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Assessing the Efficacy of Agro-Waste Biochar-Derived Nanoparticles for Purification of Municipal Wastewater, Agricultural Drainage Water and Industrial Effluents

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WATER scarcity and contamination are pressing challenges, particularly in regions like Egypt, where rapid population growth exacerbates freshwater deficits. As agricultural projects expand to meet food demand, water scarcity becomes a critical factor contributing to the food gap. Alternative sources of irrigation water, such as wastewater, agricultural drainage water and industrial, are being explored, despite potential heavy metal contamination. Therefore, the primary objective of the study is to assess the effectiveness of utilizing nanoparticles biochar derived from agro wastes in the treatment of wastewater, specifically to make it suitable for irrigation purposes under laboratory experiment. The present study utilized wastewater samples sourced from three different sources [Agricultural drainage water (NO.1), industrial effluents (NO.2) and municipal wastewater (NO.3)]. These samples were evaluated for suitability for irrigation based on international standards. The nanoparticles biochar derived from agro wastes [specifically, rice straw (RS), palm fronds (PF), and sugar cane residues (SCR)] were assessed for their capability to remove heavy metals from the examined wastewater samples. The analysis of wastewater samples from drains NO.1, NO.2, and NO.3 revealed crucial findings regarding their suitability for irrigation and associated environmental and health risks. pH values indicate that all wastewater samples are suitable for irrigation without requiring pH adjustments. Wastewater from drain NO.1 falls within acceptable salinity limits for irrigation. However, samples from drains NO.2 and NO.3 exhibit EC values exceeding acceptable limits, posing challenges for irrigation use. Wastewater from drains NO.2 and NO.3 contains Na^+ concentrations surpassing acceptable levels for irrigation, indicating potential hazards. Wastewater samples contain various heavy metals, including aluminum, mercury, silver, barium, calcium, cadmium, chromium, copper, iron, magnesium, manganese, lead, potassium, strontium, zinc, arsenic, and bismuth. Some heavy metals like arsenic show exceptionally high concentrations, indicating potential environmental and health risks. On the other hand, Nanobiochar materials derived from rice straw, palm fronds, and sugar cane residues demonstrated strong capabilities in adsorbing and removing contaminants from wastewater. All materials led to reductions in parameter values compared to untreated samples, with the most notable decrease observed in nanobiochar derived from sugar cane residues. These findings underscore the potential of nanobiochar-based treatments in enhancing wastewater quality and promoting sustainable water management practices. Generally, the practical application of nanobiochar materials derived from plant waste sources holds promise for improving wastewater treatment processes, thereby contributing to enhanced water quality and sustainable agricultural practices.

Keywords: Freshwater deficits, Alternative sources, Adsorption process, Rice straw, Palm fronds, Sugar cane residues.

1. Introduction

Agriculture relies on water, serving as a vital element for all higher plants. Egypt grapples with severe water scarcity and contends with a freshwater deficit exacerbated by a growing population. The country faces water poverty, surpassing the threshold of absolute scarcity at 1000 m^3 $capita^{-1}year^{-1}$ (Mostafa *et al.* 2024). As agricultural projects expand to address the growing food demand and population needs, the scarcity of water resources in Egypt becomes a significant factor contributing to the food gap (Abdelhafez *et al.* 2020). To bridge the gap between current water supplies and the demands of various human activities, it becomes imperative to explore alternative sources of irrigation water (Abbas

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et al. 2020; Elsherpiny *et al.* 2023). The necessity to meet water requirements prompts the utilization of secondary sources like wastewater (municipal wastewater, agricultural drainage water and industrial effluents), which may contain elevated levels of heavy metals (Al Naggar *et al.* 2018).

Egypt's water balance is at a critical juncture, facing numerous challenges that require urgent attention and comprehensive solutions. Sustainable water management practices, efficient water allocation mechanisms, and international cooperation are vital to ensure water security and foster socio-economic development in Egypt. By addressing water quantity, quality, and climate change impacts, Egypt can safeguard its water resources for future generations while promoting resilience and prosperity (Badr *et al.* 2023). Tables from 1 to 5 display Egypt's water balance for the years 2019, 2020, 2021, 2022, and 2023 according to Ministry of Water Resources and Irrigation (MWRI).

Table 1. Egypt's Water Balance (*MWRI 2019).

Water Supply	**Volume** ****(BCM/year)**	**Demand by Sector**	**Usage / Allocation** **(BCM/year)**
Fresh Water Sources		Drinking (Fresh water only)	11.1
Nile (HAD)	55.5	Industry	5.4
Deep Groundwater	2.45	Agriculture	61.5
Rainfall & Flash Floods	1.30	Drainage to Sea and Evap. losses	2.5
Desalination	0.35		
Total Supply Fresh	**59.60**		
Re-Used Water Sources			
Shallow Groundwater (Delta)	7.4		
Reuse of Ag. Drainage Water	13.5		
Total Water Re-Used	20.9		
Total Water Supply	**80.25**	Total Water Usage or Allocation	80.5

***MWRI=Ministry of Water Resources and Irrigation; ** BCM/year =Billion Cubic Meters per Year**

Table 2. Egypt's Water Balance (*MWRI 2020).

Water Supply	**Volume** ****(BCM/year)**	**Demand by Sector**	**Usage / Allocation** **(BCM/year)**
Fresh Water Sources		Drinking (Fresh water only)	11.53
Nile (HAD)	55.5	Industry	5.4
Deep Groundwater	2.50	Agriculture	61.63
Rainfall & Flash Floods	1.30	Drainage to Sea and Evap. losses	2.5
Desalination	0.38		
Total Supply Fresh	**59.68**		
Shallow Groundwater (Delta)	7.87		
Reuse of Ag. Drainage Water	13.51		
Total Water Re-Used	21.38		
Total Water Supply	**81.06**	Total Water Usage or Allocation	81.06

***MWRI=Ministry of Water Resources and Irrigation; ** BCM/year =Billion Cubic Meters per Year**

Purification of wastewater contaminated with heavy metals has garnered significant attention in the modern era due to its vital importance for environmental and public health (Hussien *et al.* 2020). With industrial activities, urbanization, and agricultural practices contributing to the release of heavy metals into water bodies, the need for effective wastewater treatment has become increasingly urgent (Shayeste and Behboody, 2020). Heavy metals, such as lead, mercury, cadmium, and arsenic, pose serious risks to ecosystems and human health, as they are persistent and can bioaccumulate in organisms, leading to various adverse effects. Efficient removal of heavy metals from wastewater is essential to prevent contamination of water sources, safeguard aquatic life, and protect human populations. Various treatment technologies, including physical, chemical, and biological methods, are employed to purify wastewater and mitigate the presence of heavy metals (Saleh *et al.* 2022).

Various techniques are employed for wastewater purification, encompassing physical, chemical, and biological approaches. Adsorption methods, employing materials like activated carbon, zeolites, and silica gel, play a significant role in this process by attracting and adhering contaminants onto their surfaces. These methods are valued for their adaptability, efficacy, and ability to target a diverse array of pollutants, making them versatile solutions for various industrial and municipal wastewater treatment applications (Mosa *et al.* 2017; Enaime *et al.* 2020).

Activated carbon is currently the most commonly used adsorbent in wastewater treatment due to its high surface area and adsorption capacity (Wong *et al.* 2018). The high cost of activated carbon has led researchers to explore alternative, cost-effective materials for adsorption. Various substances, such as fly ash, rice straw, coconut husk, sawdust, rice husk, sugar cane dusk, bagasse fly ash and clay minerals have been studied as potential replacements for activated carbon (Wang *et al.* 2021; El-Ramady *et al.* 2020; Elbasiouny *et al.* 2023).

Table 3. Egypt's Water Balance (*MWRI 2021).

Water Supply	Volume **(BCM/year)	Demand by Sector	Usage / Allocation (BCM/year)
Fresh Water Sources		Drinking (Fresh water only)	11.52
Nile (HAD)	55.5	Industry	5.4
Deep Groundwater	2.10	Agriculture	62.01
Rainfall & Flash Floods	1.30	Drainage to Sea and Evap. losses	2.5
Desalination	0.38		
Total Supply Fresh	**59.28**		
Shallow Groundwater (Delta)	8.75		
Reuse of Ag. Drainage Water	13.40		
Total Water Re-Used	22.15		
Total Water Supply	**81.43**	Total Water Usage or Allocation	81.43

***MWRI=Ministry of Water Resources and Irrigation; ** BCM/year =Billion Cubic Meters per Year**

Table 4. Egypt's Water Balance (*MWRI 2022).

Water Supply	Volume **(BCM/year)	Demand by Sector	Usage / Allocation (BCM/year)
Fresh Water Sources		Drinking (Fresh water only)	11.48
Nile (HAD)	55.5	Industry	5.52
Deep Groundwater	2.50	Agriculture	61.87
Rainfall & Flash Floods	1.30	Drainage to Sea and Evap. losses	2.5
Desalination	0.38		
Total Supply Fresh	**59.68**		
Shallow Groundwater (Delta)	6.33		
Reuse of Ag. Drainage Water	15.36		
Total Water Re-Used	22.69		
Total Water Supply	**81.37**	Total Water Usage or Allocation	81.37

***MWRI=Ministry of Water Resources and Irrigation; ** BCM/year =Billion Cubic Meters per Year**

Table 5. Egypt's Water Balance (*MWRI 2023).

Water Supply	Volume **(BCM/year)	Demand by Sector	Usage / Allocation (BCM/year)
Fresh Water Sources		Drinking (Fresh water only)	11.48
Nile (HAD)	55.5	Industry	5.52
Deep Groundwater	2.50	Agriculture	62.13
Rainfall & Flash Floods	1.30	Drainage to Sea and Evap. losses	2.5
Desalination	0.38		
Total Supply Fresh	**59.68**		
Shallow Groundwater (Delta)	6.59		
Reuse of Ag. Drainage Water	15.36		
Total Water Re-Used	21.95		
Total Water Supply	**81.63**	Total Water Usage or Allocation	81.63

***MWRI=Ministry of Water Resources and Irrigation; ** BCM/year =Billion Cubic Meters per Year.**

The application of nanoparticles biochar derived from agro wastes in wastewater treatment represents a promising and forward-thinking strategy that harmonizes environmental sustainability with technological progress. Employing nanomaterials in wastewater treatment presents numerous advantages, such as enhanced efficiency, cost-effectiveness, and the utilization of recycled materials **(Popoola and Grema 2021).** These nanomaterials exhibit distinctive characteristics, including a high surface area and reactivity, making them particularly well-suited for wastewater treatment. The incorporation of nanomaterials derived from waste sources aligns seamlessly with the principles of environmental sustainability and the cutting-edge field of materials science innovation **(Mandal *et al.* 2024).**

Therefore, the primary objective of the study is to assess the effectiveness of utilizing nanoparticles biochar derived from agro wastes in the treatment of wastewater, specifically to make it suitable for irrigation purposes.

2. Materials and Methods

A laboratory experiment was conducted to explore the removal of heavy metals from wastewater samples using certain burned plant waste materials in Nano form.

Sources of wastewater

The present study utilized wastewater samples sourced from three different sources, detailed in Table 6 and Fig1. The geographical coordinates of the study area range from 31°25′00″ to 31°26′12″N and 31°40′01″ to 31°49′17″E.

Table 6. Details of wastewater sample locations.

Number of drain	Code	Type of wastewater	Location
NO.1	**W_1**	Agricultural drainage water	The primary channel originating from Kafr Al-Batikh-Gamsa, directed towards the pumps.
NO.2	**W_2**	Industrial effluents	Damietta industrial zone
NO.3	**W_3**	Municipal wastewater	Drain, responsible for collecting wastewater from the sewage station in New Damietta Governorate

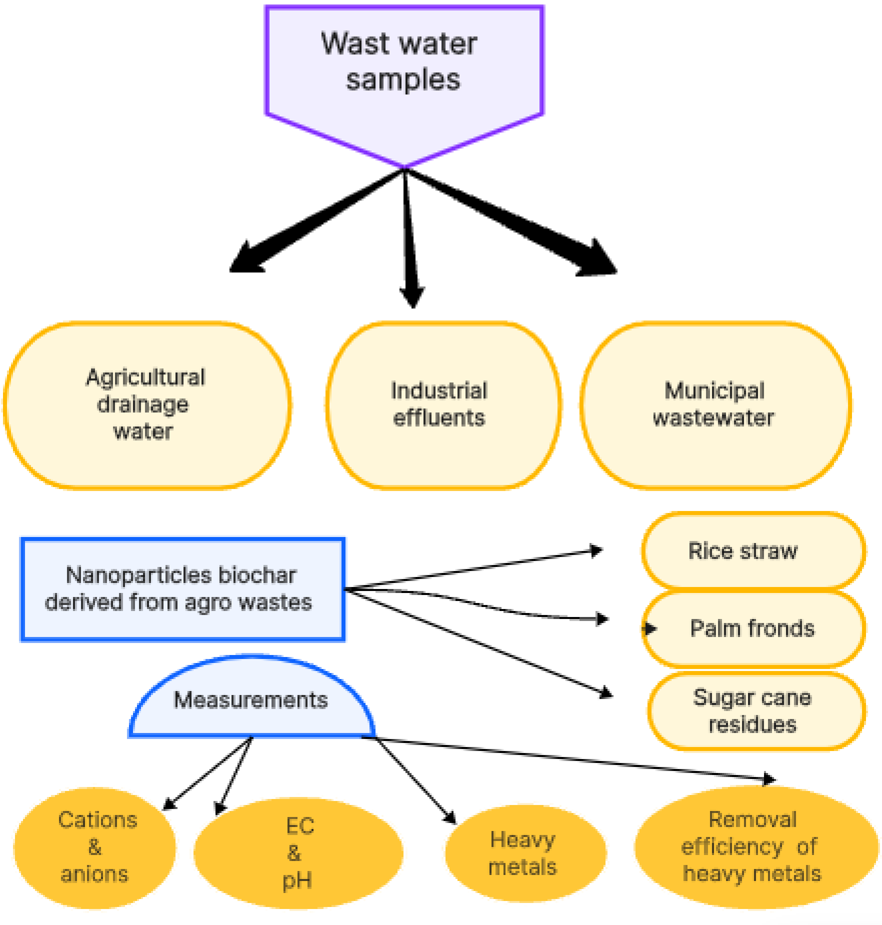

Fig. 1. Flowchart of the current experiment.

Plant waste materials (preparation)

The plant waste materials used in the current study were rice straw (RS), palm fronds (PF) and sugar cane residues (SCR). All plant waste materials were converted into biochar by the stander method recommended to obtain biochar as described by **Wang and Wang (2019).** RS , PF and SCR underwent chopping and oven drying at 70 ± 5.0 ^{o}C for 48 hours until a constant weight was achieved. Approximately 25-30 g of the dried sample was placed in tubular quartz reactors (6 cm diameter × 28 cm length glass cylinders) and introduced into a bench-top furnace (without oxygen conditions). The feedstock underwent slow pyrolysis at 600°C for 2 hours **(Wang and Wang, 2019).** The furnace temperature was initially raised to 200°C and increased at a rate of 15 °C min^{-1} until reaching 600 °C, where it was held constant for 2 hours. The resulting biochars were crushed and sieved to obtain a uniform fraction of 0.452-1mm in size. Further, sieved biochar was processed to create nanobiochar. This involved additional physical treatments, such as grinding to achieve nano-sized particles. The characteristics of different nano biochars are presented in Table 7.

Table 7. The characteristics of different nano biochars.

Traits \ Source	Rice straw	Palm fronds	Sugar cane residues
EC, dS m^{-1}	4.2	4.5	4.12
pH	8.3	8.25	8.4
CEC, cmolc kg^{-1}	65	67.5	69

Expermintal work

Wastewater samples collected from the three examined sources were placed in individual polyethylene bottles. They were promptly transported to the laboratory and stored in the refrigerator then subjected to chemical analysis to assess their characteristics. Subsequently, these samples were evaluated for suitability for irrigation based on international standards.

The nanoparticles biochar derived from agro wastes [specifically, rice straw (RS), palm fronds (PF), and sugar cane residues (SCR)] were assessed for their capability to remove heavy metals from the examined wastewater samples. Each type of the studied nanobiochar was separately added at a rate of 5.0 g (on a dry basis, equivalent to 2.0%) to flasks containing 250 ml of wastewater from each evaluated source. The mixtures of wastewater and the respective nano-biochars were introduced into a rotary shaker at room temperature (20˚C), with each flask shaken at 200 rpm for two hours. Subsequently, the samples underwent filtration using nylon membrane filters with a pore size of 0.22 mm, and the filtration process was allowed to proceed for two hours. The resulting filtrate samples were subjected to chemical analysis.

Wastewater properties determination

The chemical characteristics of the studied wastewater samples were determined on two occasions: initially in their untreated state and subsequently after treatment with nanobiochar, adhering to standard methods. For the determination of electrical conductivity (EC) and pH values, an EC meter and pH meter were employed, respectively. These measurements were conducted to gauge the changes induced by nanobiochar treatment. Additionally, heavy metal analysis was performed, encompassing elements such as V, Hg, Ag, B, Ba, Ca, Cd, Co, Cr, Cu, Fe, Ga, In, Li, Mg, Mn, Ni, Pb, K, Sr, Zn, As, Na, Bi, Se. The determination of these heavy metals was carried out using inductively coupled plasma-optical emission spectrometry (ICAP™ 7000 Plus Series ICP-OES, Thermo Scientific™, USA),after acid digestion using HNO_3 (69%) and H_2O_2 (30%) in a microwave digestion apparatus (model Milestone MLS 1200 Mega) **(Bettinelli *et al.* 2000).** This analytical technique was employed to provide accurate and comprehensive insights into the concentration levels of the specified heavy metals in both the untreated and nanobiochar-treated wastewater samples. Cations and anions were determined according to **Dewis and Freitas (1970).**

Removal efficiency of heavy metals

The removal efficiency of heavy metals ions from wastewater was calculated using the following formula.

$$Removal\ effeciency = \frac{\mathbf{I1} - \mathbf{I2}}{\mathbf{I1}} \mathbf{x\ 100}$$

Where I_1 and I_2 represent the initial and final equilibrium concentrations of heavy metals (mg L^{-1}). This formula quantifies the percentage reduction in concentration of a specific heavy metal after treatment with nanobiochar, with I_1 representing the initial concentration and I_2 representing the final equilibrium concentration (**Mosa *et al.* 2017**). The resulting percentage indicates the efficiency of the nanobiochar in removing the targeted heavy metal from the wastewater.

3. Results

Assessing initial wastewater samples for irrigation suitability

Tables 8 and 9 present the findings from the initial assessment of wastewater samples collected from various sources: agricultural drainage water from drain NO.1, originating from Kafr Al-Batikh-Gamsa and directed towards the pumps (**W_1**), wastewater from drain NO.2 sourced from the Damietta industrial zone (**W_2**) and drain NO.3, responsible for collecting wastewater from the sewage station in New Damietta Governorate (**W_3**).The data (Table 8) obtained indicate pH values of 7.86, 6.71, and 6.97 for **W_1, W_2** and **W_3** respectively.

In terms of salinity, the electrical conductivity (EC) values were recorded as 1.5, 3.97 and 30 dSm^{-1} for **W_2** and **W_1, W_3** respectively.

The soluble sodium ion (Na^+) concentrations were 8.75, 17.75 and 106.05 cmolc L^{-1} for **W_2** and **W_1, W_3** respectively. While the concentrations of chloride ions (Cl^-) concentrations were 8.3, 14.5 and 170 cmolc L^{-1} for **W_2** and **W_1, W_3** respectively.

To evaluate the heavy metal content in the studied wastewater samples, we will examine the concentrations of various heavy metals present in each sample as shown in Table 9. The significance of these concentrations will be discussed in terms of potential environmental and health implications.

In wastewater sample **W_1**, various heavy metals **(**in mg per L^{-1}) were detected, including aluminum (Al) at 13.4, vanadium (V) at 0.193, mercury (Hg) at 1.213, silver (Ag) at 2.069, barium (Ba) at 0.129, calcium (Ca) at 222.8, cobalt (Co) at 0.022, chromium (Cr) at 0.427, copper (Cu) at 1.9, iron (Fe) at 8.87, gallium (Ga) at 50.42, manganese (Mn) at 0.51, lead (Pb) at 14.69, potassium (K) at 0.840, strontium (Sr) at 2.09, zinc (Zn) at 0.35, arsenic (As) at 247.7, and bismuth (Bi) at 2.23. Notably, cadmium (Cd), indium (In), lithium (Li), nickel (Ni), and selenium (Se) were not detected in this sample.

Sample **W_2** exhibited the presence of aluminum (Al) at 9.34, mercury (Hg) at 0.721, silver (Ag) at 0.315, barium (Ba) at 0.105, calcium (Ca) at 211.63, cadmium (Cd) at 0.024, chromium (Cr) at 1.237, copper (Cu) at 0.964, iron (Fe) at 7.4, gallium (Ga) at 37.6, magnesium (Mg) at 118.2, manganese (Mn) at 0.38, lead (Pb) at 41.5, potassium (K) at 1.346, strontium (Sr) at 1.476, bismuth (Bi) at 3.34, and selenium (Se) at 0.46 **(**in mg per L^{-1}). Indium (In), lithium (Li), nickel (Ni), zinc (Zn), and arsenic (As) were not detected in this sample.

Lastly, sample **W_3** contained aluminum (Al) at 1.7, mercury (Hg) at 0.605, silver (Ag) at 1.767, barium (Ba) at 1.029, calcium (Ca) at 221.43, chromium (Cr) at 0.994, copper (Cu) at 2.337, iron (Fe) at 8.61, gallium (Ga) at 38.33, indium (In) at 9.073, magnesium (Mg) at 914, manganese (Mn) at 0.698, lead (Pb) at 212.7, potassium (K) at 2.84, strontium (Sr) at 1.810, zinc (Zn) at 0.158, arsenic (As) at 6174, and bismuth (Bi) at 1.138 **(**in mg per L^{-1}). Lithium (Li), nickel (Ni), and selenium (Se) were not detected in this sample.

Table 8. pH, EC, cations and anions of studied wastewaters samples in initial status.

Sample code	**PH**	**EC, dSm^{-1}**	**Cations , cmolc L^{-1}**				**Anions, cmolc L^{-1}**		
			Ca^{+2}	**Mg^{+2}**	**K^+**	**Na^+**	**Cl^-**	**CO_3^{-2} + HCO_3^-**	**SO_4^{-2}**
W_1	7.86	1.50	2.5	3.05	1.2	8.75	8.3	1.6	5.6
W_2	6.71	3.97	12.5	7.55	1.9	17.75	14.5	11.9	13.3
W_3	6.97	30.0	72.5	69.55	51.9	106.05	170	23.7	106.3

W_1: Agricultural drainage water collected from drain NO.1, the primary channel originating from Kafr al-Batikh-Gamsa, directed towards the pumps, **W_2:** Wastewater received by drain NO.2 from Damietta industrial zone, **W_3:** Drain NO.3, responsible for collecting wastewater from the sewage station in New Damietta Governorate

Table 9. Heavy metals content (mg L^{-1}) of studied wastewaters samples in initial status.

Sample code	**Al**	**V**	**Hg**	**Ag**	**B**	**Ba**	**Ca**	**Cd**	**Co**	**Cr**	**Cu**	**Fe**	**Ga**
	(mg L^{-1})												
W_1	13.4	0.193	1.213	2.069	ND	0.129	222.8	*ND	0.022	0.427	1.9	8.87	50.42
W_2	9.34	*ND	0.721	0.315	*ND	0.105	211.63	0.024	*ND	1.237	0.964	7.4	37.6
W_3	1.7	*ND	0.605	1.767	ND	1.029	221.43	*ND	*ND	0.994	2.337	8.61	38.33

Sample code	**In**	**Li**	**Mg**	**Mn**	**Ni**	**Pb**	**K**	**Sr**	**Zn**	**As**	**Na**	**Bi**	**Se**
	(mg L^{-1})												
W_1	*ND	*ND	67.1	0.51	*ND	*ND	14.69	0.840	2.09	0.35	247.7	2.23	*ND
W_2	*ND	*ND	118.2	0.38	*ND	*ND	41.5	1.346	1.476	*ND	703	3.34	0.46
W_3	9.073	*ND	914	0.698	*ND	*ND	212.7	2.84	1.810	0.158	6174	1.138	*ND

W_1: Agricultural drainage water collected from drain NO.1, the primary channel originating from Kafr al-Batikh-Gamsa, directed towards the pumps, **W_2:** Wastewater received by drain NO.2 from Damietta industrial zone, **W_3:** Drain NO.3, responsible for collecting wastewater from the sewage station in New Damietta Governorate

*ND= not detected

Adsorbtion and removal trial

Tables 10 and 11 present data illustrating the significant impact of nanobiochar materials derived from various plant waste sources on altering the values of studied parameters. These tables provide insights into how the properties of nanobiochar, influenced by the source of plant waste, can influence key parameters relevant to wastewater treatment processes. Table 12, on the other hand, offers insight into the efficacy of the studied nanobiochar materials in removing contaminants from the investigated wastewater samples.

This data demonstrates the practical application and effectiveness of the nanobiochar materials in wastewater treatment, showcasing their ability to adsorb and remove contaminants, thereby improving water quality. By examining the data in Tables 10, 11 and 12 collectively, it can gain a comprehensive understanding of how nanobiochar materials derived from different plant waste sources impact various parameters and their effectiveness in removing contaminants from wastewater.

All utilized materials in the treatment process, including nano biochar derived from rice straw (RS), palm fronds (PF), and sugar cane residues (SCR), exhibited a reduction in all measured parameter values compared to the untreated wastewater samples. Notably, the most substantial decrease was observed with nano biochar derived from sugar cane residues, followed by nano biochar from palm fronds, and then nano biochar from rice straw.

Table 10. pH, EC, cations and anions of the studied wastewater samples after remediation.

Source of wastewater	Treatments	PH	EC, dSm^{-1}	Ca^{+2}	Mg^{+2}	K^{+}	Na^{+}	Cl^{-}	CO$_3^{-2}$ + HCO$_3^{-}$	SO$_4^{-2}$
				cmolc L^{-1}						
W$_1$	**Initial**	**7.86**	**1.55**	**2.50**	**3.05**	**1.20**	**8.75**	**8.30**	**1.60**	**5.60**
	RS	7.80	1.53	2.45	3.00	1.11	8.70	8.22	1.56	5.50
	PF	7.77	1.50	2.32	2.92	1.10	8.66	8.20	1.45	5.35
	SCR	7.56	1.44	2.11	2.77	1.05	8.50	8.10	1.17	5.20
W$_2$	**Initial**	**6.71**	**3.97**	**12.5**	**7.55**	**1.90**	**17.75**	**14.5**	**11.9**	**13.3**
	RS	6.66	3.89	12.40	7.50	1.70	17.35	14.2	11.65	13.1
	PF	6.62	3.83	12.35	7.40	1.60	16.90	14.0	11.45	12.8
	SCR	6.59	3.75	12.21	7.34	1.50	16.45	13.85	11.00	12.65
W$_3$	**Initial**	**6.97**	**30.0**	**72.5**	**69.55**	**51.9**	**106.05**	**170**	**23.7**	**106.3**
	RS	6.90	29.2	70.5	68.4	50	103.46	165	23.06	104.3
	PF	6.82	28.7	69.44	68	48.6	101.3	163	22.04	102.3
	SCR	6.69	28.1	66.32	67.5	47.9	99	160	21.3	99.42

W$_1$: Agricultural drainage water collected from drain No.1, the primary channel originating from Kafr al-Batikh-Gamsa, directed towards the pumps, **W$_2$:** Wastewater received by drain No.2 from Damietta industrial zone, **W$_3$:** Drain No.3, responsible for collecting wastewater from the sewage station in New Damietta Governorate, **RS:** Nano biochar of rice straw, **PF:** Nano biochar of palm fronds, **SCR:** Nano biochar of sugar cane residues

Table 11a. Heavy metals in the studied wastewater samples after remediation.

Source of wastewater	Treatments	Al	V	Hg	Ag	B	Ba	Ca	Cd	Co	Cr	Cu	Fe	Ga
								mg L^{-1}						
W$_1$	**Initial**	**23.4**	**0.193**	**1.213**	**2.069**	***ND**	**0.129**	**222.8**	***ND**	**0.029**	**0.427**	**1.90**	**8.87**	**50.42**
	RS	17.72	0.05	1.095	1.860	*ND	0.120	221.75	*ND	0.024	0.293	1.83	8.33	45.03
	PF	17.70	0.03	1.093	1.717	*ND	0.116	201.3	*ND	0.019	0.263	1.55	8.05	42.66
	SCR	16.18	0.15	0.874	1.13	*ND	0.099	190.5	*ND	0.014	0.240	1.50	7.56	40.12
W$_2$	**Initial**	**9.34**	***ND**	**0.721**	**0.315**	***ND**	**0.105**	**211.63**	**0.024**	***ND**	**1.237**	**0.96**	**7.40**	**37.6**
	RS	8.75	*ND	0.701	0.300	*ND	0.100	209.6	0.020	*ND	1.115	0.90	7.03	33.3
	PF	7.50	*ND	0.227	0.215	*ND	0.075	204.9	0.015	*ND	1.100	0.87	6.79	30.6
	SCR	6.4	*ND	0.122	0.152	*ND	0.065	200.1	0.010	*ND	1.879	0.80	6.56	28.50
W$_3$	**Initial**	**1.70**	***ND**	**0.605**	**1.767**	***ND**	**1.029**	**221.43**	***ND**	***ND**	**0.994**	**2.33**	**8.61**	**38.33**
	RS	1.60	*ND	0.550	1.560	*ND	0.985	215.3	*ND	*ND	0.935	2.15	8.53	34.2
	PF	1.55	*ND	0.425	1.459	*ND	0.955	210.9	*ND	*ND	0.900	2.02	8.01	31.5
	SCR	1.45	*ND	0.400	1.326	*ND	0.900	208.5	*ND	*ND	0.856	1.89	7.89	27.9

W$_1$: Agricultural drainage water collected from drain No.1, the primary channel originating from Kafr al-Batikh-Gamsa, directed towards the pumps, **W$_2$:** Wastewater received by drain No.2 from Damietta industrial zone, **W$_3$:** Drain No.3, responsible for collecting wastewater from the sewage station in New Damietta Governorate, **RS:** Nano biochar of rice straw, **PF:** Nano biochar of palm fronds, **SCR:** Nano biochar of sugar cane residues

Table 11b. Heavy metals in the studied wastewater samples after remediation.

Source of wastewater	Treatments	In	Li	Mg	Mn	Ni	Pb	K	Sr	Zn	As	Na	Bi	Se
		mg L^{-1}												
W_1	**Initial**	*ND	*ND	67.1	0.51	*ND	*ND	18.69	0.840	2.09	0.350	247.7	2.230	*ND
	RS	*ND	*ND	59.7	0.409	*ND	*ND	17.45	0.768	1.652	0.253	193.7	1.370	*ND
	PF	*ND	*ND	56.67	0.169	*ND	*ND	16.47	0.790	1.370	0.209	143.5	1.130	*ND
	SCR	*ND	*ND	44.42	0.153	*ND	*ND	12.35	0.700	1.150	0.186	107.8	1.060	*ND
W_2	**Initial**	*ND	*ND	118.2	0.380	*ND	*ND	41.50	1.346	1.476	*ND	703.0	3.340	0.46
	RS	*ND	*ND	101.6	0.320	*ND	*ND	38.66	0.987	1.248	*ND	698.3	3.150	0.40
	PF	*ND	*ND	77.50	0.287	*ND	*ND	33.56	0.871	1.180	*ND	650.8	3.065	0.36
	SCR	*ND	*ND	69.48	0.253	*ND	*ND	22.60	0.806	1.092	*ND	313.5	2.876	0.30
W_3	**Initial**	9.073	*ND	914.0	0.698	*ND	*ND	212.7	2.84	1.810	0.158	6174	1.138	*ND
	RS	8.120	*ND	895.3	0.603	*ND	*ND	202.3	2.66	1.682	0.126	6000	1.001	*ND
	PF	7.990	*ND	845.3	0.546	*ND	*ND	198.4	2.32	1.521	0.113	5456	0.986	*ND
	SCR	7.450	*ND	810.6	0.512	*ND	*ND	190.5	2.01	1.398	0.100	4200	0.876	*ND

W_1: Agricultural drainage water collected from drain No.1, the primary channel originating from Kafr al-Batikh-Gamsa, directed towards the pumps, **W_2:** Wastewater received by drain No.2 from Damietta industrial zone, **W_3:** Drain No.3, responsible for collecting wastewater from the sewage station in New Damietta Governorate, **RS:** Nano biochar of rice straw, **PF:** Nano biochar of palm fronds, **SCR:** Nano biochar of sugar cane residues

Table 12a. Removal efficiency (%) of heavy metals.

Source of wastewater	Treatments	Al	V	Hg	Ag	B	Ba	Ca	Cd	Co	Cr	Cu	Fe	Ga
		%												
W_1	**RS**	24	74	9.7	10	*ND	6.98	0.47	*ND	17	31.3	3.68	6.	10.6
	PF	24.3	84.4	9.89	17	*ND	10.0	9.6	*ND	34	38.	18.4	9.2	15.3
	SCR	30.8	22.2	27.9	45.38	*ND	23.2	14.49	*ND	51.7	43.7	21.0	14.7	20.4
W_2	**RS**	6.3	*ND	2.77	4.76	*ND	4.7	0.95	16.6	*ND	9.86	6.25	5.0	11.43
	PF	19.7	*ND	68.5	31.74	*ND	28.57	3.18	37.5	*ND	11.07	9.375	8.24	18.61
	SCR	31.4	*ND	83.0	51.74	*ND	38.09	5.44	58.33	*ND	-51.89	16.66	11.3	24.20
W_3	**RS**	5.88	*ND	9.09	11.71	*ND	4.27	2.76	*ND	*ND	5.9	7.7	0.92	10.77
	PF	8.82	*ND	29.7	17.43	*ND	7.19	4.75	*ND	*ND	9.4	13.30	6.96	17.81
	SCR	14.7	*ND	33.8	24.95	*ND	12.53	5.83	*ND	*ND	13.88	18.88	8.36	27.21

W_1: Agricultural drainage water collected from drain No.1, the primary channel originating from Kafr al-Batikh-Gamsa, directed towards the pumps, **W_2:** Wastewater received by drain No.2 from Damietta industrial zone, **W_3:** Drain No.3, responsible for collecting wastewater from the sewage station in New Damietta Governorate, **RS:** Nano biochar of rice straw, **PF:** Nano biochar of palm fronds, **SCR:** Nano biochar of sugar cane residues

Table 12b. Removal efficiency (%) of heavy metals.

Source of waste water	Treatments	In	Li	Mg	Mn	Ni	Pb	K	Sr	Zn	As	Na	Bi	Se
		%												
W_1	**RS**	*ND	*ND	11.0	19.80	*ND	*ND	6.63	8.57	20.9	27.7	21.8	38.5	*ND
	PF	*ND	*ND	15.5	66.86	*ND	*ND	11.87	5.95	34.4	40.28	42.0	49.3	*ND
	SCR	*ND	*ND	33.8	70	*ND	*ND	33.92	16.6	44.9	46.85	56.4	52.4	*ND
W_2	**RS**	*ND	*ND	14.0	15.78	*ND	*ND	6.84	26.6	15.4	*ND	0.66	5.68	13.0
	PF	*ND	*ND	34.4	24.47	*ND	*ND	19.13	35.2	20.0	*ND	7.42	8.23	21.7
	SCR	*ND	*ND	41.2	33.42	*ND	*ND	45.54	40.1	26.0	*ND	55.4	13.8	34.7
W_3	**RS**	10.5	*ND	2.04	13.6	*ND	*ND	4.88	6.3	7.07	20.25	2.81	12.0	*ND
	PF	11.9	*ND	7.516	21.7	*ND	*ND	6.72	18.30	15.9	28.4	11.6	13.3	*ND
	SCR	17.8	*ND	11.3	26.64	*ND	*ND	10.43	29.2	22.7	36.7	31.9	23.0	*ND

W_1: Agricultural drainage water collected from drain No.1, the primary channel originating from Kafr al-Batikh-Gamsa, directed towards the pumps, **W_2:** Wastewater received by drain No.2 from Damietta industrial zone, **W_3:** Drain No.3, responsible for collecting wastewater from the sewage station in New Damietta Governorate, **RS:** Nano biochar of rice straw, **PF:** Nano biochar of palm fronds, **SCR:** Nano biochar of sugar cane residues

4. Discussion

Assessing initial wastewater samples for irrigation suitability

The values of pH suggest that all types of wastewater are suitable for irrigation purposes without requiring adjustments to their pH levels. Notably, all samples fall within the acceptable pH range (6.5-8.4) defined by Westcot and Ayers (1985).

In terms of salinity, the wastewater sample from agricultural drainage water (W_1) falls within an acceptable range for irrigation use, as its EC value does not exceed 3.0 dSm^{-1}, as per Westcot and Ayers (1985). However, the other types of wastewater pose significant challenges for irrigation purposes.

The wastewater from drain NO.3 (W_3), which collects sewage station effluents from New Damietta Governorate, exhibits an EC value of 30.0 dSm^{-1}. This exceptionally high salinity level presents severe risks to land and crops, with potential consequences that may render the land unsuitable for cultivation, as few plants can tolerate such extreme salinity.

Similarly, wastewater from drain NO.2 (W_2) also presents challenges for irrigation. With an EC value that exceeds the acceptable limit according to Westcot and Ayers (1985), W_2 may cause significant problems if used for irrigation without treatment or remediation measures, but to a lesser extent compared to the wastewater from drain NO.3 (W_3). Overall, the findings underscore the importance of evaluating wastewater quality, particularly salinity levels, before considering its use for irrigation. Treatment or remediation may be necessary to mitigate the adverse effects on soil and crops associated with high salinity levels in wastewater.

The soluble sodium ion (Na^+) concentrations in wastewater samples from drains NO.2 and NO.3 (W_2 and W_3) indicate a potential hazard associated with their use for irrigation purposes. The Na^+ content in the examined samples of W_2 and W_3 generally exceeds the threshold range of 13.6-33.6 cmolc L^{-1}. This elevated level of Na^+ suggests a risk of sodium-related issues that could adversely affect soil quality and plant growth upon irrigation with these wastewater sources (Westcot and Ayers, 1985).

Furthermore, the concentrations of chloride ions (Cl^-) and carbonate plus bicarbonate ions (CO_3 + HCO_3) are notably higher than the permissible limits established by Westcot and Ayers, (1985), in the examined samples of W_2 and W_3. According to their guidelines, the acceptable limits for chloride and CO_3 + HCO_3 are set at 10 cmolc L^{-1} and 8.5 cmolcL^{-1} respectively, indicating a higher limit for their availability for irrigation purposes. The observed exceedance of these limits suggests potential concerns regarding the suitability of the wastewater for irrigation, as high concentrations of chloride and carbonate/bicarbonate ions can negatively impact soil health and crop productivity. Overall, the findings underscore the importance of assessing and managing the levels of sodium, chloride, and carbonate/bicarbonate ions in wastewater intended for irrigation to mitigate potential risks to soil and crops. Treatment or mitigation measures may be necessary to ensure the suitability of wastewater for agricultural use while minimizing adverse impacts on agricultural productivity and environmental health.

The presence of the heavy metals in the wastewater samples suggests potential environmental and health risks, highlighting the importance of effective wastewater treatment and management strategies to mitigate their impact on ecosystems and human health when their usage for irrigation purposes. The heavy metal concentrations in the wastewater samples, as indicated in Table 7, have significant environmental and health implications; Elevated levels of aluminum can be toxic to aquatic organisms and may accumulate in soil, affecting plant growth and potentially entering the food chain (Bichi *et al.* 2013). Mercury is a highly toxic heavy metal that can bioaccumulate in organisms, posing serious health risks to humans and wildlife, particularly through the consumption of contaminated fish. While silver is not typically considered highly toxic, elevated levels can still have adverse effects on aquatic organisms and ecosystems (Bagul *et al.* 2015). High levels of barium can be harmful to both humans and animals, affecting the cardiovascular and nervous systems. While calcium itself is not typically considered a heavy metal of concern, high concentrations can affect water hardness and potentially lead to scale formation in pipes and equipment. Cadmium is a highly toxic heavy metal that can accumulate in plants and animals, posing significant health risks to humans through food consumption (Priti and Paul, 2016). Chromium can exist in various oxidation states, with some forms being highly toxic. Elevated levels of chromium can have adverse effects on aquatic life and human health. Copper is essential for various biological processes but can be toxic at elevated concentrations, particularly to aquatic organisms. While iron is an essential nutrient, excessive levels can lead to water discoloration and potentially affect aquatic organisms. Lead is a highly toxic heavy metal that can cause serious health issues, particularly neurological damage, especially in children. Elevated levels of manganese can affect water quality and may have adverse health effects, particularly neurological effects with long-term exposure. Nickel is considered a potential carcinogen and can have adverse effects on human health, particularly through inhalation and ingestion. Potassium is an essential nutrient for plants and is generally not considered a heavy metal of concern at typical concentrations. Strontium can affect bone health in humans and may have adverse effects on aquatic organisms. While zinc is essential for various biological processes, elevated levels can be toxic to aquatic organisms and may impact water quality (Omran *et al.* 2019).

Arsenic is a highly toxic heavy metal that poses significant health risks, including cancer and other serious health effects, particularly through long-term exposure. Bismuth is considered relatively non-toxic to humans and the environment at typical concentrations. Selenium is an essential nutrient but can be toxic at high concentrations, particularly to aquatic organisms (Kumar *et al.* 2021).

The presence of these heavy metals in wastewater samples highlights the importance of proper treatment and management to prevent environmental contamination and protect human health. Efforts should be made to minimize the release of heavy metals into wastewater and to implement effective treatment processes to remove or reduce their concentrations before discharge into the environment or usage for irrigation purposes.

Generally, In conclusion, the analysis of the investigated wastewater samples reveals various issues that hinder their direct suitability for irrigation purposes. However, the extent of restriction varies from one sample to another and also across different parameters.

For instance, while some samples may have acceptable pH levels, indicating no immediate need for pH adjustment before irrigation, they may still exhibit high salinity levels or contain elevated concentrations of heavy metals, posing risks to soil and crop health. Other samples may have manageable levels of salinity but exceed permissible limits for specific heavy metals or other contaminants, necessitating treatment or remediation before safe use in irrigation.

Therefore, it is evident that each wastewater sample presents unique challenges and requires tailored management strategies to address its specific limitations. This highlights the importance of comprehensive assessment and treatment processes to ensure the safe and sustainable use of wastewater for irrigation while minimizing adverse impacts on agricultural productivity and environmental quality.

Adsorbtion and removal trial

The adsorption and removal trial aimed to assess the effectiveness of nanobiochar in adsorbing and removing contaminants from wastewater. The trial involved exposing wastewater samples containing target contaminants to nanobiochar materials derived from different plant waste sources and then analyzing the concentrations of contaminants before and after treatment. Overall, the adsorption and removal trial provided valuable insights into the potential applications of nanobiochar for wastewater treatment. By understanding the adsorption mechanisms and effectiveness of nanobiochar, researchers can optimize its use for removing contaminants from wastewater, contributing to sustainable and environmentally friendly water treatment solutions.

The significant reduction in parameter values underscores the efficacy of the treatment process in improving the quality of wastewater. The ability of nano biochar to adsorb and remove contaminants from the wastewater is evident, with different feedstock sources yielding varying degrees of effectiveness.

Furthermore, the largest percentage of heavy metal removal occurred with nano biochar derived from sugar cane residues, followed by nano biochar from palm fronds, and then nano biochar from rice straw. This suggests that the specific properties of the feedstock material play a crucial role in determining the adsorption capacity and effectiveness of the nano biochar in removing heavy metals from the wastewater.

In terms of suitability for irrigation, the treated wastewater samples exhibited varying levels of improvement. The first sample (W_1) became suitable for irrigating a wide range of agricultural crops, indicating a significant enhancement in water quality after treatment. The second sample (W_2) also became suitable for irrigating agricultural crops, albeit with slightly lower suitability compared to the first sample. However, the third sample remained unsuitable for irrigation operations, suggesting that additional treatments may be necessary to further enhance its quality.

Overall, these findings highlight the potential of nano biochar-based treatments in improving wastewater quality and suitability for agricultural use. The selection of feedstock material and optimization of treatment processes are crucial factors in achieving desired outcomes, with the potential to contribute to sustainable water management practices and agricultural productivity.

Our findings align with those of Mosa *et al.* (2017), who investigated the impact of various crop residues on the removal efficiency of heavy metal ions from synthetic wastewater solutions. Their study concluded that cotton stalks exhibited the highest efficiency in removing heavy metal ions compared to other biosorbent materials tested.

This correlation suggests a consistent trend in the efficacy of agricultural residues as biosorbents for heavy metal removal across different studies. The superior performance of certain crop residues, such as cotton stalks, underscores the importance of feedstock selection in biosorption processes. These findings further support the notion that the specific properties of the biomass material, including its composition and structure, play a crucial role in determining its effectiveness as a biosorbent for heavy metal removal.

By acknowledging and corroborating the results of previous studies, our research contributes to the broader understanding of biosorption processes and emphasizes the potential of agricultural residues as sustainable and effective solutions for wastewater treatment and heavy metal removal.

5. Conclusion

Our study investigated the effectiveness of nano biochar derived from different plant waste sources in treating wastewater and removing contaminants. Through comprehensive analysis, we observed a significant decrease in various parameter values after treatment, indicating the efficacy of nano biochar in improving water quality. Notably, nano biochar derived from sugar cane residues exhibited the highest reduction in parameter values and the highest percentage of heavy metal removal, followed by nano biochar from palm fronds and rice straw. Generally, the findings underscore the potential of agricultural residues, such as sugar cane residues, as effective biosorbents for wastewater treatment and heavy metal removal.

Recommendations:

Conduct additional studies to explore the optimal conditions for nano biochar production and its application in wastewater treatment. Investigate the long-term effects of nano biochar treatment on soil health and crop productivity in agricultural settings. Explore a wider range of agricultural residues to identify alternative biosorbents with high efficiency in wastewater treatment. Investigate the potential of combining different feedstock materials to enhance the adsorption capacity of nano biochar. Optimize treatment processes, including dosage, contact time, and pH conditions, to maximize the removal efficiency of contaminants from wastewater. Investigate the potential synergistic effects of combining nano biochar with other treatment methods. Assess the environmental impact of nano biochar production and application, including energy consumption, greenhouse gas emissions, and potential leaching of contaminants into the environment. Develop sustainable production practices to minimize environmental footprint.

By implementing these recommendations, we can further advance the use of nano biochar and agricultural residues in wastewater treatment, contributing to sustainable water management practices and environmental conservation efforts.

Conflicts of interest

The authors have declared that no competing interests exist.

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