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Aquaculture Effluent as a Green Alternative to Fertilizers: A Study on Nutrient Recycling and Heavy Metal Dynamics in Soil-Plant Systems

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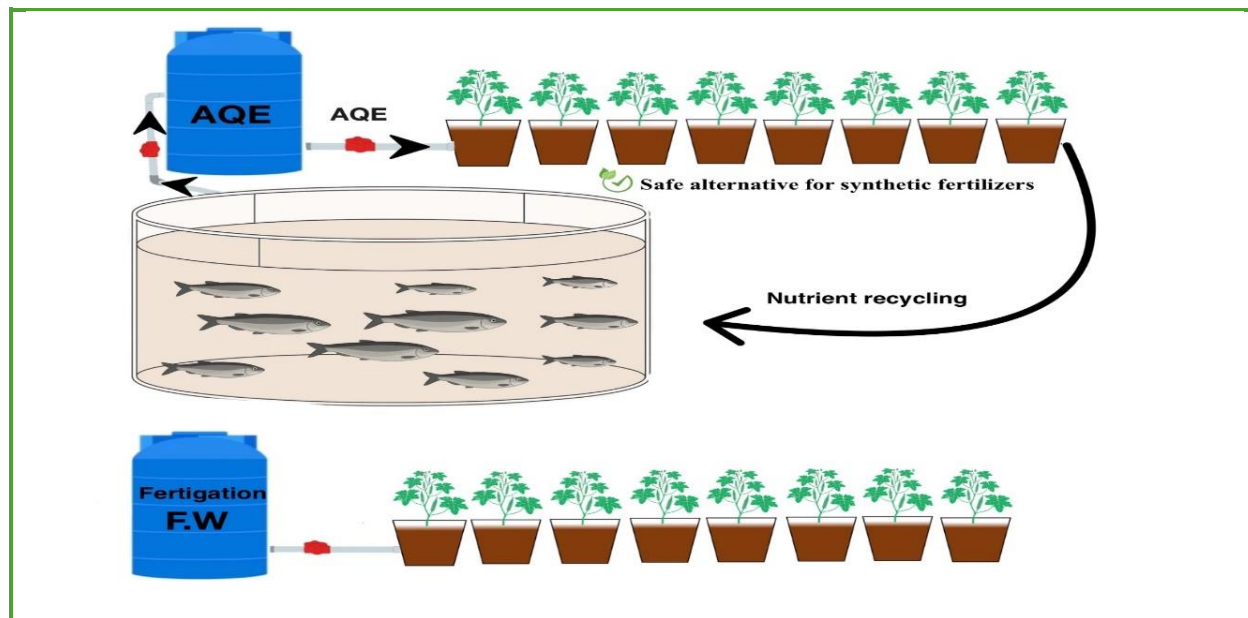
Circular economy

ABSTRACT

The valorization of waste streams is a cornerstone of circular economy and green chemistry principles. This study investigates the use of aquaculture effluent (AQE) as a green fertilizer for irrigating red leaf lettuce (*Lactuca sativa* var. *Red Sails*), proposing a sustainable agricultural solution that addresses two issues: aquaculture waste management and reduced reliance on synthetic fertilizers. A greenhouse experiment compared lettuce irrigated with tilapia AQE to a control irrigated with freshwater (FW) supplemented with a commercial fertilizer. Results showed no significant differences in plant growth parameters (branch number, leaf length, and biomass) or tissue chemical composition between treatments. Crucially, post-harvest soil analysis revealed no accumulation of heavy metals beyond initial levels and no detectable microbiological contamination. The potential of AQE for nutrient recycling was confirmed, as soil levels of total nitrogen (TN), total phosphorus (TP), and total potassium (TK) were maintained or improved. These findings demonstrate that AQE irrigation is a viable form of waste valorization, offering a safe and effective green alternative to conventional fertigation that supports circular nutrient management without compromising soil health or food safety.

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Graphical Abstract



Introduction

The principles of green chemistry emphasize waste prevention, atom economy, and the design of less hazardous chemical syntheses. A direct application of these principles is the valorization of industrial by-products, transforming waste streams into valuable resources to enhance sustainability. The rapidly growing global aquaculture sector is a significant source of nutrient-rich wastewater, often regarded as a pollutant. This study explores the potential of using this aquaculture effluent as a green alternative to synthetic fertilizers. Closing the nutrient loop by irrigating crops with effluent not only prevents waste and pollution, but also reduces the environmental footprint associated with the production and use of conventional fertilizers. This work positions AQE reuse as a viable model for sustainable agriculture within a circular economy framework. Driven by increasing demand for fish, rapid aquaculture growth produces large volumes of wastewater rich in nitrogen, phosphorus, and other essential micronutrients, primarily from fish waste,

discarded feed, and organic matter [1,2]. The discharge of aquaculture effluents has traditionally raised environmental concerns, particularly regarding aquatic ecosystems, due to risks of eutrophication, pathogen and chemical dissemination, soil salinization, and heavy metal accumulation [3,4]. However, recent research has explored the potential for treating and reusing these effluents through various techniques [5-9], highlighting their role as a sustainable and cost-effective soil amendment in agricultural systems. The use of aquaculture effluents for irrigation offers several advantages, including improved soil fertility, increased organic matter content, enhanced cost-effectiveness, and support for beneficial microbial activity. This approach not only recycles nutrients that would otherwise contribute to water pollution, but also reduces dependence on chemical fertilizers. As sustainable agriculture gains traction, the integration of aquaculture and agriculture, known as integrated aquaculture-agriculture systems (IAAS), presents a promising strategy for optimizing resource use and minimizing environmental impact. This integration embodies

a circular economy approach that promotes environmental balance and enhances crop productivity. Studies have successfully demonstrated the reuse of aquaculture effluents for irrigating halophytes and in integrated systems, noting benefits such as reduced environmental risk and economic advantages [10–12]. Recent work by Al-Wabel *et al.* showed that wastewater from aquaculture improved soil health and nutrient availability for date palms [12], while Qurie *et al.* demonstrated its successful use in celery production [13]. However, a critical and persistent research gap concerns the long-term implications for soil chemistry, specifically the fate, behavior, and potential accumulation of heavy metals [3,4]. While many studies focus on macronutrient cycling and plant growth, a comprehensive risk assessment of a full spectrum of heavy metals (*e.g.*, Cr, Cd, Pb, Zn, and Fe) within the aquaculture-agriculture continuum is lacking. The present work directly addresses this shortcoming by providing a detailed comparative analysis of soil properties, including a comprehensive heavy metal profile, before and after irrigation with tilapia aquaculture effluent compared to conventional fertigation. By demonstrating that AQE irrigation does not lead to hazardous metal bioaccumulation in *Lactuca sativa* or negatively impact soil, this study provides the necessary empirical evidence to confirm the safe and sustainable valorization of aquaculture effluents in agriculture. The objective of this project is to evaluate the effects of aquaculture effluent on soil characteristics and its impact on Red Sails lettuce (*Lactuca sativa*) growth, assessing its potential as a viable alternative to conventional fertilization methods.

Experimental

The experiment was conducted in a greenhouse at the Al-Quds University campus in Abu Dis, 5 km east of Jerusalem. It consisted of two main components: an aquaculture system and a

potted soil experiment. The water system comprised two equivalent sections: one with freshwater (FW) and the other with aquaculture effluent (AQE), both used to irrigate Red Sails Lettuce (*Lactuca sativa*) grown in pots. The FW section served as the control for the pot experiment. A commercial fertilizer (13N:13P as P_2O_5 ; 13K as K_2O) was added to the FW tanks at a rate of 1 g per liter (resulting in a concentration of 250 g/250 L).

Aquaculture system

The aquaculture system, installed in a greenhouse, consisted of a concrete, bowl-shaped pool with a 3 m diameter and 1.5 m depth, filled with 5 m³ of freshwater from the Abu Dis municipality. A hydraulic pump system was installed inside the pool to pump the AQE to a main tank located above the pot experiment for gravity-fed irrigation, with the flow rate regulated by a water valve. The pool was stocked with 150 tilapia fish (*Oreochromis spp.*), chosen for their global importance in food security, rapid growth rate, and adaptability to various environments [14]. The fish were fed once or twice a day. Approximately 25% of the water from the aquaculture pool, classified as AQE, was discharged daily for use in irrigation.

Pots irrigation system

The pot experiment consisted of 16 pots filled with the same soil type, divided into two groups connected to different irrigation systems programmed to water the plants for 10 minutes. Each system had a 0.5 m³ storage tank installed above the irrigation line for its respective media (AQE or fertigated FW). The first group (8 pots) was irrigated with AQE; the second group was irrigated with fertigated FW.

Plant selection

Red Sails Lettuce (*Lactuca sativa*) was selected for this experiment. This loose-leaf, red-bronze variety is known for its tender texture and mild flavor. It is one of the most popular vegetables grown in aquaponic systems [13,15–19]. It thrives in cool weather, maturing in 28–55 days, and prefers full sun, well-drained soil, and temperatures between 60 and 65 °F (15–18 °C). It is moderately bolt-resistant and somewhat disease-tolerant but susceptible to common lettuce pests. Nutritionally, it is low in calories (~15 kcal/100 g), rich in water (~95%), and provides vitamins A and K, folate, iron, fiber, and antioxidants such as anthocyanins. It was chosen for its bolt resistance and performance in cool environments [20].

Biological growth parameters of plants

Young Red Sails Lettuce plants were grown in the pot experiment under both irrigation treatments (FW and AQE). The experiment began on January 6th and ended on March 1st, lasting approximately 55 days. The number of branches and leaf lengths was monitored bi-weekly. Fresh and dry biomass was measured at the end of the experiment after harvest. Dry biomass was determined after air-drying the plants at room temperature. Chemical analysis was performed on the dried plant tissue.

Water and soil analysis

Water quality analysis for AQE and FW was performed according to standard methods [21]. Parameters included electrical conductivity (EC), pH, total dissolved solids (TDS), major ions (NO_3^- , Na^+ , and Ca^{2+}), total nitrogen (TN), total potassium (TK), total phosphorus (TP), and microbiological tests for total coliform (TC) and fecal coliform (FC). Soil samples were col-

lected from all pots at a 0–5 cm depth before planting and after harvest. The soil was a loamy brown type with a water permeability of 7.1×10^{-6} cm/s. Samples were sieved, extracted, and diluted for analysis according to standard procedures [22]. Analysis included pH, EC, TDS, organic carbon content (OCC), total organic carbon (TOC), organic matter (OM), TP, TN, Na^+ , K^+ , and TC/FC tests.

Statistics and yield component analysis

Results are expressed as means $\pm$ standard deviation for three replicates. All statistical analyses were performed using the Statistical Analysis System (SAS) [23]. Data comparisons were carried out using the GLM procedure. The Bonferroni correction was employed for multiple comparisons to maintain an experiment-wise error rate of 5%.

Results and Discussion

Water and soil analysis

Water analysis

Table 1 summarizes the water quality analysis before planting, during the season, and after harvesting. The AQE exhibited characteristics generally suitable for agricultural applications. The pH values for both FW and AQE (range 7.00–8.00) fell within the FAO-recommended range for irrigation water (6.5–8.4), as did the EC values [24]. The higher concentrations of macronutrients (TP, TN, and K) in the AQE are attributed to tilapia feces and uneaten or decomposing feed, which are rich sources of nutrients. It is estimated that 50–90% of nitrogen and over 85% of phosphorus from feed are discharged unconsumed in effluent [25,26]. Microbiological analysis showed no contamination (TC and FC were null).

Table 1. Water analysis of (FW) and (AQE) before planting, during the season, and after harvesting

Parameters	Before plantation		During the season	(AQE)final	After harvesting	
	(FW)	AQE			Fresh water from pots	(AQE) from pots
pH	7.43 ± 0.1	7.20 ± 0.1	7.67 ± 0.1	7.0 ± 0.20	7.9 ± 0.2	7.77 ± 0.1
EC mS\cm	500 ± 10	543 ± 0.1	820 ± 10	950 ± 20	820 ± 10	677 ± 10
TDS ppm	240 ± 10	260 ± 10	270 ± 10	480 ± 10	403 ± 10	330 ± 10
Na ppm	56.05 ± 0.1	75.20 ± 0.1	77.11 ± 0.1	60.85 ± 2.15	73.28 ± 0.1	77.38 ± 0.1
K ppm	4.01 ± 0.1	16.31 ± 0.1	31.60 ± 0.1	7.30 ± 0.19	85.55 ± 0.1	80.20 ± 0.1
Ca ppm	42.33 ± 0.1	52.76 ± 0.1	51.92 ± 0.1	48.85 ± 0.45	89.93 ± 0.1	68.35 ± 0.1
TP ppm	9.46 ± 0.1	17.22 ± 0.1	14.36 ± 0.1	10.56 ± 0.1	36.70 ± 0.1	26.88 ± 0.1
TN ppm	7.43 ± 0.1	6.91 ± 0.1	10.03 ± 0.1	11.75 ± 0.1	7.21 ± 0.1	9.56 ± 0.1
NO ₃ ppm	8.03 ± 0.1	0.88 ± 0.1	4.80 ± 0.1	5.00 ± 0.04	16.90 ± 0.1	21.71 ± 0.1
FC (cfu/100 ml)	null	null	null	null	null	null
TC (cfu/100 ml)	null	null	null	null	null	null

Soil analysis before plantation and after harvesting

Table 2 summarizes the soil analysis results before planting and after harvesting. The availability of macronutrients (N, P, and K) from both irrigation sources was confirmed. The higher concentrations of some micronutrients in AQE-irrigated soil can be attributed to the nutrient-rich composition of the Tilapia effluent [27,28]. Akindele *et al.* similarly demonstrated that fish farm effluent improves soil nutrients [29]. The concentrations of TP, TN, and K were similar between treatments (*e.g.*, TP: 3.63 vs. 3.79 mg/g for AQE and FW, respectively). No negative microbiological effects were detected in soils from either treatment. Jiajia Wu *et al.* indicated that the aquaculture using shrimp pond wastewater has the greatest effect on soil pH, water content, and bulk density, and also increased the organic carbon in soil [30].

The evaluation of heavy metal concentrations in soil before and after irrigation demonstrated variable trends (Table 3). Chromium (Cr) levels remained stable across all conditions (*e.g.*, 63.2 ppm before planting vs. 64.8 ppm after AQE), suggesting limited mobility or interaction with irrigation treatments. This stability is consistent with the known behavior of Cr in

soils, where it often persists in the less soluble and less bioavailable Cr (III) form [31].

Cadmium (Cd) concentrations slightly decreased post-irrigation (from 1.1 ppm to 0.9 ppm), potentially due to plant uptake or immobilization within the soil matrix [32]. Lead (Pb), initially present at 0.7 ppm, was undetectable after irrigation, indicating possible phytoremediation or strong sorption to soil organic matter and clay particles [33]. The decrease in Cd and disappearance of Pb are positive findings, suggesting active remediation and a reduction in ecotoxicological risk. Copper (Cu) remained below detection limits (<0.05 ppm) throughout the study, likely due to strong binding with organic ligands or low initial presence. Zinc (Zn) concentration increased significantly following AQE irrigation (from 96.0 ppm to 105.0 ppm). This increase is likely due to a combination of direct Zn input from fish feed components in the effluent and enhanced mobilization of native soil Zn facilitated by dissolved organic matter (DOM) in the AQE, which can form soluble complexes and reduce Zn sorption to soil particles [34–37]. Iron (Fe) concentrations showed a modest decrease post-irrigation, which may be attributed to plant uptake given its essential role in metabolism [38].

Table 2. Soil analysis before planting and after harvesting of Red Sails lettuce irrigated with (AQE) and (FW)

Parameters	Soil before plantation	After harvesting	
		AQE	FW
pH	8.00 ± 0.01	7.53 ± 0.13	7.43 ± 0.1
EC µS\cm	460 ± 10	483 ± 12	370 ± 10
TDS ppm	220 ± 10	240 ± 10	190 ± 10
Na mg/g	0.25 ± 0.01	2.59 ± 0.01	2.33 ± 0.01
K mg/g	0.82 ± 0.04	15.80 ± 0.01	16.41 ± 0.01
Ca mg/g	0.39 ± 0.05	20 ± 2.10	25.8 ± 1.3
TP mg/g	0.03 ± 0.01	3.63 ± 0.20	3.79 ± 0.03
TN mg/g	2.93 ± 0.1	3.15 ± 0.01	2.91 ± 0.01
OOC%	2.70 ± 0.1	2.43 ± 0.20	2.46 ± 0.20
TOC%	3.60 ± 0.1	3.26 ± 0.17	3.30 ± 0.15
OM%	6.20 ± 0.1	5.63 ± 0.20	5.69 ± 0.20
FC (cfu/100ml)	null	null	null
TC (cfu/100ml)	null	null	null

Table 3. Heavy metal analysis of soil before planting and after harvesting using (FW) and AQE

Parameters	Soil Before plantation	Soil irrigation with (FW)	Soil irrigation with AQE
Cr ppm	63.2 ± 0.10	63.1 ± 1.00	64.8 ± 0.50
Cd ppm	1.1 ± 0.05	0.9 ± 0.05	0.9 ± 0.05
Cu ppm	ND*	ND	ND
Pb ppm	0.7 ± 0.05	0.0 ± 0.05	0.0 ± 0.05
Zn ppm	96.0 ± 1.00	93.3 ± 0.10	105.0 ± 1.00
Fe ppm	30345 ± 5.00	29585 ± 5.00	29335 ± 5.00

*ND: Not detected.

Table 4. Comparison of heavy metal concentrations in soil with international guidelines (European Union) for agricultural land [39] and FAO/WHO [40, 41]

Heavy Metal	Soil Before Plantation (mg/kg)	Soil after AQE (mg/kg)	EU Limit (mg/kg)	FAO/WHO Limit (mg/kg)	Status
Cr	63.2 ± 0.10	64.8 ± 0.50	-	100	Within Safe Limits
Cu	ND*	ND	50 - 140	100	Within Safe Limits
Cd	1.1 ± 0.05	0.9 ± 0.05	1 - 3	3	Within Safe Limits
Pb	0.7 ± 0.05	0.0 ± 0.05	50 - 300	100	Within Safe Limits
Zn	96.0 ± 1.00	105.0 ± 1.00	150 - 300	-	Within Safe Limits
Fe	30345 ± 5.00	29335 ± 5.00	-	50000	Within Safe Limits

These findings indicate that while most heavy metals remained stable or decreased, AQE irrigation can influence Zn dynamics and may contribute to the redistribution of certain metal ions. As shown in Table 4, the concentrations of all analyzed heavy metals, both before and after AQE irrigation, were well below the maximum permissible limits set by European

Union [39] and FAO/WHO [40,41]. This quantitatively confirms that irrigation with AQE did not pose a significant risk of heavy metal contamination.

Plant growth parameters

Figures 1 and 2 show the variation in branch number and leaf length over time. The results for both parameters indicated no significant difference between the two irrigation treatments, with normal growth observed over time in both media. Figure 3 demonstrates that the same trend was observed for fresh and dry biomass at harvest. There were no significant differences in biomass yield between lettuce irrigated with AQE or FW. This shows that Red Sails Lettuce grows similarly with both water sources. The results of the present study agree with those of Al-Wabel *et al.* on date palm irrigation with aquaculture wastewater and Qurie *et al.* on celery irrigation with aquaculture efflu-

ent [12,13]. The irrigation of pepper using aquaculture water improves the soil physicochemical properties and soil water content, in addition to enhancing crop yield and nutrition [29]. Organic matter influences soil infiltration characteristics and thus increases the uptake of plant nutrients, indicating that aquaculture wastewater improves crop productivity [42].

Chemical plant analysis

The results indicated that all dried lettuce samples from both irrigation treatments had approximately the same concentration of Na, TK, TN, and TP (in mg/g).

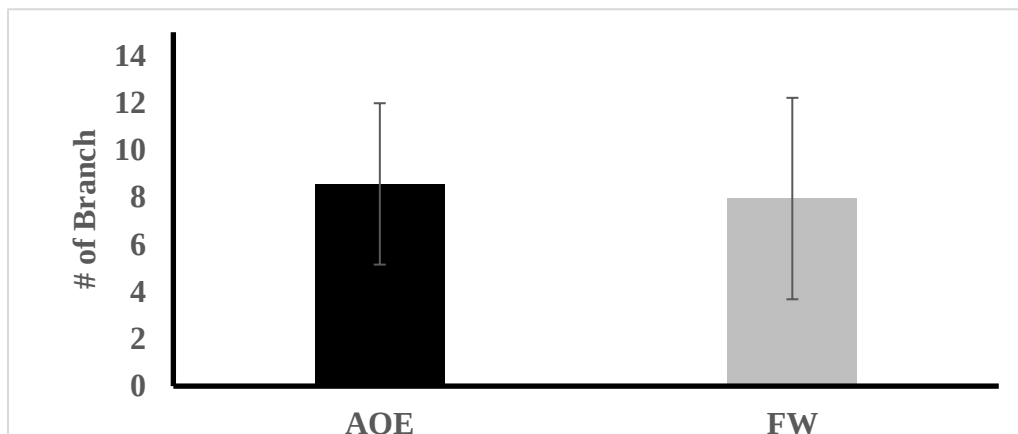


Figure 1. Variation of Red Sails Lettuce (*Lactuca sativa*) length (cm) during the pots soil experiment which irrigated with (AQE) and (FW)

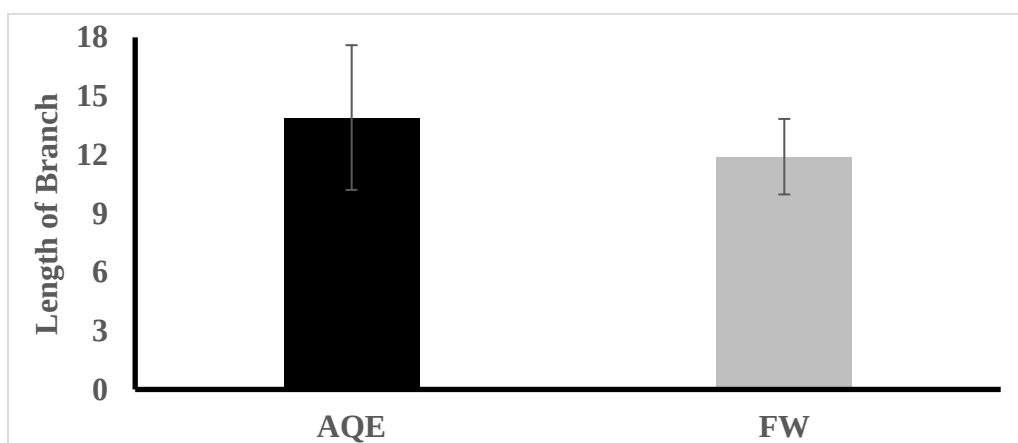


Figure 2. Variation of Red Sails Lettuce (*Lactuca sativa*) leaves length (cm) during the pots soil experiment which irrigated with (AQE) and (FW)

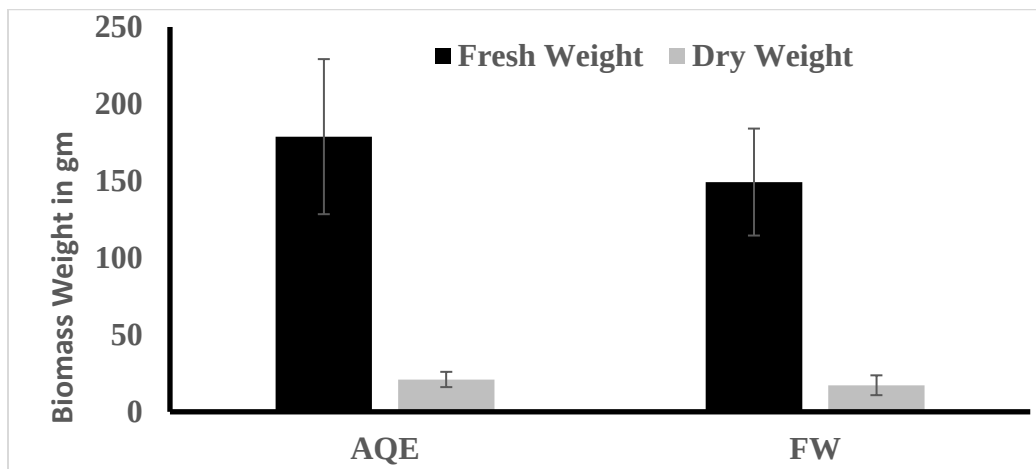


Figure 3. Variation of Red Sails Lettuce (*Lactuca sativa*) fresh and dried biomass (gm) after harvesting in pots soil experiment which irrigated with (AQE) and (FW)

Table 5. Chemical plant analysis of dried Red Sails Lettuce (*Lactuca sativa*) plants irrigated with both (FW) and AQE

Parameters	(FW)	AQE
Na mg/g	7.01 ± 0.10	7.11 ± 0.25
TK mg/g	10.24 ± 0.50	11.25 ± 0.50
TP mg/g	3.80 ± 0.02	3.63 ± 0.05
TN mg/g	1.74 ± 0.05	1.45 ± 0.05
FC (cfu/100 ml)	null	null
TC (cfu/100 ml)	null	null

The highest concentration of TK compared to other micronutrients can be attributed to the high TK concentration in the AQE effluent and varying plant uptake rates, a finding consistent with Qurie *et al.* [13]. No microbiological contamination (TC and FC) was detected in the plant tissue.

Conclusion

In conclusion, this study successfully demonstrates that aquaculture effluent is not a waste product but a valuable resource, and its application in agriculture is a practical implementation of green chemistry principles. By substituting synthetic fertilizers with AQE for *Lactuca sativa* irrigation, a dual solution is proposed: it valorizes a nutrient-rich waste stream that would otherwise threaten the environment while re-

ducing the environmental footprint of chemical fertilization. The absence of negative effects on plant growth, soil microbiology, and heavy metal accumulation, combined with efficient macronutrient recycling, underscores the safety and efficacy of this approach. The integration of aquaculture and agriculture through effluent irrigation aligns with a circular economy model, promoting sustainable agriculture, resource efficiency, and environmental protection. This strategy offers a scalable, green alternative for farmers, contributing to a more resilient and sustainable food production system.

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Disclosure Statement

No potential conflict of interest was reported by the authors in this work.

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Authors' Contributions

Mohannad Qurie, first corresponding author and Supervisor of the research project, Omar Ayyad, Second corresponding author with writing contribution. Manal Wazwaz and Ragab Razem monitoring and sample collections. Karmel Awad a master student in the project.

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References

- [1]. Nadarajah, S., Flaaten, O., [Global aquaculture growth and institutional quality](#). *Marine Policy*, **2017**, 84, 142-151.
- [2]. Naylor, R.L., Hardy, R.W., Buschmann, A.H., Bush, S.R., Cao, L., Klinger, D.H., Little, D.C., Lubchenco, J., Shumway, S.E., Troell, M., [A 20-year retrospective review of global aquaculture](#). *Nature*, **2021**, 591(7851), 551-563.
- [3]. Coldebella, A., Gentelini, A.L., Piana, P.A., Coldebella, P.F., Boscolo, W.R., Feiden, A., [Effluents from fish farming ponds: A view from the perspective of its main components](#). *Sustainability*, **2017**, 10(1), 3.
- [4]. Dauda, A.B., Ajadi, A., Tola-Fabunmi, A.S., Akinwale, A.O., [Waste production in aquaculture: Sources, components and managements in different culture systems](#). *Aquaculture and Fisheries*, **2019**, 4(3), 81-88.
- [5]. Igwegbe, C.A., Ighalo, J.O., Onukwuli, O.D., Obiora-Okafo, I.A., Anastopoulos, I., [Coagulation-flocculation of aquaculture wastewater using green coagulant from garcinia kola seeds: Parametric studies, kinetic modelling and cost analysis](#). *Sustainability*, **2021**, 13(16), 9177.
- [6]. Silva, C.P., Pereira, D., Calisto, V., Martins, M.A., Otero, M., Esteves, V.I., Lima, D.L., [Biochar-TiO₂ magnetic nanocomposites for photocatalytic solar-driven removal of antibiotics from aquaculture effluents](#). *Journal of Environmental Management*, **2021**, 294, 112937.
- [7]. Omitoyin, B., Ajani, E.K., Okeleye, O.I., Akpoilih, B.U., Ogunjobi, A., [Biological treatments of fish farm effluent and its reuse in the culture of nile tilapia \(*oreochromis niloticus*\)](#). *Journal of Aquaculture Research & Development*, **2017**, 8(2), 1-9.
- [8]. Igwegbe, C.A., Onukwuli, O.D., Onyechi, P.C., [Optimal route for turbidity removal from aquaculture wastewater by electrocoagulation-flocculation process](#). *Journal of Engineering and Applied Sciences*, **2019**, 15(1), 99-108.
- [9]. Iber, B.T., Kasan, N.A., [Recent advances in shrimp aquaculture wastewater management](#). *Heliyon*, **2021**, 7(11).
- [10]. McIntosh, D., Fitzsimmons, K., [Characterization of effluent from an inland, low-salinity shrimp farm: What contribution could this water make if used for irrigation](#). *Aquacultural Engineering*, **2003**, 27(2), 147-156.
- [11]. Abdul-Rahman, S., Saoud, I.P., Owaied, M.K., Holail, H., Farajalla, N., Haidar, M., Ghanawi, J., [Im-](#)

- proving water use efficiency in semi-arid regions through integrated aquaculture/agriculture. *Aquaculture Technology in Developing Countries*, **2016**, 77-95.
- [12]. Al-Wabel, M.I., Almutari, M.M., Ahmad, M., Al-Swadi, H.A., Ahmad, J., Al-Farraj, A.S., [Impacts of aquaculture wastewater irrigation on soil health, nutrient availability, and date palm fruit quality](#). *Scientific Reports*, **2024**, 14(1), 18634.
- [13]. Qurie, M., Mukarker, G., Jaara, E., Mtour, A., Shweiki, A., Elyan, M., Bannoura, C., Shabanah, D., Nussibah, S., Nassar, A. [Irrigation of celery \(apium graveolens\) plants with aquaculture effluent aque using hydroponic system and surface drip irrigation](#), *Journal of Chemical Health Risks*, 2024, **14**:3046
- [14]. Aiken, K., Morris, D., Hanley, F., Manning, R., [Aquaculture in Jamaica](#). *Naga*, **2002**, 25(3/4), 10-15.
- [15]. Licamele, J., [Biomass production and nutrient dynamics in an aquaponics system](#). University of Arizona, Tucson, AZ, USA, **2009**.
- [16]. Hadadi, T., Shahraki, M., Karimi, P., [Adsorption of some nitrophenols onto graphene and functionalized graphene sheets: quantum mechanics calculations, monte carlo, and molecular dynamics simulations](#). *Chemical Methodologies*, **2024**, 8(10) 753-775.
- [17]. Qurie, M., Abbadi, J., Scrano, L., Mecca, G., Bufo, S.A., Khamis, M., Karaman, R., [Inland treatment of the brine generated from reverse osmosis advanced membrane wastewater treatment plant using epuvalisation system](#). *International Journal of Molecular Sciences*, **2013**, 14(7), 13808-13825.
- [18]. Qurie, M., Daghra, S., Khamis, M., Kanan, A., Barghouthi, Z., Alimari, A., Nussiebah, S., Karaman, R., [Rosemary \(rosmarinus officinalis\) plants irrigation with secondary treated effluents using epuvalisation technology](#). *Net Journal of Agricultural Science*, **2019**, 7, 69.
- [19]. Qurie, M., Daghra, S., Khamis, M., Kanan, A., Barghouthi, Z., Alimari, A., Karaman, R., [Application of the epuvalisation technology for the tertiary treatment of secondary treated effluents using geranium plants](#). *Annals of Agricultural Sciences*, **2019**, 64(2), 237-243.
- [20]. Johnson, G.E., Buzby, K.M., Semmens, K.J., Waterland, N.L., [Year-round lettuce \(lactuca sativa l.\) production in a flow-through aquaponic system](#). *Journal of Agricultural Science*, **2016**, 9(1), 1-75.
- [21]. Rand, M., Greenberg, A.E., Taras, M.J. [Standard methods for the examination of water and wastewater](#). 14th edition, 1976, 1193.
- [22]. Ryan, J., Garabet, S., Harmsen, K., Rashid, A., [A soil and plant analysis manual adapted for the west Asia and north Africa region](#). **1996**.
- [23]. Sas, S., [User's guide: Statistics](#). *SAS Institute Inc, Cary, NC*, **1985**, 956.
- [24]. Drechsel, P., Zadeh, S.M., Pedrero-Salcedo, F., Alcon, F., Allende, A., Amerasinghe, P., Amoah, P., Ben-Gal, A., Benes, S.E., Bruning, B., [Water quality in agriculture: Risks and risk mitigation](#). *Food and Agriculture Organisation of the United Nations*, **2023**.
- [25]. Zou, Y., Hu, Z., Zhang, J., Xie, H., [Guimbaud, C., Fang, Y., Effects of ph on nitrogen transformations in media-based aquaponics](#). *Bioresource Technology*, **2016**, 210, 81-87.
- [26]. Esteves, A.F., Soares, S.M., Salgado, E.M., Boaventura, R.A., Pires, J.C., [Microalgal growth in aquaculture effluent: Coupling biomass valorisation with nutrients removal](#). *Applied Sciences*, **2022**, 12(24), 12608.
- [27]. Davy, J., Becchetti, T., Lile, D., Fulton, A., Giraud, D., [Establishing and managing irrigated pasture for horses](#). *University of California, Agriculture and Natural Resources*, **2012**.
- [28]. Griffin, G., Jokela, W., Ross, D., Pettinelli, D., Morris, T., Wilf, A., [Recommended soil nitrate-n tests](#). **1995**, 493.
- [29]. Akindele, A.J., Olufayo, A.A., Faloye, O.T., [Influence of borehole and fish wastewater on soil properties, productivity and nutrient composition of sweet pepper \(capsicum annum\)](#). *Acta Ecologica Sinica*, **2022**, 42(1), 56-62.
- [30]. Wu, J., Liu, L., Li, H., Chen, J., Chen, G., Zhu, H., Liu, J., Ye, Y., [Aquaculture types drive variability in mangrove soil carbon-nitrogen stocks and oc sources via dredging wastewater](#). *Environmental Pollution*, **2025**, 126974.
- [31]. Alloway, B.J., [Heavy metals in soils: Trace metals and metalloids in soils and their bioavailability](#). **2012**, 22.
- [32]. Wuana, R.A., Okieimen, F.E., [Heavy metals in contaminated soils: A review of sources, chemistry, risks and best available strategies for remediation](#). *International Scholarly Research Notices*, **2011**, 2011(1), 402647.

- [33]. Srivastava, P., Bolan, N., Casagrande, V., Benjamin, J., Adejumo, S.A., Sabir, M., Farooqi, Z.U.R., Sarkar, A., [Lead in soils: Sources, bioavailability, plant uptake, and remediation](#). *Appraisal of Metal (Loids) in the Ecosystem*, **2022**, 331-360.
- [34]. Gao, J., Han, H., Gao, C., Wang, Y., Dong, B., Xu, Z., [Organic amendments for in situ immobilization of heavy metals in soil: A review](#). *Chemosphere*, **2023**, 335, 139088.
- [35]. Lwin, C.S., Seo, B.-H., Kim, H.U., Owens, G., Kim, K.-R., [Application of soil amendments to contaminated soils for heavy metal immobilization and improved soil quality—a critical review](#). *Soil Science and Plant Nutrition*, **2018**, 64(2), 156-167.
- [36]. Omokaro, G.O., Osarhiemen, I.O., Idama, V., Airueghian, E.O., West, S.T., Igbigbi, F.E., Nnake, D.C., Obolokor, E., Ahmed, A., Omoshie, V.O., [The role of organic amendments and their impact on soil restoration: A review](#). *Asian Journal of Environment and Ecology*, **2024**, 23, 41-52.
- [37]. Alam, M., Hussain, Z., Khan, A., Khan, M.A., Rab, A., Asif, M., Shah, M.A., Muhammad, A., [The effects of organic amendments on heavy metals bioavailability in mine impacted soil and associated human health risk](#). *Scientia Horticulturae*, **2020**, 262, 109067.
- [38]. Malakar, A., Snow, D.D., Rudnick, D., Maharjan, B., Kaiser, M., Ray, C., [Natural reactive iron dynamics in the agricultural soil of semiarid to arid systems](#). *ACS Agricultural Science & Technology*, **2024**, 4(3), 307-316.
- [39]. Omosebi, J.G., Olorunoje, H.A., Ayodele, M.O., [Evaluation of physicochemical and metallic properties of covered and uncovered groundwater wells in Ado-Ekiti, Nigeria](#). *Eurasian Journal of Science and Technology*, **2025**, 5(4), 385-392.
- [40]. Zondo, S., [Maximum residue limits \(mrls\) of heavy metals in agricultural soil, irrigation water and crops](#). *Research & Technology BULLETIN*, **2021**.
- [41]. Kodani, S., [Characterizing the cycle of heavy metals in horticultural production for mbare musika in harare zimbabwe](#). *African Journal of Agricultural Research*, **2023**, 19(6), 598-614.
- [42]. Adabembe, B.A., Fasinmirin, J.T., Olanrewaju, O.O., Faloye, O.T., [Hydro-physical, hydrophobicity and chemical characterization of drip irrigated soil using aquaculture wastewater under sweet pepper/okra intercrop](#). *Communications in Soil Science and Plant Analysis*, **2022**, 53(18), 2460-2475.

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