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Economic and environmental comparison of open field and screenhouse vegetable farming in Nigeria

Taiwo Bintu Ayinde[1*], **Charles F. Nicholson**[2,3], **Benjamin Ahmed**[4]

1 Samaru College of Agriculture, Division of Agricultural Colleges, Ahmadu Bello University, (ABU) Zaria, Zaria, Nigeria, **2** Department of Agricultural and Applied Economics, University of Wisconsin-Madison, Madison, Wisconsin, United States of America, **3** School of Integrative Plant Science, Cornell University, Ithaca, New York, United States of America, **4** Department of Agricultural Economics, ABU Zaria, Zaria, Nigeria

* taiyeayinde2006@yahoo.com

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Abstract

This study compares screenhouse, rainfed, and irrigated vegetable farming systems in Northwest Nigeria, focusing on their economic and environmental performance. Screenhouse farming demonstrates superior yield, cost-efficiency, and sustainability, producing up to 90% more saleable output than rainfed systems and using over 95% less water per kilogram of produce. Although initial investment is higher over 600% more than rainfed farming screenhouse systems emit less than 5% of the greenhouse gases associated with conventional open-field production. Rainfed farming, while low-cost, suffers from poor resource efficiency and low productivity. Irrigated systems offer moisture stability but require substantial water and energy inputs. These findings highlight the potential of screenhouse farming and the importance of adopting sustainable irrigation strategies such as drip systems, fertigation, and rainwater harvesting to enhance long-term resilience and efficiency in vegetable production.

1. Introduction

Vegetables and fruits are essential components of global food systems, yet they contribute significantly to food miles and transport-related emissions due to their high water content and reliance on refrigeration (Carbon [1]. Leafy vegetables such as cabbage (*Brassica oleracea var. capitata*), lettuce (*Lactuca sativa*), and spinach (*Spinacia oleracea*) are nutrient-rich but require frequent irrigation and have short shelf lives, increasing spoilage risks [2,3]. Pulpy vegetables like eggplant (*Solanum melongena*), cucumber (*Cucumis sativus*), and pumpkin (*Cucurbita pepo*) offer longer shelf life and greater resilience in warmer climates [4,5], making them vital for food security in arid regions [6].

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Nigeria's vegetable market is expanding rapidly, driven by rising domestic demand. By 2025, vegetable revenue is projected to reach $31.52 billion, growing at an annual rate of 11.33% [7,8]. However, traditional open-field farming whether rainfed or irrigated faces challenges including climate variability, inefficient resource use, and low productivity [9,10]. Rainfed systems are vulnerable to erratic rainfall, while irrigated systems improve yield stability but consume substantial water.

Controlled Environment Agriculture (CEA), including screenhouse farming, offers a promising alternative by optimizing growing conditions and reducing environmental impact. Techniques such as hydroponics, aeroponics, and aquaponics have demonstrated improved water-use efficiency and reduced pest exposure [11]. However, CEA systems are energy-intensive and require substantial capital investment, raising questions about their feasibility in low-resource settings [12,13].

Innovations such as drip irrigation, fertigation, and rainwater harvesting have shown promise in improving water-use efficiency and yield [14]. Organic fertilizers and improved soil amendments also contribute to long-term sustainability [15,16]. Despite these advancements, most recent studies tend to focus on individual technologies or single crop types, without offering integrated assessments across diverse vegetable categories. For example, Fuentes-Peñailillo et al. [17] reviewed soilless systems like hydroponics and aeroponics, but emphasized their application to specific crops. Ogbonna et al. [12] examined greenhouse farming in Nigeria, focusing primarily on leafy vegetables, while Jadhav et al. [14] and Demir et al., [18], explored irrigation strategies for cabbage alone. These examples highlight a gap in comparative research that evaluates multiple farming systems and vegetable types within a unified framework particularly in the Nigerian context.

In Nigeria, crops like cabbage and cucumber are economically significant. Cucumber, in particular, is known as the "Farmers' ATM" due to its short growth cycle and profitability [19]. Yet, data on the environmental impact of these crops under different farming systems remains limited. This study addresses that gap by providing evidence-based insights into the trade-offs between productivity, cost, and sustainability across farming methods.

By focusing on Kudan Local Government Area in Kaduna State, this research aims to provide localized recommendations for policymakers, farmers, and investors. The goal is to support informed decision-making that promotes sustainable agriculture, enhances food security, and reduces environmental impact in Nigeria's vegetable production landscape.

2. Materials and methods

This study was conducted in Kudan Local Government Area (LGA) of Kaduna State, Nigeria, located at latitude 11°16'23"N and longitude 7°47'56"E. The region spans approximately 400 square kilometers and experiences two distinct seasons dry and rainy which significantly influence agricultural cycles [20]. Kudan LGA was selected as a representative semi-arid agroecological zone where challenges such as erratic rainfall, limited irrigation infrastructure, and low adoption of climate-smart technologies are particularly pronounced. Nigeria, as one of Africa's largest vegetable producers, faces persistent issues in sustainable agriculture, including inefficient water use, high post-harvest losses, and slow uptake of climate-resilient practices [21–24]. These challenges are exacerbated in regions like Kudan, where smallholder farmers dominate and rely heavily on rainfed systems, making it an ideal case study for evaluating environmental and economic performance across farming systems.

The survey was conducted during the 2024/2025 crop season, and all revenues and costs reported in this study refer specifically to that production year. Sampling involved 125 smallholder farmers cultivating the selected vegetable types leafy (cabbage, lettuce, spinach) and pulpy (eggplant, cucumber, pumpkin) across the LGA. Random sampling was applied to rainfed and irrigated open-field systems, while the Controlled Environment Agriculture (CEA) model was purposively selected from the NAERLS poly-tunnel facility at Ahmadu Bello University (ABU) Zaria, which provides a standardized hybrid cultivation environment.

Primary data were collected through face-to-face interviews, field assessments, and production records, focusing on inputs, yields, water use, and energy consumption. Revenue estimates were based on actual harvests and prevailing market prices during the 2024/2025 season. This approach ensured that both economic and environmental indicators were grounded in real farm-level practices.

To address these concerns, the study evaluates three distinct vegetable production systems: rainfed open-field farming, irrigated field-based cultivation (locally known as "*Fadama" or "Lam-bu*"), and screenhouse farming, a form of Controlled Environment Agriculture (CEA). The functional unit for comparison is defined as one kilogram of saleable, unprocessed vegetable produce. This unit allows for standardized assessment across systems and crops. The vegetable types selected leafy (cabbage, lettuce, spinach) and pulpy (eggplant, cucumber, pumpkin) reflect both nutritional importance and agronomic diversity. Leafy vegetables are fast-growing and sensitive to water stress, while pulpy vegetables require longer maturation and are more drought-tolerant [3], making them ideal for comparative analysis in semi-arid conditions [16].

Rainfed and irrigated farming systems in Kudan are widely practiced, with approximately 98% of vegetable farmers relying on open-field methods [25]. During the dry season, which spans October to April, irrigated farming becomes essential. Flood irrigation using shared wells typically one well per ten farmers is the most common technique, employed by over 95% of producers (Table A in S1 Text). In contrast, screenhouse farming utilizes drip irrigation and fertigation, enabling year-round cultivation and significantly higher productivity [5]. Leafy vegetables like lettuce and spinach can be grown 5–8 times annually in screenhouses, while pulpy crops such as cucumber and eggplant support 3–6 cycles [26,27]. Pumpkin, due to its size and growth duration, supports only 2–4 cycles per year (Table A in S1 Text).

Farmers in the region often use open-pollinated varieties due to affordability [19,28–34], although hybrid seeds offer superior yield and pest resistance [30]. Land preparation is relatively less labor-intensive compared to rainforest zones, with ox-drawn implements commonly used for tillage, ploughing, and harrowing. Pulpy vegetables thrive in sandy loamy soils with a pH range of 5.5–6.7, enriched with organic matter to promote high yields. In open-field systems, pesticide application is critical due to the lack of protective coverings. Soil amendments such as nematicides and chicken manure (1–6 tonnes per hectare) are applied to enhance fertility, water retention, and pest control. Fertilizer regimes follow a growth-stage approach: phosphates for early development, nitrogen for leaf expansion, and potassium and calcium for fruiting and stress resistance. Calcium, though essential for fruit longevity, is often underutilized.

Cucumber is typically direct-sown to avoid transplant shock, while other crops may be raised in nurseries. Proper spacing ensures optimal air circulation and nutrient uptake. For example, cabbage is spaced at 45–60 cm between plants and 60–75 cm between rows, supporting 22,000–29,000 plants per hectare. Lettuce and spinach, with higher density requirements, can reach up to 333,000 plants per hectare. Pulpy vegetables like cucumber, eggplant, and pumpkin require wider spacing due to their growth habits, with pumpkin supporting only 2,000–5,000 plants per hectare (Table B in S1 Text) [31–48].

Cucumber yields in Nigeria range from 5,000–99,000 kg per hectare, with 99–247 bags harvested depending on agronomic practices. However, post-harvest losses remain a major concern, with up to 50% of fresh produce lost due to poor handling, storage, and transportation. Additionally, non-production areas such as parking and loading zones consume up to 56% of total farm space, reducing effective cultivation area [49]. Staking is essential for pulpy vegetables to prevent fruit rot and disease, yet many farmers neglect this practice. Materials like bamboo, ropes, and nets are used to support plant structure and improve fruit quality (Table B in S1 Text).

Screenhouse farming in this study employs NAERLS freestanding structures measuring 147 m² (approximately 0.0147 hectares), similar to hoop-style houses described in previous research. These structures feature insect-proof netting that creates a regulated microclimate, optimizing temperature, humidity, light penetration, and airflow (Table B in S1 Text). This setup reduces pesticide reliance and promotes healthier crops. Screenhouses also support intensive production with high input efficiency and dense planting [50]. Despite their advantages, adoption remains low in Nigeria due to high initial investment costs and limited technical expertise.

2.1. Assessment of economic and environmental metrics

This study evaluates the economic and environmental performance of leafy (cabbage, lettuce, spinach) and pulpy vegetables (cucumber, eggplant, pumpkin) across three farming systems: screenhouse, rainfed, and irrigated. The analysis focuses on profit as the primary measure of economic performance, alongside yield efficiency and energy demand to compare sustainability and profitability. Profit was determined as the difference between total revenue calculated from actual harvest volumes multiplied by prevailing market prices during the 2024/2025 crop season and total production costs, which included inputs such as seeds, fertilizers, pesticides, labor, irrigation, and, in the case of screenhouses, structural investment. This approach ensures that the economic assessment reflects the real financial outcomes experienced by farmers under each production system.

To ensure consistency and comparability, the analysis is based on a functional unit of one kilogram of saleable, unprocessed vegetable produce. Data were collected per hectare (or per 0.0147 ha for screenhouse systems) and standardized across crop types and farming methods. For international readability, all costs originally reported in Nigerian Naira (₦) were also converted into U.S. dollars (USD) and euros (EUR) using the average exchange rate from January to March 2025, where ₦1 ≈ 0.00065 USD ≈ 0.00060 EUR [51]. Table 1 outlines the core variables used in the evaluation.

To strengthen the reliability of this comparative framework, the study incorporates statistical and economic tools. A one-way analysis of variance (ANOVA) was applied to test for significant differences in cost efficiency across the three farming systems. Additionally, a sensitivity analysis was conducted to evaluate the robustness of each system's profitability under

Table 1. Sample Economic and Environmental Metrics Across Farming Systems.

Variable	Screenhouse	Rainfed	Irrigated
Crop Type	Cabbage, Lettuce, Spinach; Cucumber, Eggplant, Pumpkin	Cabbage, Lettuce, Spinach; Cucumber, Eggplant, Pumpkin	Cabbage, Lettuce, Spinach; Cucumber, Eggplant, Pumpkin
Production Cost (₦/ha)	₦5,342,973 ≈ $3,580/ €3,045 (screenhouse structure + inputs)	₦698,972 ≈ $470/ €398 (basic inputs, no irrigation)	₦1,245,000 ≈ $835/ €710 (includes irrigation setup)
Yield (kg/ha/yr)	80,000–120,000 (leafy); 60,000–90,000 (pulpy)	15,000–25,000 (leafy); 10,000–20,000 (pulpy)	35,000–60,000 (leafy); 30,000–50,000 (pulpy)
Saleable Output (%)	85–95%	60–75%	70–85%
Energy Demand (MJ/kg)	0.09–0.15 (leafy); 0.12–0.25 (pulpy)	~0.01 (minimal energy use)	0.5–1.2 (diesel/electric pump usage)
Water Use (L/ha/day)	50,000–90,000	30,000–65,000	45,000–80,000
GHG Emissions (CO_2-eq/kg)	3.24 (lettuce); 5.10 (cucumber)	118.25 (lettuce); 140.00 (pumpkin)	45.00 (lettuce); 60.00 (pumpkin)

* Note: Exchange rate based on average values from January–March 2025: ₦1 ≈ 0.00067 USD ≈ 0.00057 EUR.

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variable market price scenarios. The price range adopted (₦400, ₦600, ₦800, and ₦1000/kg) reflects the typical farm-gate and retail price fluctuations observed for vegetables in Kaduna State and surrounding markets during the 2024/ 37 crop season. These values capture both the lower-bound prices often experienced during peak harvest (₦400–₦600/kg) and the higher-bound prices recorded during periods of scarcity or off-season production (₦800–₦1000/kg). By incorporating this range, the analysis accounts for realistic market dynamics and provides a rigorous foundation for interpreting the trade-offs between cost, yield, and sustainability, while identifying the most resilient and economically viable production models.

Screenhouse farming offers higher productivity and lower emissions but requires substantial investment. Rainfed farming is cost-effective but less reliable and environmentally efficient. Irrigated farming balances yield and cost but has higher energy and water demands. The integration of ANOVA and sensitivity analysis ensures that these comparisons are not only descriptive but statistically and economically grounded

2.2. Production costs

2.2.1. Fixed costs. Fixed costs are those expenses that do not vary with the level of output in the short run and remain constant regardless of production volume. In this study, fixed costs include land rental, infrastructure (such as drip and flood irrigation systems, wells), and equipment (tools, pumps, tanks). For screenhouse farming, fixed costs are substantially higher due to the initial investment required for protected cultivation structures. These costs were determined based on prevailing rental rates, market prices of infrastructure and equipment, and documented investment records provided by farmers and the NAERLS facility (Table C in S1 Text and Table D in S1 Text).

2.2.2. Variable costs. Variable costs are expenses that change directly with the scale of production and increase as output expands. In this study, variable costs include recurring expenditures such as seeds, fertilizers (NPK, calcium-magnesium, potassium humate), chicken manure, pesticides, and labor. Irrigation costs (diesel and electricity) were also included and calculated seasonally per hectare to ensure comparability across farming systems. These costs were determined through farmer interviews, field assessments, and production records collected during the 2024/2025 crop season (Table C in S1 Text and Table D in S1 Text).

2.2.3. Yield and saleable output. Yield is measured in kg/ha/year, with saleable output representing market-ready produce. Farmers in Kudan LGA primarily sell their vegetables through local markets, farm-gate sales to traders, and, in the case of higher-quality produce (especially from screenhouses), to supermarkets and institutional buyers in nearby urban centers such as Zaria and Kaduna. These established marketing channels provide the basis for determining the prevailing farm-gate and retail prices used in this study. This framework enables cost-per-unit analysis and highlights differences in productivity and profitability across systems (Table C in S1 Text and Table D in S1 Text).

2.3. Cumulative energy demand

Energy consumption is assessed for diesel and electric pumps in screenhouse and irrigated farming. Rainfed systems, which do not use pumps, have lower direct emissions (Table E in S1 Text).

2.3.1. Plant density & area. Screenhouse farming operates on 0.0147 ha, while irrigated systems span 1 ha. Leafy vegetables show higher densities in irrigated fields (up to 250,000 plants/ha), while screenhouses support fewer plants. Pulpy vegetables have lower densities overall (Table F in S1 Text).

2.3.2. Diesel & electric use. Diesel usage is calculated using a standard energy value of 35.8 MJ/L, with metrics including seasonal fuel use, daily consumption, and MJ/kg yield efficiency. Electric pump demand is measured in kWh/ha, with conversion to MJ for comparison (Table F in S1 Text). Average seasonal usage ranges from 250–350 kWh, with costs varying by user type (₦23.59/kWh for households, ₦38.53/kWh for businesses) [31].

2.3.3. Comparative insights. Screenhouse farming, though more intensive, offers precision irrigation benefits. Rainfed farming has minimal energy demand but lower yield efficiency. The analysis provides a comprehensive view of energy sustainability across systems (Table E in S1 Text).

2.4. Global Warming Potential (GWP)

This section evaluates greenhouse gas (GHG) emissions from nitrogen inputs across irrigated, rainfed, and screenhouse vegetable farming systems. Using Tier 1 IPCC methods, direct and indirect nitrous oxide (N_2O) emissions were calculated based on synthetic fertilizers (e.g., NPK 15-15-15, 20-10-10) and organic manure applications (Table G in S1 Text) Synthetic fertilizers have a 4% emission factor, while chicken manure emits at 20% [41].

To assess climate impact, emissions were converted to CO_2-equivalents using GWP values: 298 for N_2O, 0.014 for NH_3, and 0.001 for NO_3 (Table H in S1 Text). Diesel use in irrigated systems (375.6 L/ha) and screenhouse farming (7.51 L/0.0147 ha) also contributes to emissions, with CO_2, CH_4, and N_2O outputs quantified [22,23]. Nigeria's energy-related emissions were referenced using IRENA data (2024) [52].

Nitrogen input levels were tracked per crop and system, and emissions were calculated over a 100-year horizon. This analysis supports sustainable fertilizer strategies that reduce emissions while maintaining productivity (Table H in S1 Text).

2.5. Water Use (WU)

Water consumption in vegetable farming varies by crop type and production system. Rainfed and irrigated methods operate on a 1-hectare scale, while screenhouse farming uses a smaller, controlled 0.0147-hectare area with drip fertigation. Leafy vegetables require moderate water due to shorter growth cycles, while pulpy vegetables demand more due to longer maturation periods (Table I in S1 Text). Daily water use ranges from 30,000–65,000 L/ha for rainfed, 45,000–80,000 L/ha for irrigated, and 50,000–90,000 L/ha for screenhouse systems. Rainfed farming has the lowest irrigation demand but is less reliable due to seasonal rainfall. Irrigated systems offer moisture stability, and screenhouses provide precise water delivery for year-round cultivation. Understanding these water needs is essential for improving resource efficiency, especially in water-scarce areas like Kudan LGA (Table I in S1 Text).

3. Results and discussion

3.1. Results

A comparative analysis of leafy (Table C in S1 Text) and pulpy (Table D in S1 Text) vegetable production across screenhouse, rainfed, and irrigated systems reveals substantial differences in cost, yield, and profitability. Fixed costs are highest in screenhouse farming (₦4.7 million/ha), primarily due to infrastructure investments such as drip irrigation systems and screenhouse structures. In contrast, rainfed and irrigated systems require far less capital, with fixed costs of ₦145,250 and ₦942,750/ha, respectively. Variable costs are relatively consistent across crops, averaging ₦640,646.68/ha in screenhouse, ₦553,722.33/ha in rainfed, and ₦1,091,395.01/ha in irrigated systems.

Despite its higher upfront costs, screenhouse farming delivers substantially greater yield efficiency [32]. Annual yields reach up to 26,600 kg/ha for spinach and 21,000 kg/ha for cucumber, compared to just 700–850 kg/ha in rainfed and 2,000–2,300 kg/ha in irrigated systems. These differences are largely attributed to the controlled environment and multiple cropping cycles supported by screenhouse systems. However, other agronomic variables likely contributed to the observed outcomes. For instance, the use of hybrid seed varieties in screenhouse farming such as Tycoon F1 cabbage and Greengo F1 cucumber offers superior germination rates, disease resistance, and faster maturation compared to the open-pollinated varieties (OPVs) commonly used in rainfed and irrigated systems.

Additionally, labor input and technical expertise may have influenced productivity. Screenhouse farming often involves more skilled labor, precise planting techniques, and consistent monitoring, which can improve plant health and reduce losses. In contrast, rainfed systems typically rely on less intensive labor and are more vulnerable to environmental stressors such as erratic rainfall and pest outbreaks.

Economic analysis further highlights screenhouse profitability. Cost per kilogram of saleable produce was lowest in screenhouse farming ₦611/kg for cabbage, ₦445/kg for lettuce, ₦402/kg for spinach, ₦509/kg for cucumber, ₦703/kg for eggplant, and ₦913/kg for pumpkin compared to rainfed costs exceeding ₦1,700/kg and irrigated costs nearing ₦1,800/kg. To statistically validate these differences, a one-way ANOVA was conducted on cost per kilogram across farming systems (Table 2). The results yielded an F-statistic of 58.42 and a p-value < 0.001, confirming that the differences are statistically significant. Screenhouse farming recorded the lowest mean cost per kilogram (₦597.17), compared to ₦1,850.00 in rainfed and ₦1,897.00 in irrigated systems (Table 2).

To assess economic resilience, a sensitivity analysis was performed across four market price scenarios (₦400, ₦600, ₦800, and ₦1000/kg), reflecting the typical farm-gate and retail price fluctuations observed during the 2024/ 37 crop season Screenhouse farming became profitable for most crops at ₦600–800/kg, while rainfed systems remained unprofitable even at ₦1000/kg due to low yields and high unit costs. Irrigated systems showed moderate profitability but required higher market prices to break even (Table 3). For example, screenhouse lettuce yielded a profit of ₦4.26 million/ha at ₦800/kg, while rainfed lettuce remained in deficit even at ₦1000/kg. These results confirm that screenhouse farming is not only efficient but also robust under fluctuating market conditions.

Hybrid varieties such as Tycoon F1 cabbage, Tropicana F1 lettuce, and Jacqueline F1 pumpkin enhance resilience and yield, outperforming OPVs used in traditional systems. Precision irrigation and fertigation in screenhouses further improve nutrient delivery and reduce water waste, contributing to higher productivity and resource efficiency.

From a sustainability perspective, screenhouse farming offers superior cost efficiency, higher profitability, and better resource use. Rainfed systems, while cheaper to operate, suffer from low yields and high unit costs, making them less viable for commercial-scale production. Irrigated farming ensures moisture stability but remains water-intensive and less efficient. Overall, the integration of environmental control, improved seed genetics, skilled labor, and agronomic precision explains the compounded advantage of screenhouse farming over conventional systems. The statistical and economic analyses reinforce its position as the most resilient and scalable model for vegetable production in Nigeria.

Cumulative Energy Demand (CED)

Energy consumption varies significantly across systems. Rainfed farming has the lowest energy demand due to reliance on natural rainfall (e.g., 0.41–0.72 MJ/kg), while irrigated farming shows the highest due to pump usage (up to 10,568 MJ/ha for pumpkin). Screenhouse farming, despite its intensive setup, maintains low energy use per kilogram (e.g., 0.09 MJ/kg for spinach and 0.20 MJ/kg for cucumber), due to efficient irrigation and climate control.

Overall, screenhouse farming emerges as the most productive and sustainable system, balancing high yields, low unit costs, and moderate energy demand making it a viable model for long-term vegetable production in semi-arid regions like Kudan LGA (Table 4).

Screenhouse farming demonstrates superior energy efficiency compared to irrigated systems, offering a sustainable balance between resource use and climate control. While irrigated farming demands high energy inputs due to water pumping and infrastructure, rainfed farming is the most energy-efficient but suffers from low yields and environmental

Table 2. ANOVA Summary: Cost per Kilogram Across Farming Systems.

Vegetable	Screenhouse (₦/kg)	Rainfed (₦/kg)	Irrigated (₦/kg)	Mean (₦/kg)	Variance
Cabbage	611	1,997	2,034	1,547.33	507,061.56
Lettuce	445	1,864	1,937	1,415.33	669,636.89
Spinach	402	2,056	2,086	1,514.67	1,005,636.89
Cucumber	509	1,747	1,849	1,368.33	462,636.89
Eggplant	703	1,645	1,769	1,372.33	291,636.89
Pumpkin	913	1,792	1,808	1,504.33	210,636.89

F-statistic: 58.42 p-value: < 0.001 Interpretation: *There is a statistically significant difference in cost per kilogram across farming systems.

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Table 3. Sensitivity Analysis: Profit per Hectare Under Variable Market Prices.

Crop	System	Saleable Yield (kg/ha)	Cost (₦/ha)	Profit @ ₦400/kg	Profit @ ₦600/kg	Profit @ ₦800/kg	Profit @ ₦1000/kg
Cabbage	Screenhouse	8,750	5,342,973	–1,842,973	–92,973	1,657,027	3,407,027
	Rainfed	350	698,972	–558,972	–488,972	–418,972	–348,972
	Irrigated	1,000	2,034,145	–1,634,145	–834,145	–34,145	765,855
Lettuce	Screenhouse	12,000	5,342,973	–542,973	1,857,027	4,257,027	6,657,027
	Rainfed	375	698,972	–548,972	–473,972	–398,972	–323,972
	Irrigated	1,050	2,034,145	–1,614,145	–789,145	35,855	860,855
Spinach	Screenhouse	13,300	5,342,973	–22,973	2,637,027	5,297,027	7,957,027
	Rainfed	340	698,972	–562,972	–458,972	–354,972	–250,972
	Irrigated	975	2,034,145	–1,644,145	–659,145	325,855	1,310,855
Cucumber	Screenhouse	10,500	5,342,973	–1,142,973	957,027	3,057,027	5,157,027
	Rainfed	400	698,972	–538,972	–298,972	–58,972	181,028
	Irrigated	1,100	2,034,145	–1,594,145	–374,145	845,855	2,065,855
Eggplant	Screenhouse	7,600	5,342,973	–2,302,973	–782,973	737,027	2,257,027
	Rainfed	425	698,972	–528,972	–243,972	41,028	326,028
	Irrigated	1,150	2,034,145	–1,574,145	–344,145	885,855	2,115,855
Pumpkin	Screenhouse	5,850	5,342,973	–3,002,973	–1,832,973	–662,973	507,027
	Rainfed	390	698,972	–542,972	–308,972	–74,972	159,028
	Irrigated	1,125	2,034,145	–1,584,145	–359,145	865,855	2,090,855

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Table 4. Cumulative Energy Demand (CED) Analysis for Leafy and Pulpy Vegetables.

Vegetable Type	Crop	Production System	Area (ha)	Plant Population	Energy Equivalent (MJ)	CED (MJ/kg)
Leafy	Cabbage	Irrigated	1	25,926	6,807	1.90
	Cabbage	Rainfed	1	25,926	720	0.57
	Cabbage	Screenhouse	0.0147	381	100.24	0.22
	Lettuce	Irrigated	1	125,000	5,088	1.35
	Lettuce	Rainfed	1	125,000	648	0.48
	Lettuce	Screenhouse	0.0147	1,837	74.99	0.12
	Spinach	Irrigated	1	250,000	4,228	1.21
	Spinach	Rainfed	1	250,000	504	0.41
	Spinach	Screenhouse	0.0147	3,675	62.49	0.09
Pulpy	Cucumber	Irrigated	1	23,333	7,524	1.91
	Cucumber	Rainfed	1	23,333	900	0.63
	Cucumber	Screenhouse	0.0147	343	110.75	0.20
	Eggplant	Irrigated	1	25,926	6,879	1.67
	Eggplant	Rainfed	1	25,926	792	0.52
	Eggplant	Screenhouse	0.0147	381	101.29	0.25
	Pumpkin	Irrigated	1	3,611	10,568	2.62
	Pumpkin	Rainfed	1	3,611	1008	0.72
	Pumpkin	Screenhouse	0.0147	53	155.30	0.50

Note: Data Source: Authors' calculations

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unpredictability. Screenhouse systems, though requiring moderate energy investment, optimize energy use per kilogram of produce through continuous cropping and precision irrigation, making them a viable solution for sustainable high-yield farming.

3.2. Global Warming Potential (GWP)

Global Warming Potential (GWP) varies across farming systems due to differences in nitrogen inputs, plant density, and productivity. Screenhouse farming consistently records the lowest GWP per kilogram of produce, reflecting its high yield efficiency. Rainfed systems produce the lowest total emissions per hectare but have the highest GWP per kilogram due to limited output. For leafy vegetables, screenhouse cabbage, lettuce, and spinach emit 5.88, 3.24, and 2.93 kg CO_2-eq/kg respectively, compared to rainfed equivalents exceeding 118 kg CO_2-eq/kg. Pulpy vegetables follow similar trends, with screenhouse cucumber, eggplant, and pumpkin emitting 3.77, 5.20, and 6.76 kg CO_2-eq/kg, while rainfed versions exceed 100 kg CO_2-eq/kg (Table H in S1 Text).

Irrigated systems fall between screenhouse and rainfed methods in terms of emissions, with moderate GWP per kilogram but higher overall energy use. These findings highlight the trade-offs between total emissions and per-unit efficiency, positioning screenhouse farming as the most environmentally efficient model for vegetable production, while emphasizing the need for improved nitrogen and irrigation management in traditional systems (Table 5).

3.3. Water Use (WU)

Water consumption varies widely across irrigated, rainfed, and screenhouse systems, directly impacting crop productivity and sustainability. Screenhouse farming consistently demonstrates the highest water-use efficiency, using precision drip irrigation to support intensive vegetable production with significantly lower total seasonal consumption [53,54].

Table 5. Global Warming Potential (GWP) Per Unit Product for Rainfed, Irrigated and Screenhouse Leafy and Pulpy Vegetable Production.

Vegetable Type	Vegetable	Production System	Total GWP (kg CO_2-eq)	Saleable Product (kg/ha/year)	GWP/kg Product
Leafy	Cabbage	Irrigated	52566.58	1000	52.57
	Cabbage	Rainfed	44969.10	350	128.48
	Cabbage	Screenhouse	51456.91	8750	5.88
	Lettuce	Irrigated	51940.78	1050	49.47
	Lettuce	Rainfed	44343.30	375	118.25
	Lettuce	Screenhouse	38911.08	12000	3.24
	Spinach	Irrigated	51940.78	975	53.27
	Spinach	Rainfed	44343.30	340	130.42
	Spinach	Screenhouse	38911.08	13300	2.93
Pulpy	Cucumber	Irrigated	52566.58	1100	47.79
	Cucumber	Rainfed	44969.10	400	112.42
	Cucumber	Screenhouse	39536.88	10500	3.77
	Eggplant	Irrigated	52566.58	1150	45.71
	Eggplant	Rainfed	44969.10	425	105.81
	Eggplant	Screenhouse	39536.88	7600	5.20
	Pumpkin	Irrigated	51970.58	1125	46.20
	Pumpkin	Rainfed	44969.10	390	115.31
	Pumpkin	Screenhouse	39536.88	5850	6.76

Note: Data Source: Authors' calculations

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In irrigated systems, leafy vegetables like cabbage, lettuce, and spinach require 1.91–4.33 million liters per hectare per season, while pulpy crops such as cucumber, eggplant, and pumpkin demand up to 8.05 million liters [55]. Rainfed farming uses less water overall but faces seasonal variability, with cabbage, lettuce, and spinach consuming 1.71–3.71 million liters per hectare, and pulpy vegetables requiring up to 6.88 million liters [56–58].

Screenhouse farming, despite higher daily water needs, operates on a smaller scale and uses far less water per season, e.g., cabbage at 61,280 liters, lettuce at 42,942 liters, and pumpkin at 123,480 liters due to controlled fertigation [59].

When measured per kilogram of produce, screenhouse systems are the most efficient: cabbage uses just 7.00 liters/kg, lettuce 3.58 liters/kg, and spinach 2.38 liters/kg (Table 4). Rainfed systems are least efficient, with cabbage requiring 10,625 liters/kg and pumpkin 17,628 liters/kg (Table 6). Irrigated farming falls in between, with cabbage at 4,331 liters/kg and pumpkin at 8,050 liters/kg [60].

Comparative studies support these findings. Ketema [61] found that irrigation users in Ethiopia achieved 90% technical efficiency compared to 74% for rainfed farmers. Bwire et al. [62] also confirmed that drip irrigation and poly-mulching significantly improve water efficiency. Overall, screenhouse farming offers the best balance of water efficiency and productivity, making it the most sustainable option for vegetable cultivation in water-scarce regions like Kudan LGA (Table 6).

4. Discussion

The findings of this study strongly affirm the superiority of screenhouse vegetable farming over traditional rainfed and irrigated systems in terms of yield efficiency, cost-effectiveness, and environmental sustainability. Screenhouse farming supports multiple cropping cycles annually, enabling consistent market supply and significantly higher productivity. Leafy vegetables such as cabbage, lettuce, and spinach yielded 17,500 kg/ha, 24,000 kg/ha, and 26,600 kg/ha respectively,

Table 6. Water Use (WU) Per Unit Product for Rainfed, Irrigated and Screenhouse Leafy and Pulpy Vegetable Production.

Vegetable Type	Vegetable	Production System	Area (ha)	Average Growing Period (Days)	Total Average Water Requirement per season(liter/ season)	Saleable Product (kg/ha/yr)	Water Use (liter)/ kg Product
Leafy	Cabbage	Irrigated	1	82.5	4331250	1000	4331.25
	Cabbage	Rainfed	1	87.5	3718750	350	10625.00
	Cabbage	Screenhouse	0.0147	72.5	61280.625	8750	7.00
	Lettuce	Irrigated	1	52.5	2493750	1050	2375.00
	Lettuce	Rainfed	1	57.5	2156250	375	5750.00
	Lettuce	Screenhouse	0.0147	47.5	42942.375	12000	3.58
	Spinach	Irrigated	1	42.5	1912500	975	1961.54
	Spinach	Rainfed	1	47.5	1710000	340	5029.41
	Spinach	Screenhouse	0.0147	37.5	31696.875	13300	2.38
Pulpy	Cucumber	Irrigated	1	57.5	3018750	1100	2744.32
	Cucumber	Rainfed	1	62.5	2656250	400	6640.63
	Cucumber	Screenhouse	0.0147	52.5	48234.375	10500	4.59
	Eggplant	Irrigated	1	100	5900000	1150	5130.43
	Eggplant	Rainfed	1	107.5	5106250	425	12014.71
	Eggplant	Screenhouse	0.0147	90	89302.5	7600	11.75
	Pumpkin	Irrigated	1	115	8050000	1125	7155.56
	Pumpkin	Rainfed	1	125	6875000	390	17628.21
	Pumpkin	Screenhouse	0.0147	105	123480	5850	21.11

Note: Data Source: Authors' calculations

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while pulpy vegetables like cucumber, eggplant, and pumpkin reached 21,000 kg/ha, 15,200 kg/ha, and 11,700 kg/ha. These figures far exceed the 700–850 kg/ha in rainfed systems and 2,000–2,300 kg/ha in irrigated systems..

While these yield differences are largely attributed to the controlled environment and intensive cropping cycles of screenhouse systems, other agronomic variables likely contributed to the outcomes. One critical factor is the use of hybrid seed varieties in screenhouse farming such as Tycoon F1 cabbage and Greengo F1 cucumber which offer superior germination rates, disease resistance, and faster maturation compared to the open-pollinated varieties (OPVs) commonly used in rainfed and irrigated systems. Additionally, screenhouse farming typically involves more skilled labor, precise planting techniques, and consistent monitoring, which enhance plant health and reduce losses. In contrast, rainfed systems often rely on less intensive labor and are more vulnerable to environmental stressors such as erratic rainfall, pest outbreaks, and soil degradation.

From an economic standpoint, screenhouse farming delivers the lowest cost per kilogram of saleable produce ₦611/kg for cabbage, ₦445/kg for lettuce, ₦402/kg for spinach, ₦509/kg for cucumber, ₦703/kg for eggplant, and ₦913/kg for pumpkin compared to rainfed costs exceeding ₦1,700/kg and irrigated costs nearing ₦1,800/kg. To statistically validate these differences, a one-way ANOVA was conducted on cost per kilogram across farming systems. The results yielded an F-statistic of 58.42 and a p-value < 0.001, confirming that the differences are statistically significant. Screenhouse farming recorded the lowest mean cost per kilogram (₦597.17), reinforcing its economic advantage.

To assess the robustness of these findings under market variability, a sensitivity analysis was performed across four price scenarios (₦400, ₦600, ₦800, and ₦1000/kg). Screenhouse farming became profitable for most crops at ₦600–800/kg, while rainfed systems remained unprofitable even at ₦1000/kg due to low yields and high unit costs. Irrigated systems showed moderate profitability but required higher market prices to break even. For example, screenhouse lettuce yielded a profit of ₦4.26 million/ha at ₦800/kg, while rainfed lettuce remained in deficit even at ₦1000/kg. These results confirm that screenhouse farming is not only efficient but also resilient under fluctuating market conditions.

Environmental assessments further validate screenhouse's advantages. Water-use efficiency is markedly higher, with screenhouse spinach requiring only 2.38 liters/kg compared to 5,029 liters/kg in rainfed systems. Pulpy vegetables also show reduced water consumption per kilogram in screenhouse systems. Greenhouse gas emissions per kilogram of produce are lowest in screenhouse farming, with values ranging from 2.93 to 6.76 kg CO_2-eq/kg, compared to emissions exceeding 100 kg CO_2-eq/kg in rainfed systems. These metrics position screenhouse farming as the most sustainable option for resource optimization and climate resilience.

In summary, the integration of environmental control, improved seed genetics, skilled labor, and agronomic precision explains the compounded advantage of screenhouse farming. The statistical significance confirmed by ANOVA and the resilience demonstrated through sensitivity analysis further validate screenhouse farming as the most economically viable and environmentally efficient system. These insights suggest that future interventions should not only promote screenhouse infrastructure but also ensure access to high-quality inputs and technical training. Yield improvements in traditional systems may be possible through targeted upgrades in seed technology, labor capacity, and irrigation management—especially in regions where full screenhouse adoption may be financially or logistically constrained.

These findings should inform agricultural policy and investment strategies aimed at scaling sustainable vegetable production. Policymakers should prioritize support for screenhouse technologies, hybrid seed access, and precision irrigation systems. By aligning development efforts with evidence-based practices, Nigeria can build a more productive, resilient, and climate-smart agricultural sector (Table 7).

5. Conclusion

This study confirms that screenhouse vegetable farming offers the most viable and sustainable model for agricultural development in semi-arid regions like Kudan LGA. Across all six crops studied cabbage, lettuce, spinach, cucumber, eggplant, and pumpkin screenhouse systems consistently demonstrated superior performance in yield efficiency, cost-effectiveness, and environmental sustainability compared to traditional rainfed and irrigated farming systems.

Table 7. Performance Metrics for Screenhouse, Rainfed Field, and Irrigated Field Leafy and Pulpy Vegetable Production.

Vegetable Type	Vegetable	Production System	Area (ha)	Total Cost of Production (₦/ha)	Yield (kg/ha/yr)	Saleable Product (kg/ha/yr)	Cost/Yield(₦/Kg)	CED (MJ/kg)	GWP/kg Product	Water Use (liter)/kg Product
Leafy	Cabbage	Irrigated	1	2,034,145	2,000	1,000	2,034	1.90	52.57	4331.25
	Cabbage	Rainfed	1	698,972	700	350	1,997	0.57	128.48	10625.00
	Cabbage	Screenhouse	0.0147	5342973	17,500	8,750	611	0.22	5.88	7.00
	Lettuce	Irrigated	1	2,034,145	2,100	1,050	1,937	1.35	49.47	2375.00
	Lettuce	Rainfed	1	698,972	750	375	1,864	0.48	118.25	5750.00
	Lettuce	Screenhouse	0.0147	5,342,973	24,000	12,000	445	0.12	3.24	3.58
	Spinach	Irrigated	1	2,034,145	1,950	975	2,086	1.21	53.27	1961.54
	Spinach	Rainfed	1	698,972	680	340	2,056	0.41	130.42	5029.41
	Spinach	Screenhouse	0.0147	5,342,973	26,600	13,300	402	0.09	2.93	2.38
Pulpy	Cucumber	Irrigated	1	2,034,145	2,200	1,100	1,849	1.91	47.79	2744.32
	Cucumber	Rainfed	1	698,972	800	400	1,747	0.63	112.42	6640.63
	Cucumber	Screenhouse	0.0147	5,342,973	21,000	10,500	509	0.20	3.77	4.59
	Eggplant	Irrigated	1	2,034,145	1,150	1,150	1,769	1.67	45.71	5130.43
	Eggplant	Rainfed	1	698,972	850	425	1,645	0.52	105.81	12014.71
	Eggplant	Screenhouse	0.0147	5,342,973	15,200	7,600	703	0.25	5.20	11.75
	Pumpkin	Irrigated	1	2,034,145	1,125	1,125	1,808	2.62	46.20	7155.56
	Pumpkin	Rainfed	1	698,972	780	390	1,792	0.72	115.31	17628.21
	Pumpkin	Screenhouse	0.0147	5,342,973	11,700	5,850	913	0.50	6.76	21.11

Note: Data Source: Authors' calculation

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Yield data show that screenhouse farming supports multiple cropping cycles annually, resulting in significantly higher outputs. Leafy vegetables such as cabbage, lettuce, and spinach yielded 17,500 kg/ha, 24,000 kg/ha, and 26,600 kg/ha respectively, while pulpy vegetables like cucumber, eggplant, and pumpkin reached 21,000 kg/ha, 15,200 kg/ha, and 11,700 kg/ha. These figures far exceed the 700–850 kg/ha in rainfed systems and 2,000–2,300 kg/ha in irrigated systems.

Economic analysis further highlights screenhouse profitability. Cost per kilogram of saleable produce was lowest in screenhouse farming ₦611/kg for cabbage, ₦445/kg for lettuce, ₦402/kg for spinach, ₦509/kg for cucumber, ₦703/kg for eggplant, and ₦913/kg for pumpkin compared to rainfed costs exceeding ₦1,700/kg and irrigated costs nearing ₦1,800/kg. A one-way ANOVA confirmed that these differences are statistically significant, with an F-statistic of 58.42 and a p-value < 0.001, validating the cost-efficiency advantage of screenhouse systems.

To assess economic resilience, a sensitivity analysis was conducted across four market price scenarios (₦400, ₦600, ₦800, and ₦1000/kg). Screenhouse farming became profitable for most crops at ₦600–$_{8}$00/kg, while rainfed systems remained unprofitable even at ₦1000/kg due to low yields and high unit costs. Irrigated systems showed moderate profitability but required higher market prices to break even. These results confirm that screenhouse farming is not only efficient but also robust under fluctuating market conditions.

Environmental metrics further reinforce the superiority of screenhouse farming. Water-use efficiency was highest in screenhouse systems, with cabbage requiring only 7.00 liters/kg, lettuce 3.58 liters/kg, and spinach 2.38 liters/kg significantly lower than rainfed equivalents. Pulpy vegetables also showed reduced water consumption per kilogram in screenhouse systems. Greenhouse gas emissions per kilogram of produce were lowest in screenhouse farming, with values ranging from 2.93 to 6.76 kg CO_2-eq/kg, compared to emissions exceeding 100 kg CO_2-eq/kg in rainfed systems.

These findings have direct implications for agricultural policy and investment strategy. Policymakers should prioritize the integration of screenhouse technologies into national and regional agricultural development plans. Targeted subsidies, low-interest financing, and technical training programs can accelerate adoption among smallholder farmers. Additionally, investment in precision irrigation infrastructure such as drip systems and fertigation should be scaled to improve water efficiency and reduce energy demand in both screenhouse and open-field systems.

In conclusion, screenhouse farming offers a transformative pathway for achieving food security, economic resilience, and environmental sustainability. By aligning agricultural policy with evidence-based practices and directing investment toward climate-smart infrastructure, Nigeria can build a more productive and adaptive agricultural sector capable of meeting future challenges..

5.1. Limitations in vegetable production systems

Several challenges affect the efficiency and sustainability of rainfed, irrigated, and screenhouse production systems, impacting yield stability, environmental footprint, and economic feasibility. Key limitations include:

1. Open-Pollinated Varieties (OPVs) in Open-Field Cultivation

Inconsistent Growth and Yield Fluctuations: OPVs often exhibit variability in germination rates, crop uniformity, and maturation periods, leading to lower yield predictability compared to hybrid varieties.

Susceptibility to Pests and Diseases: OPVs generally lack enhanced resistance to pathogens, increasing the risk of infestations and productivity losses, especially in rainfed farming where pest control is limited.

Reduced Market Competitiveness: Due to their lower yield potential and quality inconsistency, OPV-grown produce often fails to meet premium market standards, reducing commercial profitability.

2. Flood Irrigation in Conventional Irrigated Farming

High Water Waste and Inefficiency: Flood irrigation results in substantial runoff and evaporation losses, with water-use efficiency dropping below 60% in most cases [55].

Soil Degradation and Nutrient Leaching: Excess water exposure compacts soil structures, disrupts root aeration, and leaches essential nutrients, leading to long-term fertility decline.

Uneven Moisture Distribution: Flood irrigation creates inconsistent soil saturation, causing drought stress or overwatering, both of which reduce crop uniformity and quality [62].

3. High Installation Costs in Screenhouse Farming

Capital-Intensive Infrastructure: Establishing a fully controlled production system requires large investments in climate control technology, irrigation automation, and fertigation systems, leading to high startup expenses.

Operational Costs and Energy Demand: Maintaining optimal indoor conditions results in higher energy consumption, increasing overall production costs despite efficiency in unit yields [61].

Limited Scalability for Small-Scale Farmers: Due to installation and maintenance expenses, widespread adoption remains restricted, making screenhouse more viable for commercial-scale rather than smallholder farming.

4. Emission Estimation Using Tier 1 IPCC, 2006 Data

Generalized Assumptions in Carbon Accounting: The Tier 1 methodology relies on standardized emission factors, which may overestimate or underestimate actual GHG outputs due to regional climate variations and soil differences.

Limited Consideration of Crop-Specific Factors: Variations in fertilizer application, organic matter decomposition, and irrigation methods are not fully integrated, reducing accuracy in estimating emissions per hectare.

Absence of Precision Mitigation Strategies: Tier 1 does not factor in modern mitigation techniques, such as carbon sequestration through regenerative practices, leading to potentially inflated emissions figures.

5.2. Recommendations

Adopt Hybrid Varieties Over OPVs to enhance yield stability, disease resistance, and market value, ensuring greater productivity per hectare.

Replace Flood Irrigation with Drip Systems to maximize water efficiency, reduce nutrient leaching, and prevent soil degradation, aligning with modern conservation strategies.

Improve screenhouse Cost-Effectiveness by integrating renewable energy sources, modular infrastructure designs, and adaptive climate control systems to lower startup and operational expenses.

Upgrade to Tier 2 or Higher Emission Accounting Methods for more crop-specific, regionally adjusted carbon assessments, increasing accuracy in environmental impact analysis.

Supporting information

S1 Text. Table A: Optimal conditions for the screen-house tomato production at Likoro in Kudan LGA of Kaduna State, Nigeria. Table B: Characteristics of CEA, rainfed, and irrigated field operations for leafy and pulpy vegetables. Table C: Average Cost Per Hectare for Screenhouse, Rainfed, and Irrigated Leafy Vegetable (Cabbage, Lettuce, and Spinach) Production. Table D: Average cost per hectare for screenhouse, rainfed, and irrigated pulpy vegetable (cucumber, eggplant, and pumpkin) production. Table E: Average diesel pump energy usage in leafy and pulpy vegetable production. Table F: Average electric pump energy usage in leafy and pulpy vegetable production. Table G: Average GHG emissions from leafy and pulpy vegetable irrigated, rainfed, and screenhouse production. Table H: Total GWP calculation from rainfed, irrigated, and screenhouse leafy and pulpy vegetable production. Table I: Average water requirements for leafy and pulpy vegetable production.
(DOCX)

Author contributions

Conceptualization: Taiwo Bintu Ayinde.

Data curation: Taiwo Bintu Ayinde.

Formal analysis: Taiwo Bintu Ayinde.

Funding acquisition: Taiwo Bintu Ayinde.

Investigation: Taiwo Bintu Ayinde.

Methodology: Taiwo Bintu Ayinde.

Project administration: Taiwo Bintu Ayinde.

Resources: Taiwo Bintu Ayinde.

Software: Taiwo Bintu Ayinde.

Validation: Taiwo Bintu Ayinde.

Visualization: Taiwo Bintu Ayinde.

Writing – original draft: Taiwo Bintu Ayinde.

Writing – review & editing: Taiwo Bintu Ayinde, Charles F. Nicholson, Benjamin Ahmed.

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