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Phytoremediation of Wastewater with Walnut Shells as Substrate

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ABSTRACT

Phytoremediation is considered an attractive and green method of treating urban wastewater, especially in developing countries, due to its low operating cost and sustainable environmental option. This research aimed to evaluate an advanced method of phytoremediation using natural media composed of walnut shells and gravel with peace lily plants (S. Cochlearispathum) for treating real wastewater with methyl orange dye. A Lab-scale of three tanks, the first one is wastewater only as a control containment (WW), the second tank includes substrate only (WS), and the third one includes substrate with the plant of S. Cochlearispathum (WSP). The experiment was operated with a batch system. The WSP tank recorded the highest treatment efficiency, where the percentage removal was found to be 61.60% for TSS, 65.70% for color, 82.35% for nitrate, and 67.90% for phosphate. Overall, walnut shells as a substrate with phytoremediation were found to significantly improve the treatment of wastewater, which can be a feasible, economical, and sustainable technique for developing regions.

Keywords: Adsorption, Methyl orange, Peace lily, Sustainable treatment, Walnut shells.

1. INTRODUCTION

Wastewater pollution is a significant issue for many countries around the world due to factors like rapid urbanization and increased populations, as well as inadequate wastewater treatment facilities, especially in developing nations **(Auied et al., 2025; Adesanmi et al., 2022).** Existing wastewater treatment techniques are effective but are often characterized by high energy demand, chemical use, and operational skills, while also yielding considerable sludge that is difficult to manage. Therefore, nature-based and sustainable wastewater treatment techniques have emerged as effective alternatives due to their cost-effectiveness and sustainability **(Sharma et al., 2024**). Phytoremediation has been developed as a promising ecological approach for wastewater treatment, which combines the capabilities of plants, microbes, and substrates in removing pollutants. In this approach, plants are used to improve oxygen transfer, microbial activity, and nutrient assimilation, while substrates are used for adsorption and biofilm formation. Commonly used methods

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for the removal of nutrients from wastewater are biological denitrification, ion exchange, membrane filtration, adsorption, etc. **(Kinidi and Salleh, 2017)**. Recently, low-cost biomass-based materials have been reported as an emerging technology for the removal of nutrients from wastewater, considering the renewability of the materials, the presence of functional groups on the surface of the materials, and the ability of the materials to exchange ions **(Janković et al., 2024; Stjepanović et al., 2022)**. The aspect of nutrient removal in advanced wetland systems is affected by the use of multiple mechanisms, such as biological, physical, and chemical, which are effective in improving the efficiency of the system. **(Biswal et al., 2022; Gaballah et al., 2025).** Mechanistically, the process of phytoremediation can be described in terms of phytoextraction, rhizofiltration, phytostabilization, and phytodegradation. In these processes, the plant absorbs the pollutants, and this helps macrophytes to remove nutrients, dyes, and heavy metals from wastewater and yet be metabolically active **(Kafle et al., 2022)**. Constructed wetlands and hydroponic phytoremediation have shown high efficiency in removing turbidity, nutrients, and organic pollutants using a combination of biological and physicochemical mechanisms **(Yuliasni, 2023)**. Substrate materials have been recognized as having significant effects on the improvement of the performance of the treatment process, including increasing the capacity of filtration, adsorption, and microbial colonization. Agricultural by-product materials, including walnut shells, have also drawn increasing attention due to their lignocellulosic composition, porosity, and availability as natural, low-cost materials. These materials can help to increase the efficiency of the removal of pollutants, especially nitrogen and phosphorus-containing compounds, through the process of adsorption, exchange, and precipitation **(Guo et al., 2026)**. Walnut shells were used as a bio-carrier for the treatment of real oilfield produced water and proved to be efficient in reducing membrane contamination due to the adsorption of oil compounds **(Hasanzadeh et al., 2023)**. Walnut shells were used as filler in CW for binding metals and supporting various functional microbes, in addition to providing a carbon source **(Chang et al., 2022)**. Another important factor that affects the efficiency of phytoremediation is the choice of plants used in the process. For example, the ornamental plants used in the study, such as S. Cochlearispathum, were found to exhibit strong tolerance to saturated and hydroponic environments and have dense fibrous root systems that allow for microbial growth and nutrient transformations in the rhizosphere. Previous studies have indicated that the genus Spathiphyllum plays a significant role in the removal of nutrients and stabilization of treatment systems in constructed wetlands and hydroponic environments **(Sandoval et al., 2019)**. Although there is an increase in research on phytoremediation systems, few research findings have evaluated the potential use of walnut shells as a natural adsorption medium coupled with ornamental plants for treating dye-contaminated wastewater. The novelty of this study lies in the integrated use of walnut shells as a sustainable substrate combined with Peace Lily plants to create a highly efficient, low-cost phytoremediation system for treating dye-contaminated urban wastewater. In addition, the effects of substrate media and plant-based systems on physicochemical and nutrient removal efficiencies are also worthy of further research, especially in regions with limited wastewater treatment plants **(Bayuo et al., 2024; Lin et al., 2025)**. Consequently, the objective of the study is to assess the efficacy of a substrate-assisted phytoremediation system with walnut shells and the plant species S. Cochlearispathum for wastewater treatment. The research is centered on the assessment of the removal efficiencies of various water quality parameters, such as turbidity, color, conductivity, total suspended solids, total dissolved solids, nitrate, total nitrogen, phosphate, and oxidation-reduction potential. Further, the research will be used to compare the removal efficiencies of the system with and without plants to ascertain the efficacy of the substrate-assisted phytoremediation system for wastewater treatment**.**

2. MATERIALS AND METHODS

2.1 Wastewater with Methyl Orange Preparation

The wastewater was obtained from the treatment plant – Baghdad – Al-Batha, which was collected from the effluent of the biological treatment basin. The methyl orange with a concentration of 3 mg/L was added to the wastewater to determine the removal efficiency of color. The collected wastewater had typical properties of domestic sewage, being moderately organic and nutrient-rich. Before being used for experimentation, wastewater analyses were done to fix the characteristics of wastewater quality, as shown in **Table 1.** The pH level in the raw sewage was near neutral; this is an ideal level that is suitable for plant growth and microorganisms.

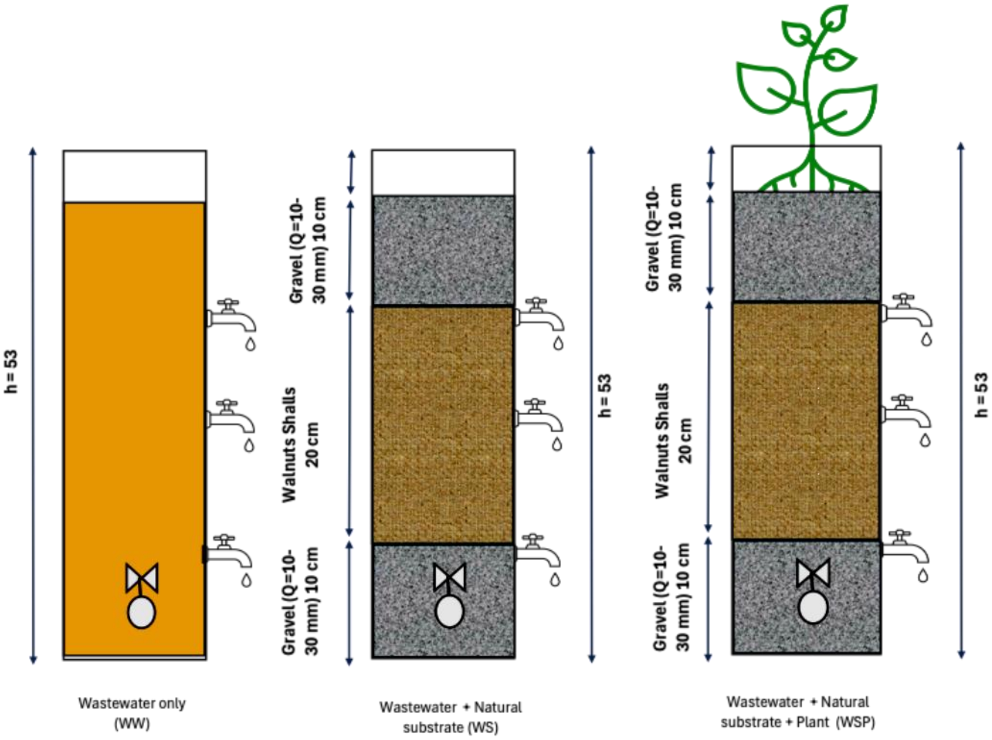
Table 1. The wastewater parameters.

Parameter	Value	Parameter	Value
Turbidity (NTU)	150	NO_3 (mg/L)	85
TSS (mg/L)	81	pH	6 ± 1
Color (Abs.)	0.968	Conductivity (μSm/cm)	3250
PO_4 (mg/L)	112	TDS (mg/L)	1625
TN (mg/L)	10	ORP (mV)	60 ± 10

2.2 Tank Design Setup

The laboratory-scale phytoremediation system, designed in a unit consisting of a stationary tank, was utilized. The system was designed to function following the normal process operating in the Sanitary Engineering Laboratory at the University of Baghdad. Tanks were operated simultaneously, with similar conditions (Laboratory temperature and lights). Three glass tanks were used in this study with dimensions of 20 cm length, 20 cm width, and 53 cm height. The first one is wastewater only as control containment (WW), the second tank includes substrate only (WS), and the third one includes substrate with the plant of S. Cochlearispathum (WSP), as shown in **Fig. 1**.

(a)



(b)

Figure 1. (a) Laboratory Tanks and (b)Tanks details,

The experiment was operated with a batch system. S. Cochlearispathum, also known as the peace lily, has been used in this research due to its tolerance to saturated and hydroponic conditions, which are common in phytoremediation systems, as shown in **Fig. 2**. The substrate included gravel and walnut shells. Gravel with a size of Φ 10-30 mm was washed before being used to remove any attached particles. The walnut shells were crushed to a size of 10-20 mm for use as substrate. The substrate contains a 10 cm thick layer of gravel at the bottom, followed by a 20 cm thick homogeneous layer of walnut shells for natural adsorption, and the last upper layer is 10 cm thick of gravel. This acts as a filter media and provides an enhanced surface area promoting bacterial attachment and growth **(Chan et al., 2022)**.

Figure 2. *S. Cochlearispathum* plant

2.3 Wastewater Sampling and Test Quality

A sample of real water from the wastewater treatment plant - Baghdad – Al-Buaitha, Baghdad, was collected in glass sample containers that were cleaned appropriately. The sample was then transported immediately to the laboratory for storage for future experiments. The methyl orange was analyzed using a spectrophotometer (DR1900, HACH Company, the USA). Total suspended solids (TSS), nitrate (NO_3). The sampling was done on days 0, 5, 7, and 14 during the experiment period for total suspended solids (TSS), color, nitrate (NO_3), and phosphate (PO_4). and phosphate (PO_4) were analyzed by a Lovibond Multi Direct microprocessor-controlled photometer (Germany) according to the standard method in the manual. The percentage of removal after 14 days of treatment was determined using Eq. (1):

$$\text{Removal } (\%) = (Ri-Rf)/Ri \times 100 \quad (1)$$

where Ri and Rf are the initial and final concentrations of (TSS, color, NO_3, and PO_4) of the sample.

2.4 Statistical Analysis Between Treatments

Statistical analysis was done with Statistical Product and Service Solutions (SPSS) 22.0 for Windows. Parameters of TSS, Color, NO_3, and PO_4 were analyzed according to two-way analysis of variance (ANOVA) to determine any significant effect of tank type on the removal efficiency of parameters **(Al-Baldawi et al., 2013).** Duncan's multiple range tests were used to evaluate statistical differences of all the parameters at the 0.05 probability level unless otherwise stated. The samplings were run in triplicate, and the results are presented as means ± standard deviation.

3. RESULTS AND DISCUSSION

3.1 Total Suspended Solids Removal

Total Suspended Solids (TSS) is a term that refers to small particles in wastewater, including dirt, microorganisms, and other organic materials. The presence of high levels of TSS in wastewater negatively affects water quality and makes the treatment of the wastewater more difficult. With respect to phytoremediation technology, TSS can be reduced through different methods **(Nabaterega et al., 2025)**. As shown in **Fig. 3**, the TSS removal efficiency of the walnut shells plant (WSP) system was the highest at 67.90%, followed by the walnut shells only (WS) system at 56.79%, and the wastewater only (WW) system at a much lower rate of 17.28%. The higher TSS removal efficiency of the WSP system is due to the substrate configuration with the plant, which is attributed to the filter bed capturing suspended particles. Other studies on the phytoremediation of TSS in constructed wetland systems have shown that the TSS removal efficiencies of the systems ranged from 50% to 80% **(Jesús et al., 2024; Nabaterega et al., 2025**). The statistical analysis of removal efficiencies between the different tanks showed significant differences between different tanks on the same day ($p<0.05$). The WSP system had the highest removal efficiency because plant roots aid in particle trapping and settling, providing stability for particles. The WS system had a relatively high removal efficiency since it involved only physical filtration, where particles are trapped using walnut shells, but without the presence of plants. On the other hand, the WW system had the lowest removal efficiency because it used only natural settling of particles without any medium.

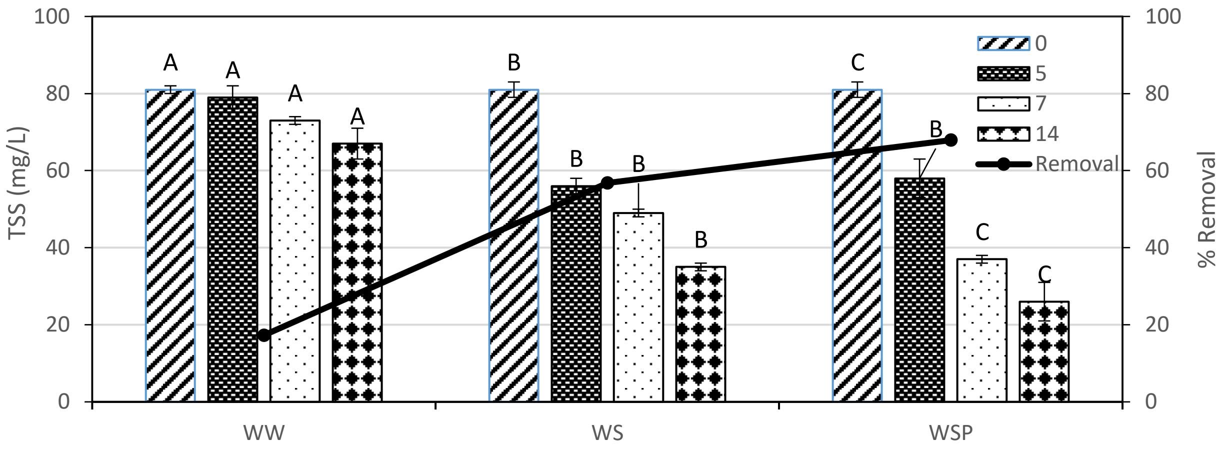


Figure 3. TSS concentration and removal efficiency in WW, WS, and WSP tanks. Data are presented as means ± standard deviation (SD). Letters A, B, and C represent statistically significant differences in TSS removal on a specific day when compared with different tanks ($p < 0.05$).

3.2 Color Removal

Recent adsorption and phytoremediation studies have shown that the removal of the dye from the water in the treatment systems takes place via different mechanisms such as adsorption, root uptake, degradation, and catalytic oxidation **(Hashem et al., 2025)**. As shown in **Fig. 4**, the walnut shells plant (WSP) process recorded the highest rate of color removal, 65.70%, followed by the walnut shells only (WS) process, which recorded a removal rate of 53.92%. On the other hand, the wastewater-only (WW) process recorded the lowest rate of removal, 38.01%.

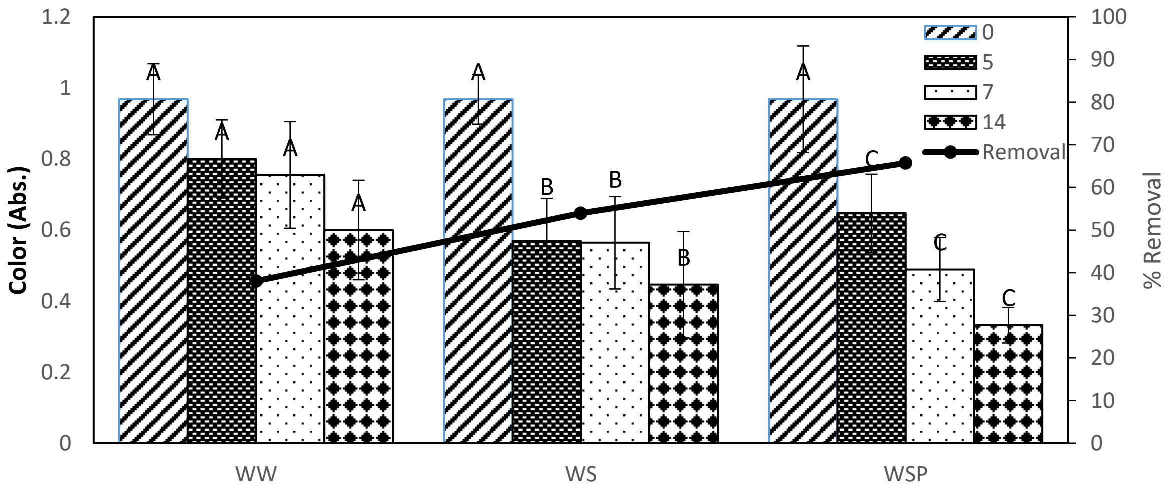
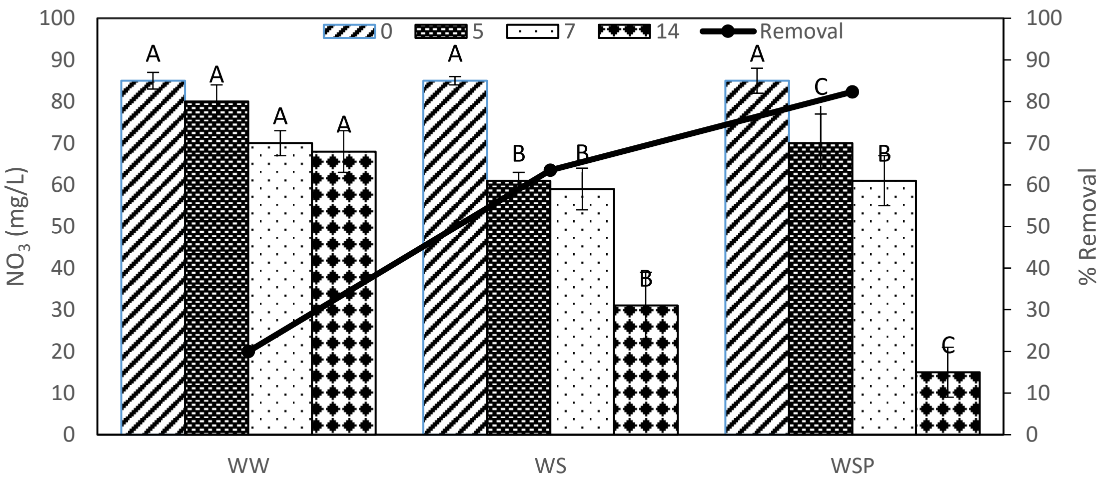


Figure 4. Color absorbance reduction and removal efficiency in WW, WS, and WSP tanks. Data are presented as means ± standard deviation (SD). Letters A, B, and C indicate statistically significant differences in TSS removal on a specific day among the tanks ($p < 0.05$).

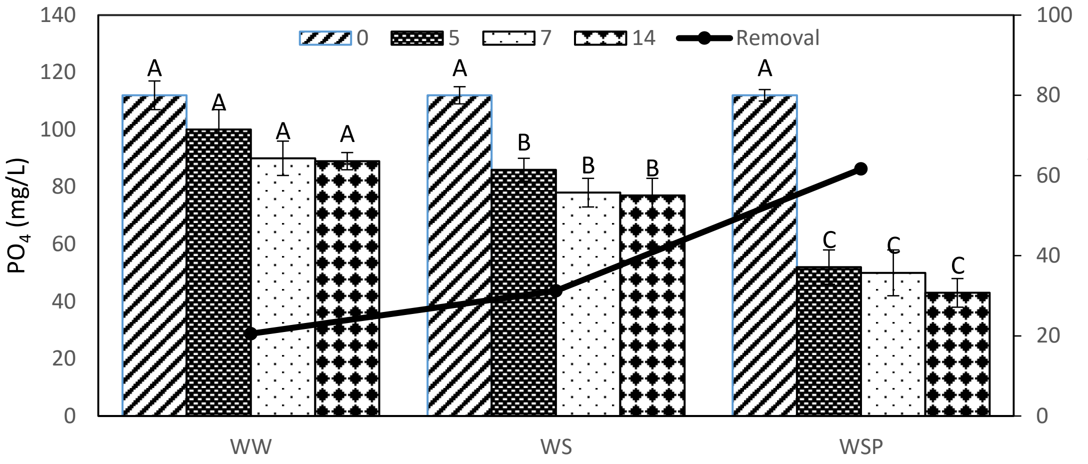
The differences between the decolorizing efficiencies of the systems are based on the varying treatment methods employed in the different systems. The WSP system exhibited high efficiency due to the interaction of dye degradation by the plant, microbial activities within the plant roots, and adsorption of contaminants on walnut shells. On the other hand, the WS system utilized only adsorption and filtration methods, leading to less efficiency owing to the exclusion of biological and plant-based treatments. The WW system had the least efficiency since it applied only sedimentation of contaminants within water without any other supportive mechanism **(Lin et al., 2025; Wu et al., 2025).**
Statistical analysis between different treatment tanks by two-way ANOVA showed significant differences ($p < 0.05$). There was a highly significant difference in WS and WSP compared with the control tank (WW) due to the role of substrate and plant in color removal. The study by **(Hashem et al., 2025)**, demonstrates the ability of indica seed to adsorb a dose of 0.6 g/50 mL wastewater with 95.3% dye removal efficiency.

3.3 Nutrient Removal

Nutrient removal, especially nitrogen and phosphorus, is an important aspect of wastewater treatment, as they are major contributors to water pollution, which affects water bodies. The use of constructed wetlands, as well as phytoremediation, is a low-cost method for enhanced nutrient removal. As shown in **Fig. 5**, it is clear that the concentration of nitrate and phosphate decreased in the different wastewater treatment tanks. The walnut shells plant tank (WSP) showed the highest rate of NO_3 and PO_4 removal, reaching 82.3 and 66%, where the concentration of nitrate and phosphate decreased from 85 to 15 mg/L and 112 to 43 mg/L, respectively. The walnut shells (WS) only system showed moderate nitrate removal, reaching 63.5 and 31.3%, where the concentration of NO_3 and PO_4 decreased to 31 and 77 mg/L. (**Stjepanović et al., 2022)** found that Hazelnut Shells were effective in nitrate removal within a pH range (2 - 10), and the highest amount of nitrate adsorbed was 25.79 mg g−1 in a model nitrate solution.



(a)



(b)

Figure 5. (a) Nitrate (NO_3) and (b) Phosphate (PO_4) reduction and removal efficiency in WW, WS, and WSP tanks. Letters A, B, and C represent statistically significant differences in TSS removal on a specific day when compared with different tanks ($p < 0.05$).

(Sandoval et al., 2019) utilized ornamental plants (Anthurium sp., Zantedeschia aethiopica, and Spathiphyllum wallisii) as vegetation to treat wastewater with removal efficiencies of nitrates and phosphates (28–44%) and (25–45%), respectively. The efficiency of these types of nature-based systems in the removal of nutrients is due to the combined action of plants, microbes, and the medium, which enhances the concentration of nutrients in the treated wastewater. While the tank with wastewater only (WW) showed a low removal efficiency (20%) of nitrate and phosphate removal, where the concentration of nitrate remained almost 68 and 89 mg/L, respectively. These results are consistent with previous research that showed that the use of plant uptake in combination with reactive substrates results in an enhancement of nitrate and phosphate removal efficiency through the mechanisms of adsorption on organic media, microbial activity in the rhizosphere, as well as direct plant uptake **(Shah et al., 2014)**. Systems that incorporate both vegetation and substrate have consistently shown higher efficiency compared to systems that use a single component, as evidenced by the results in wastewater polishing **(Guo et al., 2026).** Recent research has shown the efficiency of constructed wetland systems and phytoremediation in the removal of nutrients such as nitrogen and phosphate in the water using multiple mechanisms, such as nitrification-denitrification, adsorption on the medium, and settlement **(Wu et al., 2025)**. In addition, according to ANOVA analysis, generally there is a significant difference between treatment tanks as shown in **Fig. 5** with $p< 0.05$. The control wastewater tank low efficiency of removal than WS and WSP due to the substrate and plant role, while the WSP is the best because of the plant with substrate that integrates in wastewater polishing and treatment.

3.4 Plant Adaptation

One of the most important factors that influences the efficiency of phytoremediation systems is plant adaptation, especially in constructed wetlands used for water treatment. In this study, the plant shows tolerance and survive normal in polluted environments, **Fig. 6**. In wastewater treatment systems, plant roots are in contact with microorganisms and substrate media. This enables the formation of a rhizosphere capable of adsorption, filtration, and biodegradation of pollutants **(Shravani et al., 2025)**. These tolerance mechanisms may involve the activation of antioxidant systems, stress hormone regulation, and root and tissue alterations that increase their capacity for contaminant absorption **(Afzal et al., 2023)**.

0 Day	7 Day	14 Day
		

Figure 6. Physical plant observation

4. CONCLUSIONS

Natural biomass of floating plant (S. Cochlearispathum) has been proven to be capable of removing nutrients and methylene orange dye from dye pollutants wastewater. The best performance was in the walnut shells plant tank (WSP) with 65.7, 82.3, 61.6% removal efficiency of color, NO_3, and PO_4, respectively. The integration of plant and natural substrate led to high removal efficiency of pollutants from wastewater than WW and WS tanks. From this research, it is evident that *S.* Cochlearispathum with walnut shells can be used in wastewater treatment as a sustainable and safe treatment. Through tank and plant selection, the configuration of constructed wetlands in environmental engineering can be one of the sustainable development goals achieved in water treatment.

Credit Authorship Contribution

Mustafa Basim Hussein Writing the original draft, Validation, Methodology, and Results analysis. Israa Abdulwahab Al-Baldawi: Final scientific and proofreading review.

Declaration of Competing Interest

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

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المعالجة النباتية لمياه الصرف باستخدام قشور الجوز كوسط داعم

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الخلاصة

تُعد المعالجة النباتية (Phytoremediation) طريقة جذابة وصديقة للبيئة لمعالجة مياه الصرف الحضرية، ولا سيما في الدول النامية، وذلك بسبب انخفاض تكاليف التشغيل وتقليل إنتاج الحمأة. هدفت هذه الدراسة إلى تقييم طريقة متقدمة للمعالجة النباتية باستخدام أوساط نمو طبيعية مكوّنة من قشور الجوز ونبات زنبق السلام (S. Cochlearispathum) لمعالجة عينات حقيقية من مياه الصرف جُمعت من محطة معالجة مياه الصرف الصحي في الكرخ بمدينة بغداد، العراق، والمُلوّثة بصبغة الميثيل البرتقالي. تم تصميم وبناء مفاعل تجريبي بثلاثة خزانات مصنوعة من مادة الزجاج. سجّل نظام قشور الجوز المزروع بالنبات أعلى كفاءة معالجة، حيث بلغت نسب الإزالة 65.70% للون، و61.60% للمواد الصلبة العالقة الكلية (TSS)، و82.35% للنترات، و67.90% للفوسفات. وبشكل عام، وُجد أن قشور الجوز بالاقتران مع المعالجة النباتية تُحسّن بشكل ملحوظ معالجة مياه الصرف، ويمكن أن تكون تقنية قابلة للتطبيق، اقتصادية، ومستدامة للمناطق النامية.

الكلمات المفتاحية: قشور الجوز، زنبقة السلام، المعالجة المستدامة.