*ND
Hg 184.950 {482} (Radial)	0.510 ppm
Ag 328.068 {103} (Radial)	*ND
B 249.773 {135} (Radial)	4.417 ppm
Ba 455.403 {74} (Radial)	0.315 ppm
Ca 393.366 {86} (Radial)	521.245 ppm
Cd 226.502 {449} (Radial)	0.050 ppm
Co 228.616 {447} (Radial)	0.421 ppm
Cr 283.563 {119} (Radial)	0.137 ppm
Cu 324.754 {104} (Radial)	3.925 ppm
Fe 259.940 {130} (Radial)	2.895 ppm
Ga 294.364 {114} (Radial)	*ND
In 325.609 {103} (Radial)	*ND
Li 670.784 {50} (Radial)	*ND
Mg 279.553 {121} (Radial)	736.962 ppm
Mn 257.610 {131} (Radial)	1.069 ppm
Ni 216.556 {456} (Radial)	0.368 ppm
Pb 220.353 {453} (Radial)	*ND
K 766.490 {44} (Radial)	1,885.949 ppm
Sr 407.771 {83} (Radial)	8.540 ppm
Zn 213.856 {458} (Radial)	25.145 ppm
As 189.042 {478} (Radial)	0.450 ppm
Na 589.592 {57} (Radial)	5,525.818 ppm
Bi 223.061 {451} (Radial)	*ND
Se 206.279 {463} (Radial)	*ND

***ND= not detected**

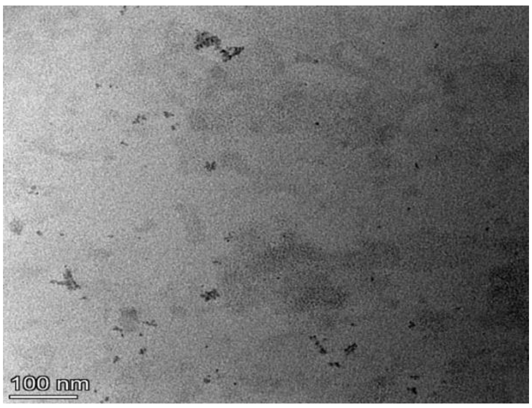

Fig. 2. Normal Gamasa City seawater (Mediterranean Sea)

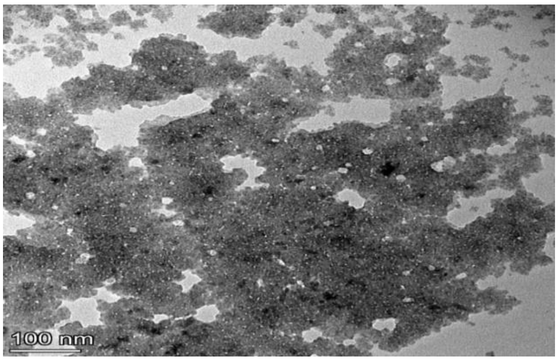

Fig. 3. Algae-based nanoparticles of seawater of Gamasa city (Mediterranean Sea)

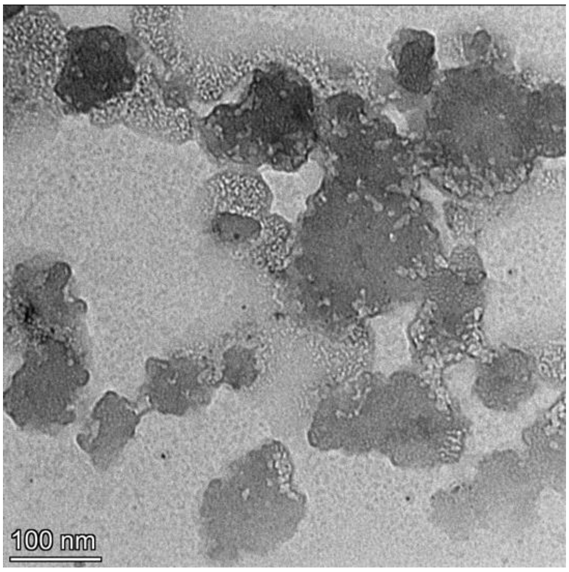

Fig. 4. Normal Safaga City seawater (Red Sea)

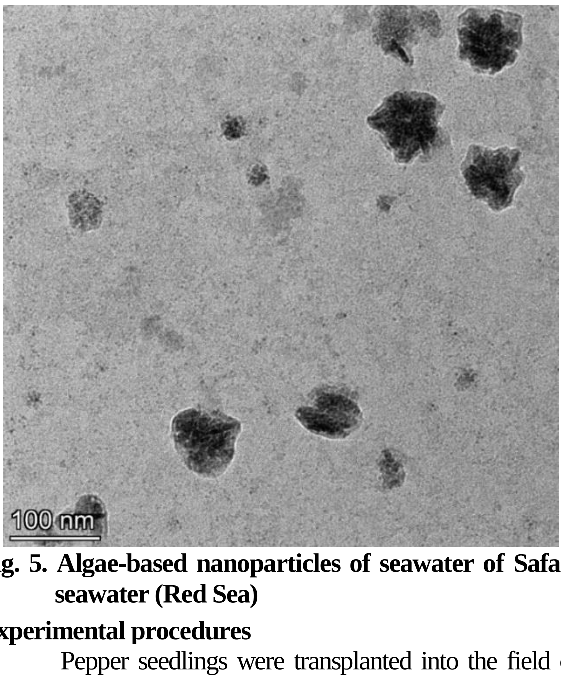

Fig. 5. Algae-based nanoparticles of seawater of Safage seawater (Red Sea)

Experimental procedures

Pepper seedlings were transplanted into the field on January 1st, 2024, following standard agricultural practices recommended by the Ministry of Agriculture and Soil Reclamation (MASR) in Egypt for pepper cultivation. The application of various seawater treatments was conducted three times, commencing on February 25th, with intervals of 14 days between each spraying session. The foliar of the seawater treatment was applied during the early morning to reduce evaporation and prevent leaf burn. The method of application involved using a fine mist to ensure even coverage without excessive runoff. The plants were rinsed with fresh water after a few hours to remove any residual salt with avoid applying seawater treatments during periods of high heat or strong sunlight, as this can increase the risk of foliar burn. Harvesting commenced on March 30th and continued until May 25th.

Measurements

After 60 days from planting, various growth parameters including plant height (cm), number of leaves per plant, fresh weight of leaves (g per plant), dry weight of leaves (g per plant), and leaf area (cm^2 per plant) were measured. Additionally, the levels of photosynthetic pigments such as chlorophyll a and b, as well as carotene (mg per g), were determined following the method described by Lichtenthaler (1987).

At harvest time, measurements were taken for fruit-related characteristics, including fruit length (cm), fruit diameter (cm), fruit dry matter content (%), average fruit weight (g), number of fruits per plant, and fruit yield (tons per hectare). Moreover, fruit quality parameters such as carbohydrates content (%), total sugar content (%), vitamin C concentration (mg per 100g), total dissolved solids (TDS %), and acidity (%) were determined using standard methods as outlined by AOAC (2000).

Statistical analysis

Statistical analysis involved conducting an analysis of variance (ANOVA) following the methodology outlined by Duncan (1955) and Gomez and Gomez (1984).

RESULTS AND DISCUSSION

Results

Growth parameters (after 60 days from transplanting)

Table 6 presents the effects of different seawater treatments on the growth performance of pepper plants after 60 days from planting. This table provides data on various growth parameters including plant height(cm), number of leaves $plant^{-1}$, foliage fresh and dry weights (g $plant^{-1}$) and leaf area (cm^2 $plant^{-1}$).

Observing the data, it's evident that the treatments had varying impacts on the growth of pepper plants. In general, it appears that the application of seawater treatments, particularly nano-seawater and combinations with salt solutions, resulted in enhanced growth compared to the control group irrigated with tap water.

For instance, under the Gamasa City seawater treatment, both normal and algae-based nanoparticles of seawater at concentrations of 10 ml L^{-1} and 50 ml L^{-1} showed increases in plant height, number of leaves, fresh weight, dry weight, and leaf area compared to the control group. Similar trends were observed for the Safaga City seawater treatments.

Moreover, the combination of algae-based nanoparticles of seawater with a salt solution showed the most significant improvements in growth parameters across all treatments, indicating a synergistic effect between seawater and added nutrients. The LSD values provided at the bottom of the table indicate the level of significance. These values confirmed that the observed differences between treatments are statistically significant.

Overall, the results of Table 6 show that the sequence of treatments from less to more effective is as follows. The control treatment, which involved tap water, was found to be the least effective in enhancing the growth parameters of pepper plants. This was followed by the use of normal Gamasa City seawater at concentrations of 10 then 50 ml L^{-1}. Similarly, normal Safaga City seawater at 10 then 50 ml L^{-1} showed slightly better results than the Gamasa City seawater treatments. The algae-based nanoparticles of seawater of Gamasa city at 10 then 50 ml L^{-1} exhibited further improvement in plant growth performance.

Likewise, algae-based nanoparticles of seawater of Safaga city at 10 and 50 ml L^{-1} showed enhanced effects compared to the nano-treated Gamasa City seawater. When combining algae-based nanoparticles of seawater with a salt solution, the treatments showed significantly better results. The combination of Gamasa City nano seawater with a salt solution at 10 then 50 ml L^{-1} proved to be highly effective. Finally, the most effective treatments were the combinations of Safaga City nano seawater with a salt solution at 10 then 50 ml L^{-1}, which resulted in the highest improvements in growth performance of the pepper plants.

Table 6. Effect of seawater treatments on the growth performance of pepper plants after 60 days from planting

Treatments			Plant height, cm	No. of leaves plant^{-1}	Fresh weight, g plant^{-1}	dry weight, g plant^{-1}	Leaf area, cm^2 plant^{-1}
Tap water (control)			42.04k	11.33g	174.55h	26.00i	271.00g
Gamasa City Sea water	Normal sea water	10 ml L^{-1} (equal 1%)	42.48k	11.67fg	177.75gh	26.40i	277.67g
		50 ml L^{-1} (equal 5%)	44.26j	12.00efg	179.58fg	27.04h	286.33fg
	Algae-based nanoparticles of seawater	10 ml L^{-1} (equal 1%)	49.17g	12.67c-g	185.53de	29.26f	308.33de
		50 ml L^{-1} (equal 5%)	50.40f	13.00b-f	187.02cd	29.63ef	317.00cd
	Algae-based nanoparticles of seawater + salt solution	10 ml L^{-1} (equal 1%)	54.13c	14.00bc	192.01ab	31.18bc	332.00abc
		50 ml L^{-1} (equal 5%)	54.99b	14.33b	192.02ab	31.39b	338.67ab
Safaga City Sea water	Normal sea water	10 ml L^{-1} (equal 1%)	45.73i	12.33d-g	181.49fg	27.64g	294.00ef
		50 ml L^{-1} (equal 5%)	46.88h	12.67c-g	182.77ef	28.07g	299.00ef
	Algae-based nanoparticles of seawater	10 ml L^{-1} (equal 1%)	51.78e	13.33b-e	188.65bcd	30.20de	322.00cd
		50 ml L^{-1} (equal 5%)	53.02d	13.67bcd	190.21abc	30.62cd	328.00bc
	Algae-based nanoparticles of seawater + salt solution	10 ml L^{-1} (equal 1%)	55.14ab	16.00a	192.75a	32.68a	341.67ab
		50 ml L^{-1} (equal 5%)	55.83a	16.67a	192.79a	32.91a	345.33a
LSD at 5%			0.80	1.46	3.78	0.59	15.71

Means within a row followed by a different letter (s) are statistically different at a 0.05 level

Photosynthetic pigments (after 60 days from transplanting)

Data in Table 7 illustrate the effect of various seawater treatments on the photosynthetic pigments (chlorophyll a, chlorophyll b and carotene, mg g^{-1} F.W) in the leaves of pepper plants 60 days after transplanting. This assessment highlights the impact of seawater treatments on critical components of photosynthesis, which directly influence plant growth and productivity.

Table 7. Effect of seawater treatments on the photosynthetic pigments in leaves of pepper plants

Treatments			Chlorophyll a, mg g^{-1} F.W	Chlorophyll b, mg g^{-1} F.W	Carotene, mg g^{-1} F.W
Tap water (control)			0.730h	0.558j	0.273i
Gamasa City sea water	Normal sea water	10 ml L^{-1} (equal 1%)	0.732h	0.566ij	0.280h
		50 ml L^{-1} (equal 5%)	0.743h	0.578hi	0.285gh
	Algae-based nanoparticles of seawater	10 ml L^{-1} (equal 1%)	0.815f	0.618f	0.304e
		50 ml L^{-1} (equal 5%)	0.827f	0.626ef	0.310de
	Algae-based nanoparticles of seawater + salt solution	10 ml L^{-1} (equal 1%)	0.874cd	0.652bc	0.322b
		50 ml L^{-1} (equal 5%)	0.880bc	0.654bc	0.324b
Safaga City sea water	Normal sea water	10 ml L^{-1} (equal 1%)	0.765g	0.586gh	0.292fg
		50 ml L^{-1} (equal 5%)	0.782g	0.599g	0.296f
	Algae-based nanoparticles of seawater	10 ml L^{-1} (equal 1%)	0.845e	0.636de	0.314cd
		50 ml L^{-1} (equal 5%)	0.857de	0.647cd	0.319bc
	Algae-based nanoparticles of seawater + salt solution	10 ml L^{-1} (equal 1%)	0.895ab	0.666ab	0.332a
		50 ml L^{-1} (equal 5%)	0.899a	0.670a	0.336a
LSD at 5%			0.018	0.014	0.007

Means within a row followed by a different letter (s) are statistically different at a 0.05 level

The data clearly show that the treatments had varying impacts on the values of photosynthetic pigments of pepper plants. Overall, the application of seawater treatments, particularly nano-seawater and its combinations with salt solutions, resulted in enhanced photosynthetic pigments (chlorophyll a, chlorophyll b, and carotene) compared to the control group treated with tap water. For example, under the Gamasa City seawater treatment, both normal and nano-seawater at concentrations of 10 ml L^{-1} and 50 ml L^{-1} showed increases in photosynthetic pigments compared to the control group. Similar trends were observed for the Safaga City seawater treatments. Additionally, the combination of nano-seawater with a salt solution showed the most significant improvements in photosynthetic pigments across all treatments, indicating a synergistic effect between seawater and added nutrients.

Overall, the results of Table 7 illustrate the sequence of treatments from least to most effective. The control treatment with tap water was the least effective in enhancing the photosynthetic pigments in pepper plant leaves. This was followed by the use of normal Gamasa City seawater at concentrations of 10 ml L^{-1} and then 50 ml L^{-1}. Similarly, normal Safaga City seawater at 10 ml L^{-1} and then 50 ml L^{-1} showed slightly better results than the Gamasa City seawater treatments. The nano-Gamasa City seawater at 10 ml L^{-1} and then 50 ml L^{-1} exhibited further improvements in photosynthetic pigments.

Likewise, nano-Safaga City seawater at 10 ml L^{-1} and 50 ml L^{-1} showed enhanced effects compared to the nano-treated Gamasa City seawater. When combining nano-seawater with a salt solution, the treatments showed significantly better results. The combination of Gamasa City nano-seawater with a salt solution at 10 ml L^{-1} and then 50 ml L^{-1} proved to be highly effective. Finally, the most effective treatments were the combinations of Safaga City nano-seawater with a salt solution at 10 ml L^{-1} and then 50 ml L^{-1}, resulting in the highest improvements in the photosynthetic pigments of the pepper plants.

Fruit yield and physical characteristics (at harvest time)

Table 8 presents the impact of different seawater treatments on various fruit yield and physical traits of pepper plants at harvest time. The measured parameters include fruit length (cm), fruit diameter (cm), fruit dry matter (%), average fruit weight (g), number of fruits plant^{-1} and fruit yield (ton ha^{-1}, Fig 6). The control group, which was treated with tap water, had the smallest fruit length (4.09 cm) and diameter (3.21 cm). The normal seawater treatments (both 10 ml L^{-1} and 50 ml L^{-1}) showed slight increases in fruit length and diameter compared to the control. Algae-based nanoparticles of seawater of Gamasa city and its combinations with salt solutions significantly enhanced these parameters, with the highest values observed for the combination treatments. Similar trends were observed for Safaga City seawater treatments. The combination of nano-Safaga City seawater with salt solutions at both concentrations resulted in the longest and widest fruits, with values reaching up to 8.72 cm in length and 5.97 cm in diameter. Also, in this respect, the control group had the lowest fruit dry matter percentage (16.88%). Normal Gamasa City seawater showed slight improvements, while nano-seawater and combinations with salt solutions resulted in significant increases, reaching up to 19.50%. The highest fruit dry matter percentages were observed in the Safaga City nano-seawater with salt solution treatments, with values reaching up to 19.68%.

Table 8. Effect of seawater treatments on the fruit yield and physical traits of pepper plants

Treatments			Fruit length, cm	Fruit diameter, cm	Fruit dry matter, %	Average fruit weight, g	No. of fruits plant^{-1}	Fruit yield ton ha^{-1}
Tap water (control)			4.09i	3.21j	16.88i	41.42	21.00h	29.56j
Gamasa City sea water	Normal sea water	10 ml L^{-1} (equal 1%)	4.33i	3.57i	17.07hi	42.25	22.00gh	31.60ij
		50 ml L^{-1} (equal 5%)	4.68h	3.73hi	17.37gh	42.79	23.00fg	33.45hi
	Algae-based nanoparticles of seawater	10 ml L^{-1} (equal 1%)	6.19f	4.47f	18.46e	44.86	24.33def	37.11ef
		50 ml L^{-1} (equal 5%)	6.66e	4.73ef	18.74de	45.35	25.00cde	38.55def
	Algae-based nanoparticles of seawater + salt solution	10 ml L^{-1} (equal 1%)	7.74c	5.26c	19.44ab	46.51	26.33abc	41.66bc
		50 ml L^{-1} (equal 5%)	8.10b	5.42bc	19.50ab	47.02	26.33abc	42.09abc
Safaga City sea water	Normal sea water	10 ml L^{-1} (equal 1%)	5.01g	3.96gh	17.60fg	43.30	23.33fg	34.36gh
		50 ml L^{-1} (equal 5%)	5.29g	4.06g	17.91f	44.35	24.00ef	36.17fg
	Algae-based nanoparticles of seawater	10 ml L^{-1} (equal 1%)	6.95e	4.90de	18.92cd	45.89	25.33b-e	39.53cde
		50 ml L^{-1} (equal 5%)	7.38d	5.10cd	19.19bc	46.37	25.67bcd	40.47bcd
	Algae-based nanoparticles of seawater + salt solution	10 ml L^{-1} (equal 1%)	8.48a	5.70ab	19.64a	47.10	26.67ab	42.70ab
		50 ml L^{-1} (equal 5%)	8.72a	5.97a	19.68a	47.27	27.67a	44.46a
LSD at 5%			0.32	0.33	0.38	1.02	1.61	2.68

Means within a row followed by a different letter (s) are statistically different at a 0.05 level

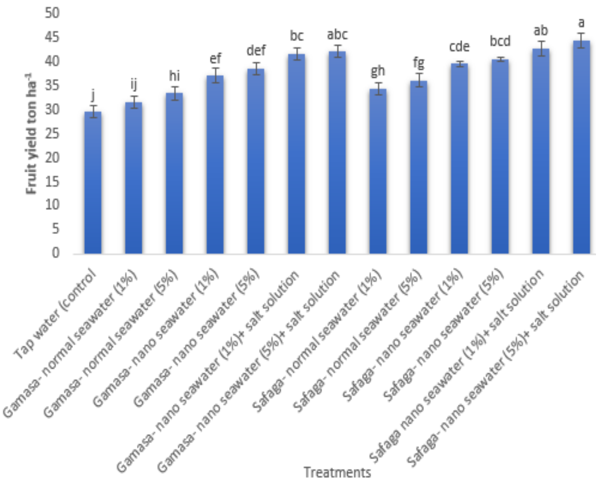

Fig. 6. Effect of seawater treatments on the fruit yield (ton ha^{-1})

Regarding the average fruit weight, the control group had an average fruit weight of 41.42 g. Incremental improvements were noted with the application of both normal and algae-based nanoparticles of seawater of Gamasa City, with the highest average fruit weight recorded at 47.02 g in the nano-seawater with salt solution treatment. Similar enhancements were observed, with the combination treatments showing the highest values, reaching up to 47.27 g.

Concerning the number of fruits plant^{-1}, the control group produced the least number of fruits per plant (21.00). Normal seawater treatments showed modest increases, while algae-based nanoparticles of seawater and its combinations with salt solutions showed more significant improvements, with the highest being 26.33 fruits per plant. The highest number of fruits per plant was recorded in the Safaga City algae-based nanoparticles of seawater with salt solution treatment at 50 ml L^{-1}, with 27.67 fruits per plant.

As for fruit yield (ton ha^{-1}), the lowest fruit yield was observed in the control group (29.56 ton ha^{-1}). The application of normal seawater resulted in incremental yield increases, while algae-based nanoparticles of seawater and its combinations with salt solutions showed more substantial yield enhancements, reaching up to 42.09 ton ha^{-1}. The highest fruit yield was recorded in the Safaga City algae-based nanoparticles of seawater with salt solution at 50 ml L^{-1}, with a yield of 44.46 ton ha^{-1}.

Generally, the results in Table 8 clearly demonstrate that seawater treatments, particularly algae-based nanoparticles of seawater and combinations with salt solutions, significantly improve the fruit yield and physical characteristics of pepper plants. The control group (tap water) consistently showed the lowest values across all parameters. The most effective treatments were the combinations of algae-based nanoparticles of seawater with salt solutions, with Safaga City seawater treatments showing slightly better results than Gamasa City seawater treatments. The statistical significance indicated by the LSD values confirms that these differences are substantial and not due to random variation

Fruit quality characteristics (at harvest time)

Table 9 illustrates the impact of various seawater treatments on the fruit quality traits of pepper plants at harvest time. The treatments varied, including normal seawater, algae-based nanoparticles of seawater, and combinations of algae-based nanoparticles of seawater with a salt solution, with concentrations of 10 ml L^{-1} (1%) and 50 ml L^{-1} (%5). The control group (tap water) had the lowest carbohydrate content at 18.45%. Normal Gamasa City seawater treatments showed a slight increase in carbohydrates, with 18.64% at 10 ml L^{-1} and 19.01% at 50 ml L^{-1}. Nano-Gamasa City seawater at the same concentrations showed even higher values (20.16% and 20.40%, respectively). The combination with salt solutions led to a significant increase, reaching 21.31% at 10 ml L-1 and 21.35% at 50 ml L^{-1}. Similar trends were observed with Safaga City seawater treatments. Carbohydrate content increased to 19.31% at 10 ml L^{-1} and 19.52% at 50 ml L^{-1} with normal Safaga City seawater, and further to 20.70% and 20.97% with nano-Safaga City seawater. The highest values were seen with nano- Safaga City seawater plus salt solution (21.60% and 21.63%).

Regarding total sugar (%), the lowest total sugar content was observed in the control group at 6.89%. Normal Gamasa City seawater treatments showed an increase to 6.93% and 7.25%. Nano-Gamasa City seawater further increased the total sugar content to 8.17% and 8.34%, while combinations with salt solutions resulted in 8.90% and 9.00%. For Safaga City seawater, total sugar increased from 7.51% to 7.71% with normal seawater and further to 8.58% and 8.71% with algae-based nanoparticles of seawater. The highest values were observed with the nano-seawater plus salt solution treatments (9.04% and 9.13%).

Concerning vitamin C (mg $100g^{-1}$), the control group had 85.99 mg $100g^{-1}$ of vitamin C. Normal Gamasa City seawater treatments showed slight increases (86.06 mg and 86.44 mg). algae-based nanoparticles of seawater of Gamasa City increased vitamin C content further (87.69 mg and 87.96 mg), and the highest values were observed with the addition of salt solutions (89.09 mg and 89.23 mg). Similar trends were observed with Safaga City seawater, with normal seawater showing 86.78 mg and 87.13 mg, algae-based nanoparticles of seawater showing 88.40 mg and 88.73 mg, and the highest values with salt solutions (89.40 mg and 89.64 mg).

As for TDS (%), the control group had the lowest TDS at 4.90%. The values of TDS increased with normal seawater treatments (4.98% and 5.26%), algae-based nanoparticles of seawater (6.06% and 6.24%), and the highest values with salt solutions (6.90% and 7.20%). Normal Safaga City seawater treatments showed increases to 5.50% and 5.68%, algae-based nanoparticles of seawater to 6.49% and 6.70%, and the highest values with salt solutions (7.25% and 7.28%).

Concerning acidity (%), the control group had the highest acidity at 0.340%. Acidity decreased with normal Gamasa City seawater (0.338% and 0.334%), algae-based nanoparticles of seawater (0.317% and 0.315%), and the lowest values with salt solutions (0.297% and 0.293%).

As for Safaga City seawater, the normal seawater showed acidity at 0.327% and 0.323%, algae-based nanoparticles of seawater at 0.311% and 0.299%, and the lowest values with salt solutions (0.290% and 0.281%).

Generally, the results indicate that the application of seawater treatments, especially algae-based nanoparticles of seawater and its combinations with salt solutions, significantly improved fruit quality traits compared to the control. Carbohydrate and total sugar contents increased, vitamin C levels were higher, TDS was elevated, and acidity was reduced in treated plants. These trends suggest that seawater treatments, particularly in nano form with added salts, enhance the nutritional quality of pepper fruits.

Table 9. Effect of seawater treatments on the fruit quality traits of pepper plants

Treatments			Carbohydrates, %	Total sugar, %	Vitamin C, mg $100g^{-1}$	TDS, %	Acidity, %
Tap water (control)			18.45i	6.89h	85.99e	4.90j	0.340a
Gamasa City sea water	Normal sea water	10 ml L^{-1} (equal 1%)	18.64hi	6.93h	86.06e	4.98j	0.338ab
		50 ml L^{-1} (equal 5%)	19.01gh	7.25g	86.44de	5.26i	0.334ab
	Algae-based nanoparticles of seawater	10 ml L^{-1} (equal 1%)	20.16e	8.17d	87.69a-e	6.06f	0.317cd
		50 ml L^{-1} (equal 5%)	20.40de	8.34d	87.96a-e	6.24e	0.315cd
	Algae-based nanoparticles of seawater + salt solution	10 ml L^{-1} (equal 1%)	21.31ab	8.90b	89.09ab	6.90b	0.297efg
		50 ml L^{-1} (equal 5%)	21.35ab	9.00ab	89.23ab	7.20a	0.293fg
Safaga City sea water	Normal sea water	10 ml L^{-1} (equal 1%)	19.31fg	7.51f	86.78cde	5.50h	0.327abc
		50 ml L^{-1} (equal 5%)	19.52f	7.71e	87.13b-e	5.68g	0.323bcd
	Algae-based nanoparticles of seawater	10 ml L^{-1} (equal 1%)	20.70cd	8.58c	88.40a-d	6.49d	0.311de
		50 ml L^{-1} (equal 5%)	20.97bc	8.71c	88.73abc	6.70c	0.299ef
	Algae-based nanoparticles of seawater + salt solution	10 ml L^{-1} (equal 1%)	21.60a	9.04ab	89.40a	7.25a	0.290fg
		50 ml L^{-1} (equal 5%)	21.63a	9.13a	89.64a	7.28a	0.281g
LSD at 5%			0.41	0.19	2.13	0.15	0.016

Means within a row followed by a different letter (s) are statistically different at a 0.05 level

Discussion

Growth parameters (after 60 days from transplanting)

The control group, irrigated with tap water, exhibited the lowest values across all measured parameters, indicating that seawater treatments, in general, had a positive impact on growth performance.

At concentrations of 10 ml L^{-1} and 50 ml L^{-1}, normal Gamasa City seawater showed improvements over the control group. However, the improvements were modest, suggesting that while normal seawater does provide some benefit, its impact is limited without further enhancement.

Similar to Gamasa City seawater, normal Safaga City seawater at both 10 ml L^{-1} and 50 ml L^{-1} concentrations showed better results than the control group and the normal Gamasa City seawater treatments. This indicates that Safaga City seawater might have a slightly more beneficial composition or that its geographic source has inherent advantages for plant growth.

Algae-based nanoparticles of seawater of Gamasa city at 10 ml L^{-1} and 50 ml L^{-1} concentrations demonstrated significant improvements in plant height, number of leaves, fresh weight, dry weight, and leaf area compared to normal seawater treatments. This indicates that converting seawater to nano form enhances its efficacy, possibly due to increased availability and uptake of nutrients.

Similarly, algae-based nanoparticles of seawater of Safaga city at the same concentrations outperformed nano-treated Gamasa City seawater, further reinforcing the potential geographical advantages of Safaga City seawater and the benefits of nano-treatment.

The most significant improvements were observed in the treatments that combined algae-based nanoparticles of seawater with a salt solution (containing vanadium, zirconium, and titanium). Both Gamasa City and Safaga City seawater in this combination showed substantial enhancements in all growth parameters. This suggests a synergistic effect where the salt solution augments the benefits of algae-based nanoparticles of seawater, possibly by providing additional essential nutrients or by enhancing the uptake and utilization of nutrients.

Seawater contains essential minerals and elements necessary for plant growth. When treated to nano form, these nutrients become more bioavailable, allowing plants to absorb them more efficiently. The use of nano-particles likely improves nutrient delivery to plants, ensuring that they receive a more consistent and accessible supply of nutrients, leading to better growth performance (Fawcett *et al.* 2017; Mukherjee *et al.* 2021). Algae play a crucial role in converting seawater into a more plant-friendly form through a process known as biogenic synthesis. This method involves using algae to produce nanoparticles from seawater, which significantly enhances the bioavailability of nutrients while reducing the toxicity associated with high salinity. Algae-based nanotechnology helps to encapsulate essential nutrients such as magnesium, calcium, and trace elements like zinc and iodine in nano form. These nanoparticles are more readily absorbed by plant tissues due to their small size and high surface area, which facilitates efficient uptake through the stomata and cuticle of the leaves. High salinity in seawater can cause osmotic stress and ion toxicity in plants. The use of algae-based nanoparticles of seawater mitigates these effects by controlling the release of nutrients and limiting the direct exposure of plants to harmful salts. Algal nanoparticles act as carriers that release nutrients slowly and steadily, thereby preventing the accumulation of toxic levels of sodium and chloride in plant tissues.The bioactive compounds in algae, such as polysaccharides, amino acids, and growth hormones, further enhance plant health by stimulating root and shoot development, increasing chlorophyll content, and improving overall plant vigor.This leads to improved photosynthetic efficiency and greater tolerance to environmental stresses.

The addition of a salt solution with specific elements (vanadium, zirconium, and titanium) likely provides a further boost. These elements might play roles in enhancing metabolic processes, improving stress tolerance, or optimizing nutrient uptake and utilization. Titanium (Ti) in nano form may have contributed to non-nitrogen fixation and enhanced the efficiency of photosynthesis, vanadium (V) in nano form may have played a role in nitrogen metabolism and enzyme activation, while zirconium (Zr) in nano may have improved pepper plant growth and stress resistance (Taha *et al.* 2017; Hanus-Fajerska *et al.* 2021; Ghazi *et al.* 2022; El-Ghamry *et al.* 2024).

The observed differences between Gamasa City and Safaga City seawater treatments might be attributed to variations in the mineral composition of seawater from different sources, which can influence plant growth differently.

Photosynthetic pigments (after 60 days from transplanting)

The control group, sprayed with tap water, exhibited the lowest levels of chlorophyll a, chlorophyll b and carotene. This indicates that the absence of seawater nutrients limits the photosynthetic capacity of the pepper plants. The application of normal Gama's seawater at both 10 ml L^{-1} and 50 ml L^{-1} resulted in slight increases in photosynthetic pigments compared to the control. However, the improvements were minimal, suggesting that normal seawater without additional treatment provides limited enhancement to pigment concentration. On the other hand, a significant increase in chlorophyll a & b and carotene was observed with nano-Gamasa City seawater at both concentrations. This improvement indicates that the nano-treatment enhances the availability and absorption of essential nutrients, thus boosting photosynthetic efficiency.

Additionally, the combination of nano-Gamasa City seawater with a salt solution (vanadium+ titanium+ zirconium) led to further significant increases in photosynthetic pigment levels, indicating a synergistic effect. This combination provides additional essential elements (vanadium, zirconium, titanium) that likely play crucial roles in enhancing chlorophyll synthesis and overall photosynthetic activity.

Vanadium is not considered an essential nutrient for plants but can play a beneficial role in certain physiological processes. It can act as a substitute for molybdenum in nitrate reductase, an enzyme involved in nitrogen assimilation, especially under molybdenum-deficient conditions. Vanadium can enhance plant growth by promoting chlorophyll synthesis and improving nitrogen fixation in some plants (Taha *et al.* 2017; Hanus-Fajerska *et al.* 2021).

Zirconium is not recognized as an essential element for plant growth, but it can contribute to plant health and development. It can stimulate the uptake of other essential nutrients, such as phosphorus, enhancing root growth and overall plant vigor. Zirconium has been observed to improve the structural integrity of cell walls and enhance the plant's resistance to stress (El-Ghamry *et al.* 2024).

Titanium is considered a beneficial element for plants. It is known to enhance photosynthesis and stimulate growth. Titanium can increase chlorophyll content, thereby improving the efficiency of photosynthesis. It enhances enzyme activities related to plant metabolism and promotes the uptake of essential nutrients (Ghazi *et al.* 2022).

The combination of vanadium, zirconium, and titanium in plant nutrition can have synergistic effects, enhancing plant growth and productivity more effectively than individual applications.

These elements can improve nutrient uptake, enhance photosynthetic activity, and strengthen plant structures, leading to better growth performance and stress resistance.

When added to algae-based nanoparticles of seawater, these elements can further improve the efficiency of nutrient delivery and absorption by plants. The nano-scale treatment ensures that these elements are more readily available to plants, enhancing their beneficial effects while minimizing potential toxicity risks (Fawcett *et al.* 2017; Mukherjee *et al.* 2021).

Normal Safaga City seawater showed better results compared to normal Gamasa City seawater, reflecting slight geographical differences in seawater composition that may favor the photosynthetic process in plants. Nano- Safaga City seawater treatments resulted in marked increases in photosynthetic pigments, with 50 ml L^{-1} showing higher levels than 10 ml L^{-1}. The nano-treatment improves nutrient delivery and uptake, contributing to enhanced pigment concentrations.

This combination exhibited the highest levels of chlorophyll a, chlorophyll b, and carotene, demonstrating the most effective treatment in enhancing photosynthetic pigments. The synergy between algae-based nanoparticles of seawater and the salt solution significantly boosts the photosynthetic capacity of the pepper plants, leading to better growth performance.

Generally, it can be said that Nano-treatment increases the bioavailability of nutrients in seawater, making them more accessible for plant absorption and utilization, which directly contributes to higher levels of chlorophyll and carotene.

The combination of algae-based nanoparticles of seawater with a salt solution containing specific elements (vanadium, zirconium, titanium) likely enhances enzymatic activities and metabolic pathways involved in chlorophyll synthesis, leading to significant improvements in photosynthetic pigments.

Differences in the mineral composition of Gamasa City and Safaga City seawater can affect the efficacy of treatments, with Safaga City seawater showing slightly better results, possibly due to its inherent nutrient profile (El-Said and Sikaily, 2013; Abdelmongy and El-Moselhy, 2015).

Finally, it can be noticed that the application of nano-seawater, especially in combination with a salt solution, significantly enhances the photosynthetic pigment levels in pepper plants. This results in improved photosynthetic efficiency and overall plant growth, highlighting the potential of these treatments to optimize agricultural productivity.

Fruit yield and physical characteristics (at harvest time)

The notable improvements in fruit yield and physical characteristics of pepper plants treated with algae-based nanoparticles of seawater and its combinations with salt solutions can be scientifically explained by several key mechanisms. Nano-seawater significantly increases the bioavailability of essential nutrients. The nanoparticles facilitate more efficient absorption and transport of nutrients such as magnesium, calcium, potassium, and trace elements. These nutrients are vital for various physiological processes, including cell division, expansion, and fruit development. Enhanced nutrient uptake leads to better overall plant health and more resources available for fruit growth (Mukherjee *et al.* 2021; Abideen *et al.* 2022).

The addition of vanadium, zirconium, and titanium to algae-based nanoparticles of seawater provides additional benefits. Vanadium is known to enhance enzymatic activities involved in chlorophyll synthesis and nitrogen metabolism, which are critical for plant growth and development. Zirconium and titanium contribute to improved nutrient utilization efficiency and antioxidant activity, reducing oxidative stress and promoting healthier, more robust plants. These elements likely work in synergy with the nutrients in seawater to optimize growth conditions and enhance fruit production.

The significant increases in photosynthetic pigments (chlorophyll a, chlorophyll b, and carotenoids) observed in plants treated with algae-based nanoparticles of seawater indicate higher photosynthetic efficiency. Chlorophyll is directly involved in capturing light energy for photosynthesis, and carotenoids protect the photosynthetic apparatus from oxidative damage. Enhanced photosynthesis means more energy and assimilates are available for fruit development, resulting in larger, heavier fruits with higher dry matter content.

Nanoparticles can influence the osmotic properties of plant cells, helping plants maintain turgor pressure and sustain growth even under saline conditions. This osmotic adjustment capacity allows plants to better manage water uptake and retention, improving water use efficiency. Efficient water management is crucial for fruit development, as it ensures a steady supply of water and nutrients to the growing fruits, leading to improved fruit size, weight, and overall yield.

The combination of algae-based nanoparticles of seawater and salt solutions enhances the plants' ability to tolerate environmental stresses, particularly salinity. Saline conditions can negatively impact plant growth and fruit production by causing ionic imbalances and osmotic stress. However, the treated plants exhibit better stress tolerance due to the protective effects of enhanced nutrient uptake, improved photosynthetic efficiency, and osmotic regulation. This results in healthier plants that can allocate more resources towards fruit production.

Generally, the enhanced fruit yield and physical characteristics of pepper plants treated with algae-based nanoparticles of seawater and its combinations with salt solutions are due to the combined effects of improved nutrient availability and uptake, synergistic benefits of added salt solutions, increased photosynthetic efficiency, better osmotic regulation and water use efficiency, and enhanced stress tolerance. These factors collectively contribute to the superior fruit yield and quality observed in the treated plants.

Fruit quality characteristics (at harvest time)

The improvement in fruit quality traits observed in pepper plants treated with seawater can be attributed to several scientific reasons. One key factor is the presence of essential nutrients in seawater, including various minerals and trace elements, which are absorbed by the plants and contribute to their overall health and quality. These nutrients, such as potassium, magnesium, and calcium, play crucial roles in various physiological processes within the plant, including fruit development and quality formation.

Additionally, the application of seawater treatments can positively influence the physiological processes involved in fruit metabolism. For example, seawater treatments have been reported to enhance photosynthetic activity and carbon assimilation in plants, leading to increased carbohydrate production. This, in turn, can result in higher levels of sugars and other carbohydrates in the fruits, contributing to improved taste and sweetness.

Furthermore, seawater treatments have been shown to enhance the antioxidant capacity of plants, including peppers, by increasing the levels of antioxidant compounds such as Vitamin C. Antioxidants play a crucial role in protecting plant cells from oxidative stress and damage caused by reactive oxygen species. By increasing the antioxidant content in fruits, seawater treatments can improve their shelf life, nutritional value, and overall quality.

The salinity stress imposed by seawater treatments can also trigger physiological responses in plants that lead to the accumulation of osmolytes, such as sugars and organic acids, in fruit tissues. These osmolytes help plants maintain cellular turgor pressure and osmotic balance under saline conditions, contributing to improved fruit quality traits such as firmness and texture.

Moreover, the synergistic effects of nano-seawater and salt solutions can further enhance the uptake and utilization of nutrients by plants, leading to improved fruit quality. Nano-sized particles have been shown to increase the efficiency of nutrient absorption by plant roots and enhance nutrient translocation within the plant tissues. By combining nano-seawater with salt solutions containing essential nutrients such as nitrogen, phosphorus, and micronutrients, plants can benefit from a more balanced nutrient supply, resulting in improved fruit quality traits such as size, color, and nutritional content.

The superiority of Red Sea water treatments over Mediterranean Sea water treatments for growing peppers when sprayed can be attributed to several factors related to the unique characteristics of the Red Sea. The Red Sea is known for its rich biodiversity, including a wide variety of seaweed and algae. These organisms are capable of producing a plethora of bioactive compounds such as phytohormones, amino acids, vitamins, and minerals that can significantly enhance plant growth and development. Seaweed and algae extracts are rich in substances that promote plant growth, such as cytokinins, auxins, and gibberellins. These can improve various physiological processes in plants, including nutrient uptake, photosynthesis, and stress tolerance. The Red Sea has a higher salinity compared to the Mediterranean Sea, which means it contains higher concentrations of certain minerals and trace elements. These elements, such as magnesium, calcium, and potassium, are essential for plant growth and can improve the nutritional status of the plants when applied as foliar sprays. The Red Sea water may contain higher levels of beneficial trace elements like zinc, manganese, and iron, which are crucial for various enzymatic and physiological functions in plants. Bioactive compounds from Red Sea algae can help plants to better resist environmental stresses such as drought, salinity, and extreme temperatures. These compounds enhance the plants' stress response mechanisms, leading to improved growth and yield. Some seaweed and algae extracts have antimicrobial properties that can protect plants from pathogens, reducing the incidence of diseases and improving overall plant health.

Generally, the scientific reasons underlying the improvement in fruit quality traits observed in pepper plants treated with seawater include the presence of essential nutrients, enhanced physiological processes, increased antioxidant capacity, accumulation of osmolytes, and synergistic effects of nano-seawater and salt solutions. These factors collectively contribute to the enhancement of fruit's nutritional value. Model in Fig 7 explains the relationship between seawater-foliar applications on pepper plants. Generally, the current findings show that algae-based nanoparticles of seawater, particularly when combined with specific salt solutions, can significantly enhance the growth performance, photosynthetic efficiency, and yield of pepper plants.

Fig. 7. Model illustrating the relationship between seawater-foliar applications and pepper plant responses

CONCLUSION

The findings of this study underscore the potential of seawater as a promising resource for enhancing the growth, productivity, and quality of pepper plants. Through a comprehensive evaluation of various seawater treatments, including normal seawater, nano-seawater, and combinations with salt solutions, significant improvements were observed in growth parameters, photosynthetic pigments, fruit yield, and quality traits of pepper plants. The results demonstrate that the application of seawater treatments, particularly nano-seawater combined with salt solutions can effectively supplement traditional irrigation methods and contribute to sustainable agriculture practices.

Based on the results obtained, several recommendations can be made for future research and practical applications. Firstly, further investigations are warranted to explore the underlying mechanisms and physiological responses of pepper plants to seawater treatments, including the uptake and translocation of nutrients, osmotic regulation, and antioxidant metabolism. Understanding these processes will facilitate the optimization of seawater application strategies and the development of tailored management practices for different crop species and environmental conditions.

Additionally, efforts should be made to evaluate the long-term effects of seawater treatments on soil health, microbial communities, and ecosystem sustainability. Assessing the potential risks and benefits associated with seawater irrigation will inform decision-making processes and support the development of guidelines and regulations for its safe and responsible use in agriculture.

Furthermore, future research endeavors should focus on scaling up seawater-based agricultural practices and exploring innovative technologies for seawater desalination, purification, and distribution. Collaborative efforts between scientists, policymakers, and stakeholders are essential to address the technical, economic, and socio-environmental challenges associated with seawater agriculture and promote its widespread adoption on a global scale.

When using seawater as a foliar application in agriculture, it's important to follow specific controls to maximize benefits and minimize risks. The timing of application is crucial; seawater should be applied during early morning or late afternoon to reduce evaporation and prevent leaf burn. Choosing the right location is also important; applying seawater in areas with good air circulation can help the foliage dry more quickly, reducing the risk of salt buildup. The method of application should involve using a fine mist to ensure even coverage without excessive runoff. Precautions include using diluted seawater to prevent salt toxicity and regularly monitoring the plants for any signs of stress or damage. It's essential to rinse the plants with fresh water after a few hours to remove any residual salt and to avoid applying seawater during periods of high heat or strong sunlight, as this can increase the risk of foliar burn. By carefully managing these factors, seawater can be effectively used as a foliar spray to provide beneficial nutrients to plants.

Finally, the integration of seawater into agricultural systems offers a promising solution to address water scarcity, enhance crop productivity, and ensure food security in water-stressed regions. By harnessing the potential of seawater as a sustainable resource, we can create resilient and environmentally sound agricultural systems that contribute to the well-being of both present and future generations.

Conflicts of interest

Authors have declared that no competing interests exist. The authors contributed equally to put the research methodology and implementing it at all stages.

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استخدام مياه البحر كرش ورقي تحت الري بالمياه العذبة: كيف يمكن تسخير الموارد الغير مكلفة للعناصر المفيدة من خلال تحويلها إلى مقياس النانو لزراعة الفلفل؟

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قسم الأراضي كليه الزراعه جامعه المنصورة

الملخص

تمثل مياه البحر، وهي المورد المائي الأكثر وفرة على وجه الأرض، حلاً محتملاً للزراعة المستدامة. ومع ذلك، فإن ملوحتها العالية تشكل تحديًا لنمو النباتات وصحة التربة، مما يستلزم اتباع أساليب مبتكرة. تهدف هذه الدراسة إلى تقييم جدوى استخدام مياه البحر رشاً ورقياً تحت الري بالمياه العذبة علي نباتات الفلفل. وشملت المعاملات مياه البحر من البحر الأبيض المتوسط والبحر الأحمر، في صورة طبيعية أو جسيمات نانوية تعتمد على الطحالب، بالإضافة إلى محلول ملحي (الفناديوم، والزركونيوم، والتيتانيوم). تم اختبار مياه البحر من جمصة وسفاجا، بتركيز 1% و5%، في صورتها الطبيعية و النانوية، مع وبدون المحلول الملحي من خلال تصميم تجريبي كامل العشوائية. أشارت النتائج إلى أن مياه البحر الطبيعية من جمصة وسفاجا، حتى عند التركيزات الأعلى، أظهرت تحسنًا محدودًا مقارنة بالمياه العادية (الكنترول). وأظهرت الصورة النانوية المعتمدة على الطحالب نموًا وإنتاجية أفضل للنباتات، خاصة مع مياه سفاجا. لقد تفوق مزيج مياه البحر النانوية مع المحلول الملحي بشكل كبير على المعاملات الأخرى؛ مع المعاملة المدمجه لمياه سفاجا، تظهر أعلى زيادة في أداء النمو، وصبغات التمثيل الضوئي، وإنتاجية الثمار، وسمات الجودة لنباتات الفلفل. تسلط هذه الدراسة الضوء على إمكانات مياه البحر للاستخدام الزراعي، وكذلك تشير إلى أن تحول مياه البحر الي الصورة النانوية المعتمدة على الطحالب، خاصة عندما تقترن بمحلول ملحي، يمكن أن يعزز بشكل فعال إنتاجية المحاصيل. وينبغي أن تركز الأبحاث المستقبلية على تحسين هذه التقنيات لتعظيم الفوائد وتقليل الآثار الضارة، مما يمهد الطريق لمياه البحر كمورد حيوي في الزراعة المستدامه