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Low-Cost Soilless Lettuce Production under Saline Irrigation Using Local Substrates and a Commercial-Fertilizer Nutrient Solution

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ABSTRACT

Soilless cultivation is a practical option for vegetable production in arid regions where soil salinity and freshwater scarcity limit conventional farming. However, the high cost of imported substrates and specialized nutrient solutions restricts adoption by small growers. This study assessed lettuce (*Lactuca sativa* L.) grown in local low-cost substrates under fresh and saline irrigation. The experiment was conducted at Shambat, Sudan, using a two-factor randomized complete block design with three replicates. Four media were compared: gravel, coarse sand, a Conocarpus-derived biochar-sand mixture, and local clay soil. Fresh water and saline water gradually adjusted to 3 dS m^{-1} were used. A nutrient solution was prepared from commercial fertilizers available in local markets. Under saline irrigation, the biochar-sand medium recorded the highest plant height (18.20 cm), leaf number (13.80 leaves $plant^{-1}$), leaf area (178.4 cm^2), shoot dry weight (12.10 g), root dry weight (2.90 g), and water-use efficiency (1.44 g L^{-1}). Coarse sand also performed well, with 16.80 cm plant height, 158.7 cm^2 leaf area, and the greatest water saving relative to clay soil (18.75%). Clay soil recorded the lowest values under saline irrigation, including plant height (12.10 cm), leaf area (98.6 cm^2), shoot dry weight (6.50 g), and water-use efficiency (0.68 g L^{-1}). The integrated saline performance index ranked biochar-sand first (100/100), followed by coarse sand (74.70/100), gravel (54.71/100), and clay soil (0/100). The biochar-sand medium requires repeated washing before use because residual soluble salts may restrict early establishment. These findings support the use of local substrates and commercial fertilizers as a practical pathway for low-cost lettuce production under moderate salinity in arid environments.

Keywords: lettuce, soilless culture, saline irrigation, local substrates, Conocarpus biochar, commercial fertilizers, water-use efficiency, arid agriculture

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1. INTRODUCTION

Vegetable production in arid and semi-arid regions is under increasing pressure from water scarcity, soil salinity, and the cost of agricultural inputs. In these environments, rainfall is low, evaporation is high, and irrigation is essential for crop production. When marginal or saline water is used, salts can build up in the root zone and reduce plant water uptake, nutrient balance, and growth [1, 2].

Lettuce (*Lactuca sativa L.*) is an important leafy vegetable with a short growth cycle and high market demand. It is sensitive to salinity, particularly during establishment and leaf expansion. Salinity can reduce leaf area, biomass, and market quality because the harvested product depends on rapid vegetative growth [3, 4, 20, 21].

Soilless cultivation is a practical alternative to soil-based production where soils are saline, compacted, poorly drained, or affected by soil-borne diseases. In substrate-based systems, roots grow in materials such as sand, gravel, perlite, cocopeat, rockwool, or organic mixtures, while nutrients are supplied through irrigation water. This allows direct management of water supply, aeration, drainage, pH, and nutrient availability [5, 6].

The use of saline or marginal water in soilless systems has received growing attention. These systems do not remove salinity risk, but they can make it easier to manage when the substrate has good drainage and irrigation is applied carefully. Coarse media such as gravel and sand can help move salts away from the active root zone when leaching and nutrient balance are managed [7, 8].

Adoption of soilless cultivation remains limited among many small-scale farmers because imported substrates and ready-made nutrient solutions are expensive. Materials such as rockwool, perlite, vermiculite, and cocopeat may also be difficult to obtain. Wider adoption requires practical systems based on local materials that can be prepared and managed with low investment [5, 9].

Locally available gravel and coarse sand are attractive because they are stable, simple to wash, and widely available in arid regions. Their main limitation is low nutrient and water retention. Biochar may improve part of this limitation when used as a substrate component, but its effect depends on feedstock, production temperature, particle size, pH, electrical conductivity, soluble salts, and mixing rate [9-17].

In Sudan and similar arid regions, *Conocarpus erectus* is widely planted as an ornamental tree, and pruning produces large amounts of woody biomass. Converting this biomass into biochar can create a local substrate component and reduce waste disposal pressure. Because woody biochar can be alkaline and saline, washing and chemical testing are required before using it with salt-sensitive crops [9-12, 15-17].

The nutrient solution is another key factor in the cost and success of soilless cultivation. A practical option is to prepare nutrient solutions from commercial fertilizers available in local markets. Such formulations must supply the main macro- and micronutrients needed by lettuce, especially nitrogen, potassium, calcium, magnesium, phosphorus, iron, and trace elements [6, 13].

Most previous studies on biochar have focused on its use as a soil amendment rather than as a component of low-cost soilless media. There is also limited practical evidence on systems that combine local substrates, biochar from pruning waste, saline irrigation water, and nutrient solutions prepared from commercial fertilizers [10, 14, 15]. Therefore, this study evaluated the growth and water use of lettuce grown in gravel, coarse sand, a Conocarpus-derived biochar-sand mixture, and local clay soil under fresh and saline irrigation. The study also assessed the practical performance of a nutrient solution prepared from commercial fertilizers. The working hypothesis was that local soilless substrates would support better lettuce growth than clay soil under saline irrigation through improved drainage, aeration, and root-zone conditions.

2. MATERIALS AND METHODS

2. 1. Experimental site and environmental conditions

The experiment was conducted at the Experimental Farm of the College of Agricultural Studies, Sudan University of Science and Technology, Shambat, Khartoum, Sudan (15.65° N, 32.52° E; Figure 1). The study was carried out during the winter growing season from November 2022 to March 2023. The site lies within a semi-desert environment, where irrigation is required for vegetable production because rainfall is limited during the growing season. Air temperature during the experimental period generally ranged from 18 °C to 35 °C.

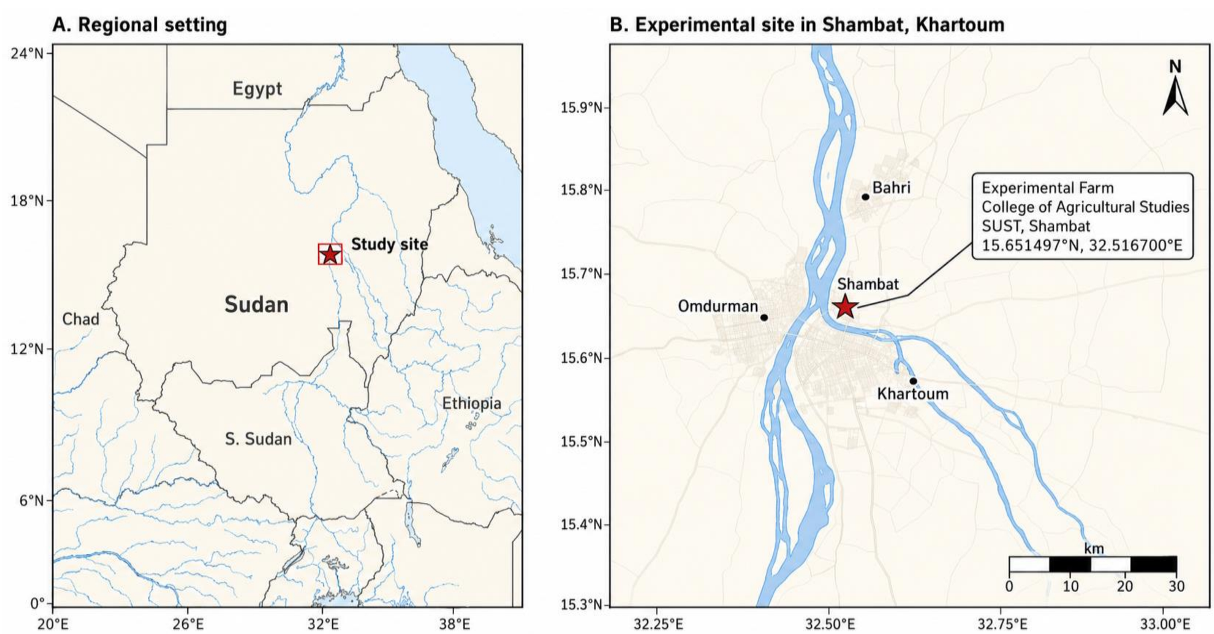

Figure 1. Location map of the lettuce soilless-culture experiment at the Experimental Farm, College of Agricultural Studies, Sudan University of Science and Technology, Shambat, Khartoum, Sudan.

Table 1. Summary of the experimental approach.

Item	Description
Study type	Pot-based substrate culture experiment
Experimental design	Two-factor randomized complete block design

Factors	Growing medium (4 levels) and irrigation-water quality (2 levels)
Replicates	Three
Experimental units	24 pots
Crop	Lettuce (*Lactuca sativa L.*), local cultivar
Main purpose	Test local substrates and a commercial-fertilizer nutrient solution under fresh and saline irrigation

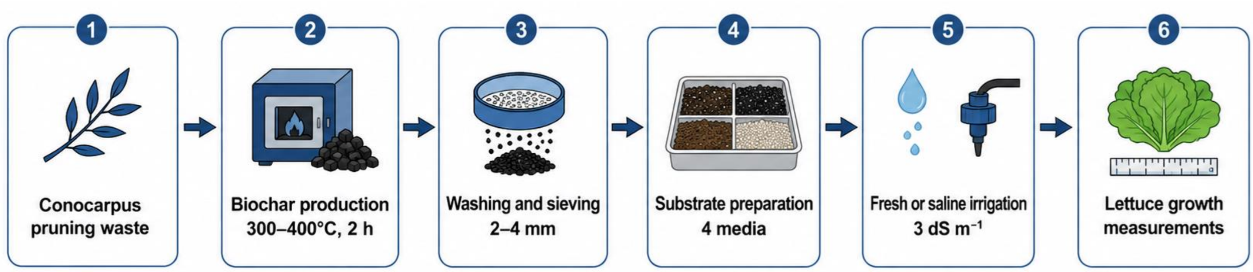

Figure 2. Experimental workflow from biomass collection to plant measurements.

2. 2. Plant material, substrates, and biochar preparation

A local cultivar of lettuce was used because of its short growth cycle, local relevance, and clear vegetative response to growing conditions. Four media were evaluated: gravel, coarse sand, a Conocarpus-derived biochar-sand mixture, and local Shambat clay soil as a control.

Gravel was collected locally, washed thoroughly to remove fine particles, and added to pots at 800 g per pot. Coarse sand was collected from the Tuti area, sieved, and washed five times with distilled water. Shambat soil was collected from the local agricultural area, air-dried, crushed, sieved through a 2-mm sieve, and added to pots at 800 g per pot.

Table 2. Growing media and preparation procedures.

Medium	Source	Preparation	Amount per pot	Role
Gravel	Local gravel	Washed thoroughly	800 g	Inert high-drainage medium
Coarse sand	Tuti area	Sieved and washed five times	800 g	Low-cost coarse substrate
Biochar-sand	Conocarpus biochar + coarse sand	Biochar washed 6-7 times and mixed with sand	600 g biochar + 200 g sand	Organic-mineral substrate component
Shambat soil	Local agricultural soil	Air-dried, crushed, sieved to 2 mm	800 g	Clay soil control

Biochar was produced from pruning waste of *Conocarpus erectus* collected from the university campus. The biomass was cut into 10-15 cm segments and air-dried under direct sunlight for three days. Carbonization was carried out in a traditional kiln under oxygen-limited conditions at approximately 300-400 °C for two hours. After carbonization, the kiln was left to cool for 24 hours. The produced biochar was crushed and sieved to obtain particles of about 2-4 mm. The biochar was soaked and washed 6-7 times using tap water and distilled water before use. The biochar-sand medium was prepared using 600 g biochar and 200 g coarse sand per pot, corresponding to a 3:1 biochar-to-sand ratio by weight.

2. 3. Nutrient solution formulation

The nutrient solution was prepared from commercial fertilizers available in local agricultural-input markets. To reduce precipitation risk, two stock solutions were prepared. Solution A contained calcium nitrate, Fe-EDTA, and the micronutrient mixture. Solution B contained NPK 20-20-20, potassium nitrate, and magnesium sulfate. Before application, the stock solutions were diluted at a 1:10 ratio. The nutrient solution was applied once every five days instead of one regular irrigation event, and the applied volume was adjusted according to plant growth stage.

Table 3. Composition of the commercial-fertilizer nutrient solution.

Fertilizer	Formula or type	Rate ($g\ L^{-1}$)	Stock solution	Main role
Potassium nitrate	KNO_3	1.20	B	N and K source
Calcium nitrate	$Ca(NO_3)2$	3.00	A	N and Ca source
Magnesium sulfate	$MgSO_4$	1.50	B	Mg and S source
NPK fertilizer	20-20-20	2.00	B	Balanced N, P, and K source
Chelated iron	Fe-EDTA 13%	0.15	A	Iron source
Micronutrient mix	Commercial mix	0.25	A	Trace-element source

2. 4. Experimental design and salinity management

The experiment was arranged as a two-factor randomized complete block design with three replicates. The first factor was growing medium with four levels: gravel, coarse sand, biochar-sand mixture, and Shambat clay soil. The second factor was irrigation-water quality with two levels: fresh water with EC ≤ 1 dS m^{-1} and saline water adjusted to 3 dS m^{-1}. The combination of four growing media and two water qualities produced eight treatment combinations and 24 experimental pots.

Saline irrigation water was prepared by adding commercial sodium chloride to fresh water. To reduce osmotic shock, salinity was increased gradually by 500 µS cm^{-1} at each irrigation event until the target EC of 3000 μS cm^{-1} was reached. This level was maintained until the end of the experiment. Pots were irrigated every two days during the cooler part of the season and daily when temperature increased. Water loss was monitored using the pot-weight method, and the difference in pot weight was replaced as irrigation water.

Table 4. Treatment combinations used in the experiment.

Code	Growing medium	Water quality	Target EC	Replicates
G-FW	Gravel	Fresh water	≤ 1 dS m^{-1}	3
G-SW	Gravel	Saline water	3 dS m^{-1}	3
S-FW	Coarse sand	Fresh water	≤ 1 dS m^{-1}	3
S-SW	Coarse sand	Saline water	3 dS m^{-1}	3
BCS-FW	Biochar-sand	Fresh water	≤ 1 dS m^{-1}	3
BCS-SW	Biochar-sand	Saline water	3 dS m^{-1}	3
Soil-FW	Clay soil	Fresh water	≤ 1 dS m^{-1}	3
Soil-SW	Clay soil	Saline water	3 dS m^{-1}	3

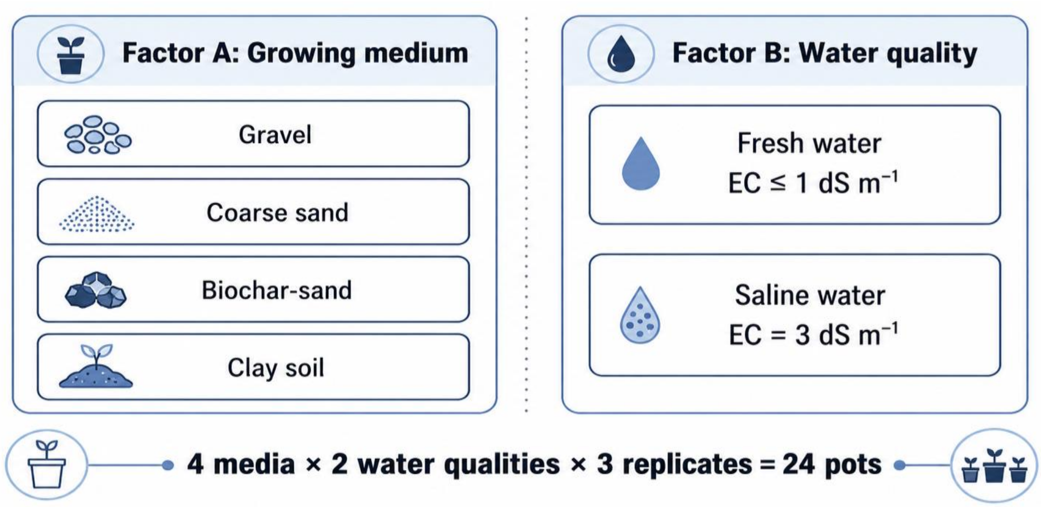

Figure 3. Factorial structure of the experiment.

2. 5. Measurements and data processing

Plant growth was monitored through repeated non-destructive measurements and final harvest measurements. Plant height was measured every three days. Leaf number and leaf area were recorded every seven days. Leaf area was estimated by tracing the largest leaf and calculating its surface area. Stem diameter was measured twice during the experiment using a Vernier caliper. At harvest, plants were separated into shoot and root fractions. Shoot fresh weight, root fresh weight, shoot dry weight, root dry weight, and root length were recorded. Dry weights were determined after oven-drying at 70 °C until constant weight. Water-use efficiency was calculated as shoot dry biomass divided by the total volume of irrigation water applied.

Table 5. Measurement schedule and purpose.

Variable	Timing	Method	Purpose
Plant height	Every 3 days	Ruler	Vegetative growth rate
Leaf number	Every 7 days	Manual counting	Canopy development
Leaf area	Every 7 days	Leaf tracing and area calculation	Leaf expansion
Stem diameter	Twice during the experiment	Vernier caliper	Stem vigor
Water loss	During irrigation events	Pot-weight method	Water use estimation
Shoot and root biomass	At harvest	Fresh and dry weight	Biomass allocation
Root length	At harvest	Manual measurement	Root response to substrate

Treatment means were calculated for growth, biomass, and water-use traits. Relative salinity reduction was calculated as [(fresh-water mean - saline-water mean) / fresh-water mean] × 100. Water saving was calculated relative to the clay-soil treatment under saline irrigation. An integrated saline performance index was calculated using min-max normalization of positive indicators: plant height, leaf number, leaf area, shoot dry biomass, root dry biomass, and water-use efficiency. The index was used as a practical comparative ranking tool across substrates.

3. RESULTS AND DISCUSSION

3. 1. Properties of the growing media

The Conocarpus-derived biochar and the Shambat soil differed strongly in chemical and physical behavior. The biochar was alkaline and retained measurable soluble sodium after repeated washing, while the soil was a heavy clay with moderate alkalinity. These properties are important because substrate pH, electrical conductivity, aeration, drainage, and nutrient retention influence root-zone performance in soilless and container systems [9-11].

Table 6. Chemical properties and interpretive value of Conocarpus-derived biochar.

Property	Mean ± SD	Interpretive value
pH (1:5)	8.97 ± 0.02	Alkaline reaction
EC (μS cm^{-1})	738.3 ± 41.2	Residual soluble salts after washing
Soluble Na (meq L^{-1})	9.17 ± 1.60	Potential early salt constraint
Soluble Ca + Mg (meq L^{-1})	3.33 ± 0.58	Moderate soluble divalent cations
SAR	7.03 ± 0.61	Moderate sodicity indicator
Available P (mg kg^{-1})	21.29 ± 2.68	Potential P contribution

Table 7. Selected physical and chemical properties of Shambat clay soil.

Property	Mean ± SD	Interpretive value
Texture class	Clay	Fine-textured control medium
Clay (%)	53.3 ± 1.15	High water-holding and salt-retention potential
pH (saturated paste)	7.78 ± 0.01	Slightly alkaline
ECe (dS m^{-1})	1.12 ± 0.11	Low baseline salinity
SAR	6.87 ± 1.78	Moderate sodium adsorption indicator
Bulk density (g cm^{-3})	1.27 ± 0.12	Moderate compaction risk
$CaCO_3$ (%)	4.73 ± 0.38	Calcareous condition

3. 2. Growth performance under saline irrigation

Table 8. Lettuce growth traits under saline irrigation (3 dS m^{-1}).

Medium	Plant height (cm)	Leaf number	Leaf area (cm^2)	Stem diameter (mm)
Gravel	15.20	11.50	142.3	7.10
Coarse sand	16.80	12.40	158.7	7.60
Biochar-sand	18.20	13.80	178.4	8.30
Clay soil	12.10	9.20	98.60	5.80

Under saline irrigation, all three soilless substrates maintained higher growth values than clay soil. The biochar-sand medium produced the highest plant height, leaf number, and leaf area among saline treatments, followed by coarse sand. Clay soil produced the lowest values for all measured growth traits under saline irrigation. This pattern indicates that the tested soilless substrates provided a more favorable root-zone environment than the local clay soil [5, 7, 8].

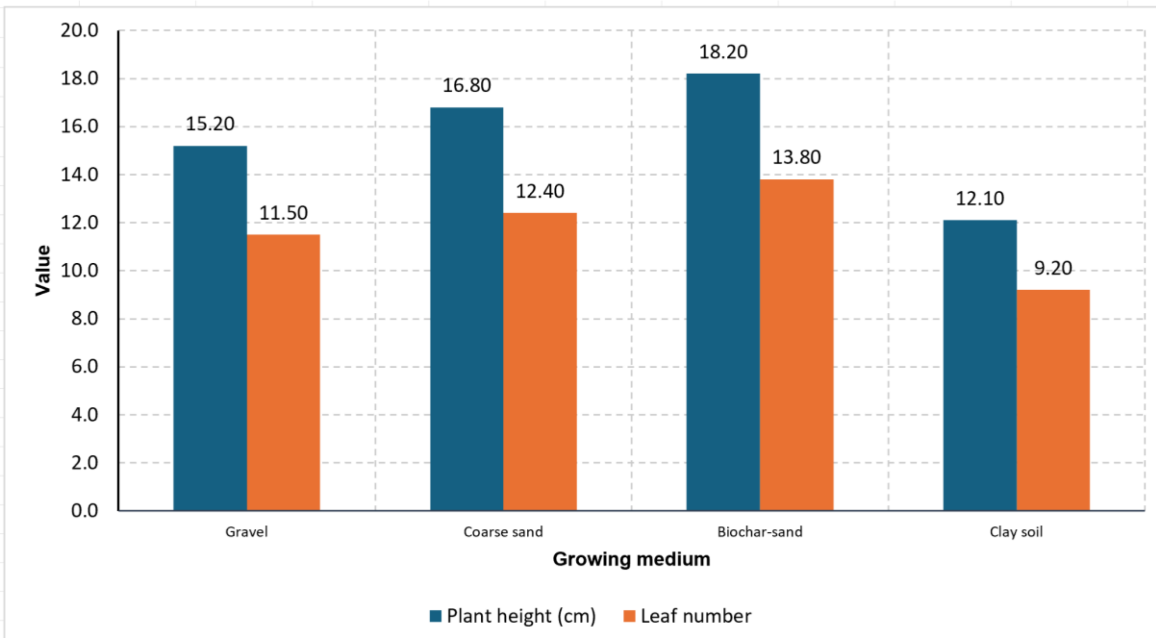

Figure 4. Plant height and leaf number under saline irrigation across growing media.

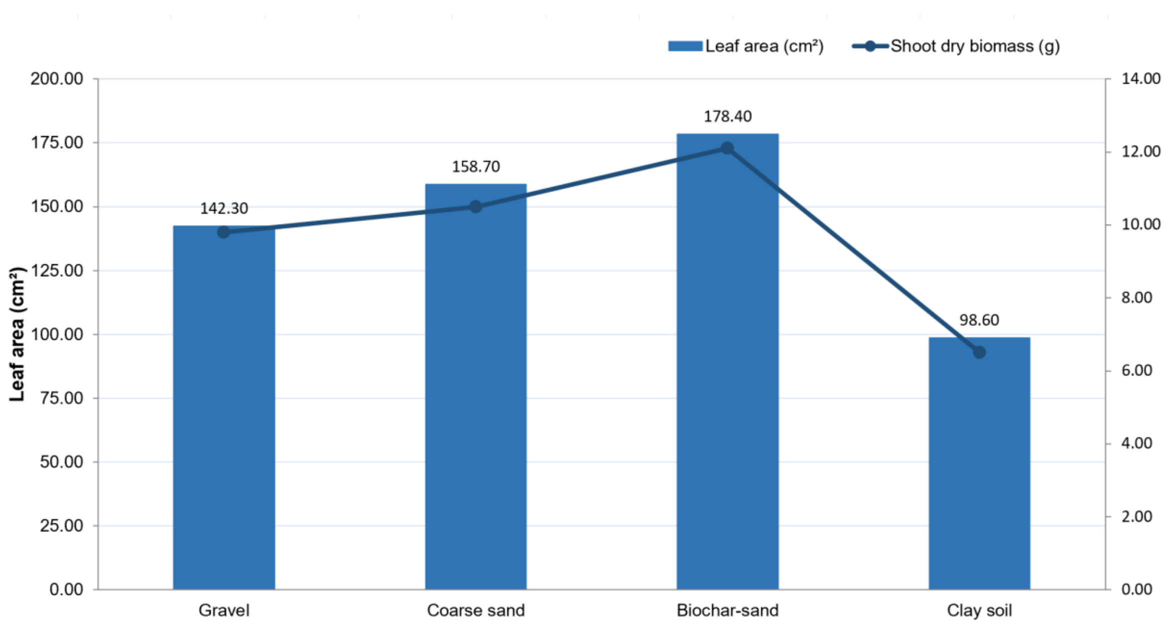

Figure 5. Leaf area and shoot dry biomass under saline irrigation.

3. 3. Salinity-induced reduction within each medium

The relative reduction analysis showed clear differences among media in response to saline irrigation. Clay soil recorded the greatest proportional reduction in leaf area, shoot dry biomass, and root dry biomass. The biochar-sand medium recorded the lowest reduction for these traits, followed by coarse sand. This response suggests that biochar-sand and coarse sand reduced the expression of salinity stress at the plant level through improved substrate conditions [1, 2, 7].

Table 9. Percentage reduction caused by saline irrigation relative to fresh-water treatment.

Medium	Plant height reduction (%)	Leaf area reduction (%)	Shoot dry biomass reduction (%)	Root dry biomass reduction (%)
Gravel	17.39	23.33	20.97	25.00
Coarse sand	12.04	20.01	22.79	22.58
Biochar-sand	10.34	16.05	18.24	17.14
Clay soil	26.67	36.06	36.27	36.36

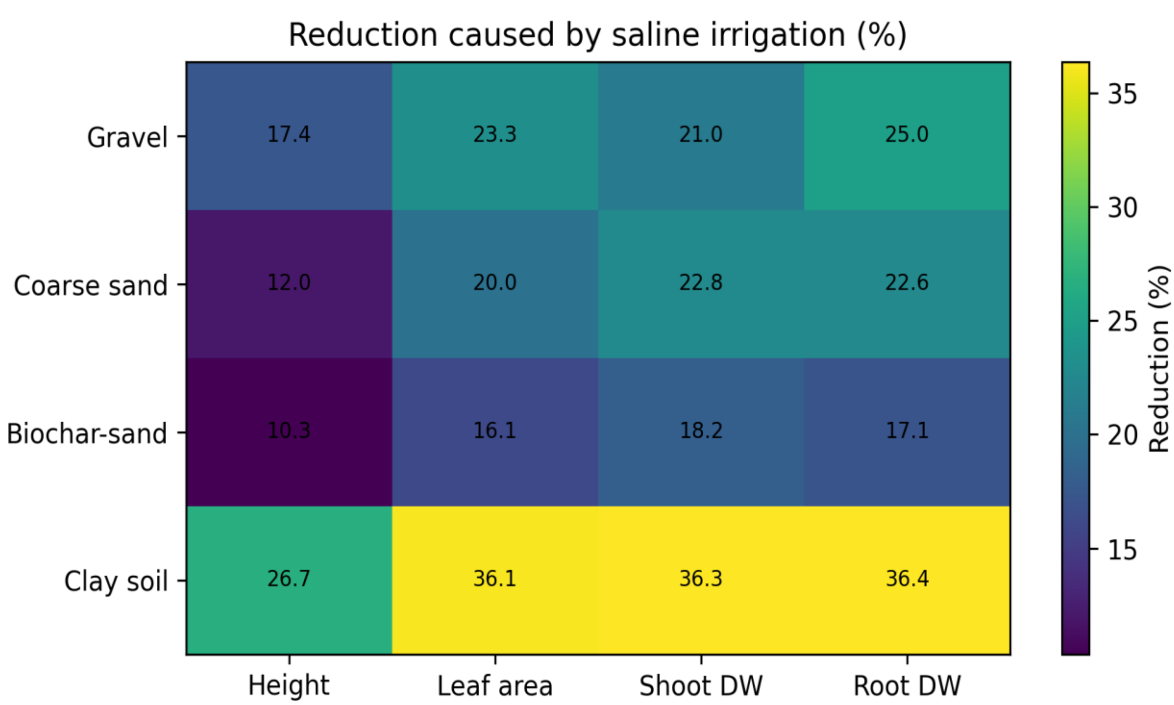

Figure 6. Reduction in selected growth and biomass traits under saline irrigation (%).

3. 4. Biomass production and water-use efficiency

Shoot and root biomass followed the same general trend observed for leaf development. Under saline irrigation, the biochar-sand medium produced the highest shoot fresh weight, shoot dry weight, root fresh weight, and root dry weight. Coarse sand ranked second, while clay soil produced the lowest biomass values. These differences indicate that substrate choice influenced both canopy growth and root development under moderate salinity [4, 14, 16].

Table 10. Shoot and root biomass under saline irrigation.

Medium	Shoot fresh weight (g)	Shoot dry weight (g)	Root fresh weight (g)	Root dry weight (g)
Gravel	112.6	9.80	22.10	2.10
Coarse sand	124.8	10.50	24.50	2.40
Biochar-sand	142.5	12.10	29.80	2.90
Clay soil	78.40	6.50	14.80	1.40

Water-use efficiency varied among the saline treatments. The biochar-sand medium had the highest WUE, followed by coarse sand and gravel. Clay soil had the lowest WUE because it combined higher water application with lower shoot dry biomass. Coarse sand showed the highest water saving relative to clay soil, followed by gravel and biochar-sand.

Table 11. Water application, shoot dry biomass, WUE, and water saving under saline irrigation.

Medium	Total water applied (L)	Shoot dry weight (g)	WUE ($g\ L^{-1}$)	Water saving vs clay soil (%)
Gravel	8.20	9.80	1.19	14.58
Coarse sand	7.80	10.50	1.35	18.75
Biochar-sand	8.40	12.10	1.44	12.50
Clay soil	9.60	6.50	0.68	0.00

3. 5. Integrated substrate ranking under saline irrigation

The integrated saline performance index ranked biochar-sand first, followed by coarse sand, gravel, and clay soil. This ranking combined growth, biomass, and water-use traits into one comparative index. The index provides a practical summary of substrate performance under saline irrigation and supports the selection of biochar-sand and coarse sand as promising low-cost media for further testing.

Table 12. Integrated performance ranking of growing media under saline irrigation.

Medium	Integrated saline performance index (0-100)
Biochar-sand	100.0
Coarse sand	74.70
Gravel	54.71
Clay soil	0.00

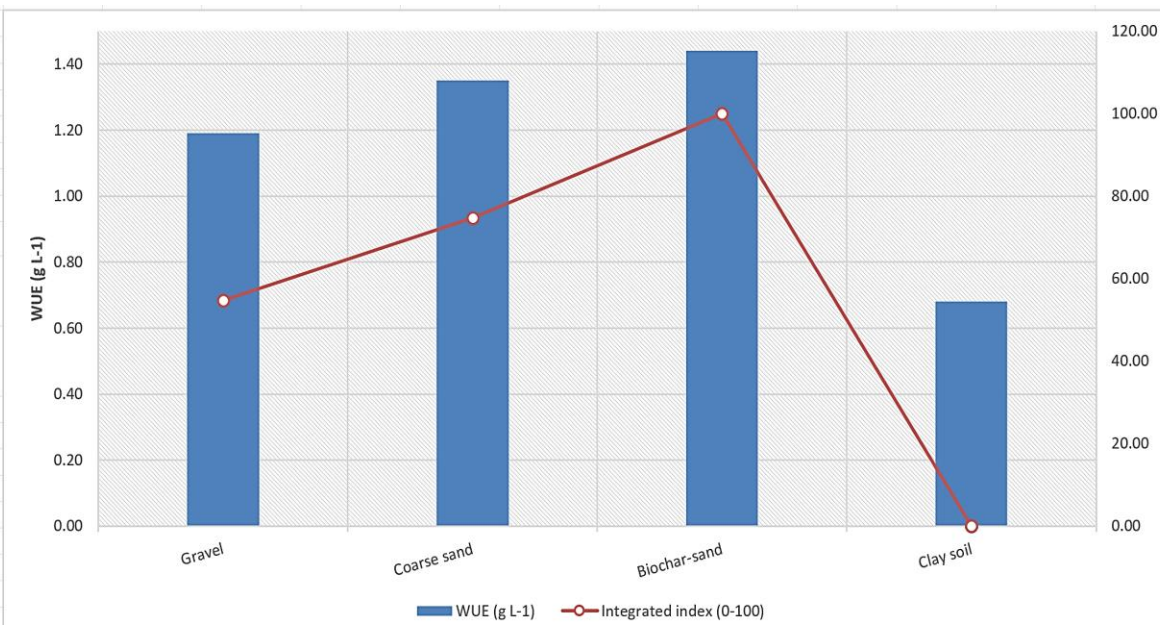

Figure 7. Water-use efficiency and integrated substrate ranking under saline irrigation.

3. 6. Interpretation of substrate performance

The results show that low-cost soilless substrates can support lettuce production under moderate saline irrigation. The main advantage of the tested media was the creation of a more favorable root-zone environment than the clay soil control. In substrate culture, root-zone conditions are strongly influenced by pore distribution, drainage, aeration, irrigation frequency, and nutrient management [5, 6, 8].

The weaker performance of clay soil under saline irrigation is consistent with the general response of plants to salinity. Salt stress reduces growth through osmotic limitation, ion-related stress, and nutrient imbalance, especially in salt-sensitive crops [1-4]. In this study, clay soil had a high clay content and a higher water requirement under saline irrigation. This combination likely increased root-zone constraints and reduced vegetative growth compared with coarse soilless substrates.

The biochar-sand mixture showed the strongest overall performance under saline irrigation. Biochar can increase water and nutrient retention when added to coarse substrates, but its effect depends on feedstock, production temperature, pH, electrical conductivity, particle size, and application rate [9-12]. In this study, the biochar was alkaline and contained residual soluble salts after washing. This confirms the importance of washing and chemical testing before using woody biochar with salt-sensitive crops.

Coarse sand performed well in plant height and water saving. This result is important because sand is locally available, inexpensive, easy to wash, and simple to handle. Its limitation is weak nutrient buffering capacity, which means that plant performance depends on regular nutrient solution application. Gravel showed similar practical advantages in drainage and simplicity, although its lower water and nutrient retention capacity may limit biomass production compared with biochar-sand.

Table 13. Practical interpretation of substrate performance for low-cost lettuce production.

Medium	Main strength	Main limitation	Practical recommendation
Gravel	Good drainage; simple and available	Low nutrient retention	Use with regular fertigation
Coarse sand	Strong plant height and water saving	Low nutrient buffering capacity	Promising low-cost option for simple systems
Biochar-sand	Best integrated saline performance	Residual salts and high pH require washing	Promising after washing and EC testing
Clay soil	Familiar local soil medium	High clay content and greater salinity risk	Avoid under saline irrigation unless drainage is improved

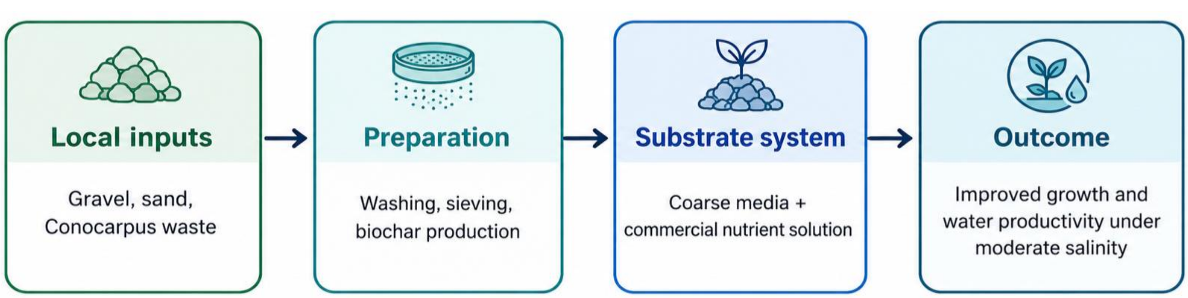

Figure 8. Conceptual interpretation of the low-cost soilless production pathway.

The commercial-fertilizer nutrient solution is an important applied contribution of the study. In low-resource settings, specialized hydroponic solutions can be expensive or difficult to access. The use of potassium nitrate, calcium nitrate, magnesium sulfate, NPK fertilizer, Fe-EDTA, and micronutrients provides a practical route for preparing a local nutrient solution. Nutrient solutions in soilless culture should be matched to crop demand, water quality, substrate behavior, and production system [6, 13, 17].

Water-use efficiency is a critical outcome for arid-region horticulture. The higher WUE observed in biochar-sand and coarse sand under saline irrigation reflects the combined effect of greater biomass production and efficient water application. This finding supports the use of substrate-based cultivation where water scarcity limits conventional production [5, 19].

3. 7. Low-cost production pathway

The low-cost value of the system comes from replacing imported substrates and specialized nutrient formulations with locally available materials and commercial fertilizers. The system does not depend on high-grade substrates such as rockwool or perlite. Instead, it uses gravel, coarse sand, and biochar produced from pruning waste. The nutrient solution is also prepared from fertilizers commonly used in local agricultural markets. This structure can reduce input barriers for small growers while keeping the production system technically manageable.

Table 14. Input-localization pathway supporting the low-cost production concept.

Input component	Conventional high-cost route	Local route tested	Practical implication
Growing medium	Imported rockwool, perlite, or cocopeat	Gravel, coarse sand, and Conocarpus-derived biochar-sand	Lower substrate dependence
Biochar source	Purchased substrate amendment	Conocarpus pruning waste converted to biochar	Waste valorization
Nutrient solution	Ready-made hydroponic formulations	Commercial fertilizers prepared as two stock solutions	Lower formulation barrier
Salinity management	Fresh water preference	Gradual adjustment to 3 dS m-1 using NaCl	Moderate-salinity testing
Water management	Automated fertigation systems	Manual irrigation guided by pot-weight method	Simple small-scale management

4. CONCLUSIONS

This study demonstrates the potential of locally available substrates for developing low-cost soilless lettuce production systems under moderate saline irrigation. Compared with local clay soil, the tested soilless media provided a more suitable root environment through better drainage and aeration. Coarse sand supported strong plant height and water saving, while the

Conocarpus-derived biochar-sand mixture improved leaf area, leaf number, biomass production, and integrated saline performance.

The commercial-fertilizer nutrient solution supported lettuce growth across the tested substrates, indicating that locally available fertilizers can reduce the input barrier of substrate-based cultivation. This finding is important for small growers in regions where imported substrates and ready-made hydroponic formulations are expensive or difficult to obtain.

The biochar-sand mixture showed practical value, but its initial salt content remains a key management point. Repeated washing and chemical characterization are necessary before using Conocarpus-derived biochar as a substrate component for salt-sensitive crops. Overall, the findings support the use of local substrates and commercial fertilizers as a practical pathway for low-cost lettuce production under moderate salinity in arid and semi-arid regions.

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