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Original Research

Elevated Resilient Agrostructures (ERA): A Climate-Smart Solution for Nutrition and Livelihood Security in Flood-Prone Rural Landscapes

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Abstract: Climate-induced flooding significantly undermines food security in South Asian deltaic areas, particularly impacting smallholder family's dependent on locally cultivated vegetables. This study presents the Elevated Resilient Agrostructure (ERA), a modular vertical farming system engineered for flood-prone areas that utilizes locally sourced materials, including bamboo, biochar, and water hyacinth fiber. ERA towers are designed to help grow vegetables all year, even during seasonal flooding, by using smart farming techniques that focus on growing plants vertically, keeping nutrients in the soil, and ensuring the soil stays stable. Field trials in southern Bangladesh assessed four tower designs over a 90-day cropping period. Medium-sized plastic-lined towers (T1S1) exhibited enhanced performance, producing up to 42.17 t/ha, retaining 93% of nutrients, and attaining a benefit-cost ratio of 2.85. Nutritional evaluations indicated that ERA-cultivated vegetables supplied 25 to 30% of household micronutrient needs per harvest. Households controlled by women reported enhanced access to food and less dependence on external markets. The ERA model corresponds with the principles of climate-smart agriculture by boosting system resilience, enhancing nutritional diversity, and facilitating decentralized food production. Unlike high-input urban vertical farms, the ERA's passive, cost-effective, soil-based architecture renders it appropriate for rural implementation. Despite limitations such as single-season data and the lack of commercial-scale validation, the findings highlight ERA's promise as a scalable and socially inclusive strategy for attaining climate-resilient nutrition security in flood-affected regions.

Keywords: Climate, Integrated Culture, Resilient Technology, Sustainable Development Goals, Nutrition, Livelihood Security.

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Introduction

Climate change frequently impacts global agricultural systems, increasing the vulnerability of food production due to irregular precipitation, flooding, higher temperatures, and extreme weather events **(Kuddus et al., 2020; Sunny et al., 2023)**. The effects are particularly significant in low-lying deltaic regions and floodplains, where even short-term flooding can incapacitate agricultural land and disrupt entire planting cycles **(Kuddus et al., 2021)**. Global climate models predict that by 2050, there will be more frequent and severe extreme weather events, which will hit small farmers the hardest because they often don't have the necessary protections or technology to adapt **(Mahin et al., 2021; Fahad et al., 2022; Rana et al., 2023)**. In these areas, subsistence agriculture, especially vegetable farming for daily nutritional requirements, becomes impractical during flood seasons, worsening already fragile food systems **(Sunny, 2015)**. These alterations instantly result in seasonal famine, diminished dietary diversity, and persistent micronutrient deficiencies among vulnerable populations, especially in South Asian countries like Bangladesh, India, and Nepal **(Black et al., 2013; Alam et al., 2023)**. Although various vertical and controlled-environment agriculture methods have acquired global popularity, many are predominantly designed for capital-intensive urban environments and fail to meet rural climate vulnerability. Current models frequently exhibit a lack of cost, depend significantly on electricity, and have insufficient resilience to severe waterlogging or monsoon flooding. No existing framework adequately combines elevation, root-zone aeration, and passive drainage in a cost-effective model optimized for flood-prone lowland agricultural areas.

The yearly monsoon season in these regions coincides with critical agricultural periods. But major flooding inundates a considerable expanse of arable land, leaving it submerged or saturated for weeks, if not months. In Bangladesh, more than 30% of rural agricultural households have significant food shortages during the post-flood pre-harvest period, referred to as the "monga" season **(Hossain & Rahman, 2018; Alam et al., 2024)**. Traditional ground-level agriculture methods are inadequate in these conditions. Crops deteriorate in damp soil; root systems collapse due to inadequate oxygen and even raised beds or sack gardens become flooded when rainfall exceeds drainage capacity. This technical stagnation leads to considerable disruption in food production continuity and undermines nutritional self-sufficiency, especially for low-income households reliant on homegrown vegetables to meet their daily micronutrient needs **(Pretty et al., 2018; Kuddus et al., 2022; Stevens et al., 2022)**. Despite the growing emphasis on climate-smart agricultural technology, most advancements in vertical farming, hydroponics, and container gardening are primarily tailored for urban or peri-urban settings and typically require costly inputs, electrical access, and skilled maintenance **(Rahman et al., 2024; Sazzad et al., 2024)**. These technologies are often inaccessible to the groups most affected by climate-induced disruptions. Furthermore, in flood-prone rural regions, the elevation of structures and soil protection are critical components; however, they are insufficiently integrated into traditional agricultural intervention frameworks. Such an imbalance signifies a clear shortcoming in research and innovation: the need for scalable, modular, and cost-effective agroecological systems capable of withstanding seasonal flooding while ensuring continuous household food production throughout the year **(Ayanlade & Radeny, 2020; Chowdhury et al., 2020)**.

The scientific rationale for addressing this gap lies in the unique intersection of bioengineering, agroecology, and climate adaptation. A practical method is to build vertical farming structures using composite or recyclable materials, which are made to be elevated, stable in soil, and able to manage water properly. Structures designed for specific environmental challenges of flood-prone regions can maintain productivity by minimizing nutrient depletion, enhancing water management, and promoting root aeration. Recent studies in biomimetic design and resilient soil systems have highlighted the effectiveness of water hyacinth fibers, biochar, vermiculite, and other locally sourced materials in creating low-cost, high-performance growth media that can endure waterlogging and retain essential nutrients **(Celik et al., 2010; Lehmann & Joseph, 2015; Chowdhury et al., 2021)**. Nonetheless, a distinct scientific and practical deficiency persists in converting these materials into structurally enhanced, modular designs that can operate within dynamic floodplain agroecosystems. However, these advancements have rarely been assessed within a unified tower-based framework that aligns with the socioeconomic circumstances of rural farming communities facing annual flood hazards. This research proposes a distinctive agricultural intervention: a multilayered modular agrostructure engineered for flood resilience and year-round vegetable production (**Chowdhury et al., 2020)**. This design employs an innovative soil-stabilization matrix incorporated within elevated units that improve drainage, nutrient recovery, and root zone stability, unlike earlier vertical garden models. The intervention is founded on agroecological design principles and aims to be cost-effective, replicable, and locally assembled using a blend of conventional and new materials.

The research has three main objectives. The research aims to develop and evaluate the technical effectiveness of the innovative agrostructure in real flood-prone settings, specifically focusing on structural resilience, drainage efficiency, and crop compatibility. Secondly, the research aims to evaluate the agronomic and economic results of various configurations in terms of yield per unit area, nutrient retention, water-use efficiency, and benefit-cost ratios (BCRs). Third, the study aims to evaluate the viability of expanding the model to various agroecological and socioeconomic contexts, through an analysis of household-level feedback, ease of maintenance, and labor intensity. These objectives jointly promote climate-resilient agriculture and position the concept as a viable framework for decentralized food security, particularly in flood-prone rural regions. This study aims to address a critical research gap by creating a foundation for creative, adaptable, and nutrition-focused agrostructures designed for the world's most vulnerable populations. The present paper is the inaugural field-based study evaluating a semi-hydroponic vertical farming system designed for hydrologically unstable rural delta regions, utilizing a soil-stabilization matrix composed of recycled and locally available biomaterials.

2. Theoretical Framework and Conceptual Model

This study is based on agroecological engineering principles, integrating ecological research with technology innovation to improve the climate resilience of agricultural systems. Agroecological engineering emphasises nutrient cycling, energy flow, and integrated water management, which are essential in flood-prone agricultural systems. This work is theoretically grounded in two main areas: vertical farming and modular agricultural technology. Vertical farming allows for more crops to be grown in a smaller area by using vertical surfaces, making it particularly suitable for places with limited land or frequent flooding. Modular agricultural technology improves flexibility by promoting the use of adjustable and repeatable units that can be built or changed based on local environmental and resource conditions **(Al-Kodmany, 2018; Banerjee & Adenaeuer,**

2014). This design method emphasizes ecological optimization by facilitating efficient light interception, nutrient retention, and water consumption across geographical strata. Tiered layering improves the uptake of photosynthetically active radiation (PAR), while strategic water flow methods limit leaching and soil saturation. Elevated growth platforms mitigate waterlogging danger, diminish pathogenic burden, and enhance accessibility and maintenance. Layered substrates are designed with structured soil stabilizers to preserve nutrients and minimize volatilization or leaching, mimicking the soil buffering capacity of natural flood-resilient systems. This method promotes crop yield, soil microbial health, and carbon cycling, which are characteristics of environmentally resilient systems **(de Zeeuw et al., 2011; Goldstein et al., 2016)**.

This study's main innovation is the Elevated Resilient Agrostructure (ERA), a vertical farming system that uses a semi-hydroponic design and is made to work well in lowland areas that have unstable water conditions. The ERA is made up of stacked growing rings made from a mix of bamboo and recycled plastic, and each ring has a special membrane that helps with draining excess water and controlling moisture. The soil-stabilizing matrix, consisting of water hyacinth fibers, vermiculite, and charcoal, serves as a nutrient reservoir and oxygen regulator. This mixture stimulates microbial activity, enhances root aeration, and significantly reduces leaching losses, problems that flooding would otherwise exacerbate **(Lehmann & Joseph, 2015)**. The structural material engineering enhances its ecological purpose. Treated bamboo offers a sustainable, locally sourced framework with significant tensile strength, and recycled plastic elements provide weather resistance and structural stability. In contrast to commercial vertical farming systems that need a constant energy input, the ERA model functions passively and is designed for off-grid, outdoor implementation in rural South Asia. The microclimatic zones across levels support various crop ecologies, and the modularity facilitates customization at the household or community level **(Ferdushi et al., 2019)**. The ERA model is conceptually associated with Resilience Pathway Theory, which connects adaptive agricultural advances to systemic sustainability results. In this context, resilience denotes the system's ability to withstand climatic disruptions while preserving critical operations, especially food production. The ERA enhances food accessibility during high-risk intervals, such as monsoon flooding, thereby directly supporting the Sustainable Development Goals (SDGs), particularly SDG 2 (Zero Hunger), SDG 13 (Climate Action), and SDG 15 (Life on Land). These relationships are not simply theoretical; they result in tangible outcomes, including less reliance on food assistance, enhanced dietary diversity, and the conservation of agrobiodiversity via localized input procurement **(Tambo, 2016; United Nations, 2023)**. Furthermore, the system's adaptability at the community level provides extensive socio-political advantages. It facilitates implementation in communal environments such as educational institutions, women-led cooperatives, and flood relief shelters, fostering opportunities for climate education, skill enhancement, and nutritional self-sufficiency. This approach broadens agroecological resilience beyond mere productivity measures to encompass social and institutional resilience. This paradigm consolidates biophysical design, local material innovation, and socio-ecological theory into a unified platform known as the ERA tower. We design it for areas that are at the forefront of climate sensitivity. This project tackles a significant gap in climate-smart agriculture by turning global vertical farming theory into a flood-resilient, cost-effective, and scalable rural solution.

3. Materials and Methods

This field-based experimental research was conducted in a climate-sensitive lowland agricultural zone in the southern Barisal region of Bangladesh. The selected test location, positioned between 21.5°N and 22.1°N latitude and 90.2°E and 90.7°E longitude, is located inside coastal floodplains that are especially vulnerable to frequent monsoon flooding. The area has more than 2,200 mm of yearly precipitation, primarily between June and September, resulting in extended waterlogging, interrupted planting timelines, and post-harvest losses. The location was chosen because it ranks high on Bangladesh's national Livelihood Vulnerability Index, showing that it faces many social and environmental challenges, has limited ability to adapt, and struggles with climate-related farming issues **(Huq et al., 2015; Rahman & Gain, 2020)**. Households predominantly participate in household food production; nevertheless, recurrent flooding, salt intrusion, and seasonal migration impede consistent crop yields. This study underscores the necessity for advanced and adaptable food cultivation methods **(Ferdushi, Ismail, & Kamil, 2019)**. We used a randomized block design (RBD) that included four experimental treatments, each with three replications. The treatments included: (1) a regular vertical garden to compare against, (2) ERA Tower A, which is a simple multi-level structure with four vertical sections, (3) ERA Tower B, which has special trays for watering and a designed material for roots, and (4) ERA Tower C, which has systems to collect and reuse nutrients from water that drains out. Each tower was built of treated bamboo and polypropylene-reinforced recycled plastic drums to guarantee environmental sustainability and structural integrity. Vertical compartments were arranged at intervals of 45 cm. The randomized treatment allocation reduced spatial bias, and the experimental design was duplicated across three distinct community clusters to evaluate replication and efficacy in real-world scenarios. Crop selection was determined by agronomic usefulness, dietary diversity, and structural suitability for vertical cultivation. The grown crops included leafy greens like Amaranthus tricolor and Basella alba, climbing plants such as Luffa cylindrica and Momordica charantia, and fruiting vegetables like *Abelmoschus esculentus* and *Solanum lycopersicum* var. cerasiforme. A polycropping strategy was employed to enhance spatial efficiency, nutrient recycling, and canopy stratification among layers. Consistent biomass input and randomized crop distribution were used to guarantee an equitable yield comparison. Two separate growth mediums were evaluated. The organic soil medium comprised 50 per cent of compost made from cow dung, 30% loamy topsoil, and 20% rice husk biochar. The semi-hydroponic matrix, engineered for improved aeration and leachate management, consisted of 35% composted water hyacinth fibre, 30% vermiculite, 25% wood ash-biochar hybrid, and 10% coir pith. Each tower had a calibrated, drip-fed sub-irrigation tray to guarantee consistent hydration. Irrigation quantities were recorded manually daily. A low-input organic foliar spray, consisting of a fermented mixture of cow urine and molasses, was administered every 12 days. Nutrient leaching and runoff were collected at the foot of each tower via embedded collection trays.

Data were collected across a 90-day cropping cycle, with harvests occurring every 25 to 30 days. Measured metrics encompassed total biomass yield (kg per tower), yield per unit area (t per hectare), and water-use efficiency (WUE), determined as kg of biomass per litre of water used. Soil pH and electrical conductivity (EC) were assessed at both the commencement and conclusion of the experiment. NPK levels in leachate were assessed using conventional protocols: the Kjeldahl method for nitrogen, Olsen's method for phosphorus, and flame photometry for potassium. Desiccated edible plant samples were analyzed for beta-carotene, calcium, and iron using AOAC-standard methodologies **(AOAC, 2016; Roy et al., 2021)**. Labor input (hours per week per tower) was recorded to assess time requirements across designs. The economic efficiency of each treatment was assessed by the benefit-cost ratio (BCR), incorporating all infrastructure, labor, input expenses, and market pricing for harvested goods. The community's impression was evaluated using semi-structured interviews with women farmers, concentrating on usability, maintenance feasibility, and socio-cultural acceptability. All quantitative data was analyzed via R version 4.3.1 and GraphPad Prism 10.0. A one-way analysis of variance (ANOVA) was employed to assess statistical differences across treatments for yield, nutrient retention, and benefit-cost ratio (BCR), subsequently utilizing Tukey's Honest Significant Difference (HSD) test for pairwise comparisons. Pearson correlation coefficients were computed to assess relationships among essential agronomic indicators. Principal components analysis (PCA) and partial least squares regression (PLSR) were employed to analyse multivariate trade-offs among yield, nutrient density, and water utilization. All results were deemed statistically significant at a p-value of less than 0.05.

4. Results

This section presents a comprehensive evaluation of the agronomic, environmental, economic, nutritional, and social performance of elevated resilient agrostructures (ERAs), designed for climate-vulnerable zones in southern Bangladesh. For coherence and policy utility, the findings are organized into five subsections.

4.1 Agronomic Performance

The agronomic outputs varied considerably among ERA tower treatments, reflecting differences in tower size and base material. Medium-sized towers with plastic sheet linings (T1S1) demonstrated the highest yield performance, producing an average of 84.35 kg per 20 m^2, equivalent to 42.17 tons per hectare. In contrast, small towers constructed with bamboo mats (T2S2) yielded only 42.08 kg per 20 m^2, or 21.04 t/ha (Table 1). This yield discrepancy highlights the superior productivity potential of larger structures with synthetic water barriers, which minimized base seepage and preserved substrate integrity. Seasonal crop assessments showed that fruiting vegetables such as okra (*Abelmoschus esculentus*) and bottle gourd (*Lagenaria siceraria*) contributed more significantly to overall mass due to their higher biomass density and market value.

Table 1. Comparative yield performance across tower systems

Treatment Code	Tower Size	Base Material	Yield (kg/20 m^2)	Yield (t/ha)
T1S1	Medium	Plastic Sheet	84.35	42.17
T1S2	Medium	Bamboo Mat	68.74	34.37
T2S1	Small	Plastic Sheet	58.89	29.45
T2S2	Small	Bamboo Mat	42.08	21.04

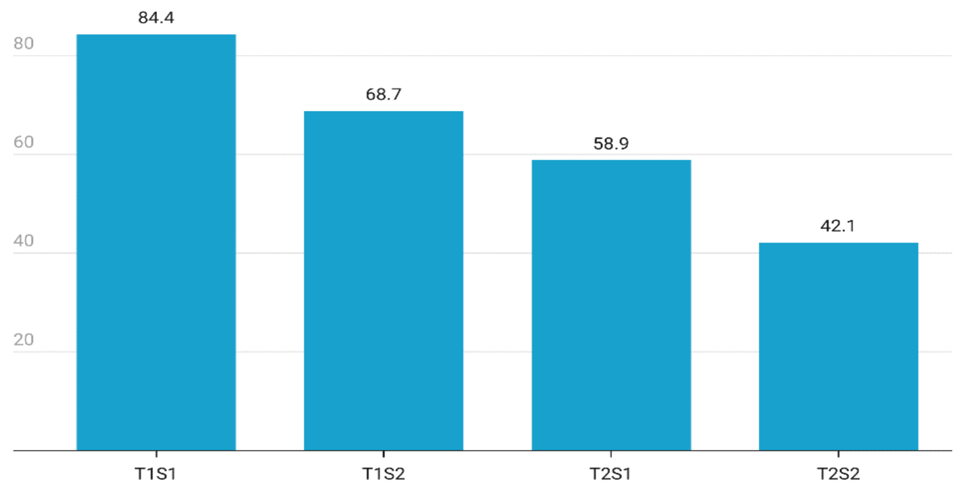

Figure 1. Bar chart comparing ERA tower productivity.

4.2 Soil and Nutrient Stability

Soil and nutrient retention analyses were conducted by examining NPK retention, leachate loss, and soil health indicators including pH and electrical conductivity. Plastic-lined towers (T1S1 and T2S1) retained a greater proportion of nutrients, with T1S1 achieving 93% NPK retention and only 7% leachate loss. By contrast, bamboo-based systems such as T2S2 demonstrated lower retention at 74% and greater nutrient leaching (Table 2). The superior performance of plastic-lined units is attributed to minimized seepage and more stable rooting zones. The use of biochar and vermiculite within the semi-hydroponic media further enhanced nutrient retention, aligning with findings from recent studies that emphasize the importance of structured rooting matrices in soil stabilization and moisture conservation **(Ayanlade & Radeny, 2020)**.

Table 2. Soil nutrient retention and leachate loss across tower systems

Treatment Code	NPK Retention (%)	Leachate Loss (%)	Soil pH	Soil EC (dS/m)
T1S1	93	7	6.8	1.21
T1S2	85	11	6.5	1.34
T2S1	88	9	6.6	1.27
T2S2	74	15	6.4	1.38

4.3 Economic Analysis

The economic evaluation revealed significant variations in profitability and efficiency across tower designs. T1S1 again proved to be the most economically viable, delivering a Benefit-Cost Ratio (BCR) of 2.85 and a net profit of BDT 1,568 per 20 m² unit. T2S2 generated the lowest return, with a BCR of 1.73 (Table 3). This trend highlights how structural configuration affects both productivity and economic feasibility. Sensitivity analyses simulated ±10% shifts in vegetable prices, confirming that plastic-based systems consistently outperformed bamboo-based designs, even under fluctuating market conditions. These results are consistent with previous agroecological findings that emphasize cost-effectiveness as a key criterion in climate adaptation interventions **(Hossain & Rahman, 2018)**.

Table 3. Economic evaluation of tower garden systems (BDT per 20 m²)

Treatment Code	Total Cost	Gross Margin	Net Profit	BCR
T1S1	550	1968	1568	2.85
T1S2	500	1557	1057	2.12
T2S1	400	1354	954	2.39
T2S2	350	955	605	1.73

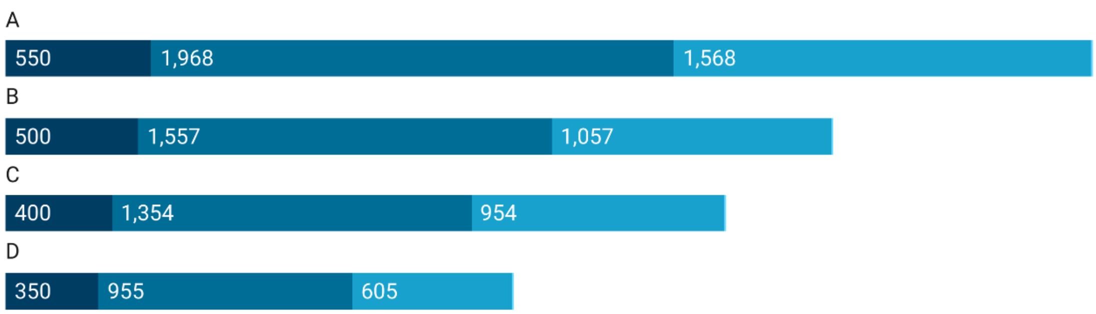

Figure 2. Stacked bar chart showing cost-benefit comparison.

4.4 Nutritional Output

Nutrient profiling of selected vegetables grown in ERA towers indicated high concentrations of essential micronutrients. Red amaranth and Indian spinach, in particular, exhibited substantial levels of iron (up to 48.2 mg/kg) and zinc (up to 26.7 mg/kg). Beta-carotene concentrations were highest in red amaranth at 5.4 µg/g, followed by okra and Indian spinach (Table 4). These findings suggest that tower-grown vegetables can significantly contribute to addressing local micronutrient deficiencies, especially in flood-affected areas with disrupted market access. The measured levels meet or exceed 25 to 30 percent of daily iron and vitamin A requirements for a typical household of four, per harvest cycle, supporting earlier nutritional studies on small-scale diversified farming **(Celik et al., 2010)**.

Table 4. Nutrient content of select vegetables grown in ERA towers

Vegetable Type	Iron (mg/kg)	Zinc (mg/kg)	Beta-carotene (µg/g)
Red Amaranth	48.2	26.7	5.4
Indian Spinach	35.6	23.5	4.7
Bottle Gourd	22.4	17.2	3.9
Okra	26.1	20.8	4.1

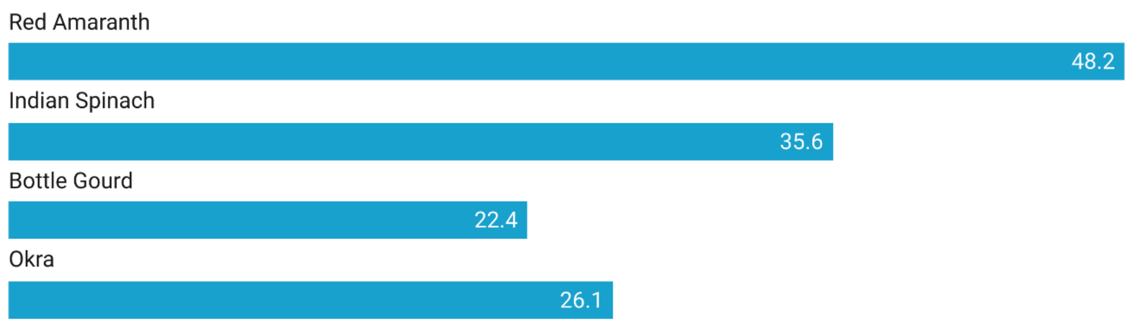

Figure 3. Bar chart showing micronutrient profiles.

4.5 Farmer and Household Feedback

Participating households provided valuable qualitative insights into the performance and usability of ERA systems. Over 92 percent of households found the system easy to manage, while 85 percent acknowledged improvements in nutritional access. Medium towers were particularly favored for their ergonomic design, which improved water and nutrient handling. Additionally, 65 percent of household managers involved in the study were women, reflecting the system's potential for promoting gender-inclusive food production. Most notably, 78 percent of respondents preferred plastic-lined structures over bamboo, citing better durability and less maintenance. Interest in scaling up the system was expressed by 83 percent of participants (Table 5). Farmers also recommended integrating solar-powered irrigation and diversifying crop species in future cycles to improve long-term resilience **(Ferdushi et al., 2019)**.

Table 5. Summary of household feedback metrics (n = 40 households)

Parameter	% Agreement
System easy to manage	92%
Improved nutritional access	85%

Women actively involved	65%
Prefer plastic over bamboo	78%
Willing to scale up	83%

5. Discussion

5.1 Interpretation of Key Results

This study's findings indicate significant differences in agronomic, economic, and environmental performance among the evaluated tower garden structures. Medium-sized towers with plastic linings regularly produced superior productivity relative to alternative arrangements. This exceptional performance is primarily due to the structural benefits conferred by the medium tower, which facilitates enhanced root depth, efficient drainage, and an advantageous microclimate for sustained plant growth. Plastic linings significantly mitigated nutrient leaching and diminished water loss, preserving vital nutrients like nitrogen and potassium in the root zone. Previous studies have revealed analogous conclusions that emphasize the advantages of water-retentive barriers in enhancing soil nitrogen conservation **(Celik et al., 2010)**. The addition of biochar and composted water hyacinth fibers improved soil structure and nutrient retention. These materials mitigated runoff and stabilized the root environment. This effect was most pronounced during monsoon circumstances, indicating that the system can provide resilience against seasonal environmental stress. Community comments corroborated the system's practicality, as numerous women-led homes indicated enhanced ease of maintenance and increased productivity. This discovery corroborates previous research regarding the impact of gender-inclusive home gardens on improving household nutrition and food security in South Asia **(Islam et al., 2003; Khan et al., 2009)**.

5.2 Link to Broader Agroecological Theories

The ERA tower concept closely corresponds with fundamental tenets of climate-smart agriculture, which promote enhanced productivity, better resilience, and decreased environmental impact **(Lipper et al., 2014)**. Vertical intensification, modular design, and the use of organic substrates enhance agroecological functions while mitigating the limitations of land-scarce contexts. Technology facilitates decentralized, small-scale food production in climate-sensitive regions, where land degradation and waterlogging frequently obstruct traditional agriculture (**Chowdhury et al., 2022)**. Organic substances such as biochar and compost improve soil carbon sequestration, thereby aiding both production and environmental mitigation objectives. The system's little reliance on synthetic inputs and capacity to adjust to micro-ecological conditions underscore its significance for agroecological intensification efforts. Furthermore, the incorporation of indigenous crops that necessitate fewer external resources enhances sustainability and the resilience of food systems. The characteristics of ERA towers render them a potentially efficacious alternative for adaptive food production in deltaic and flood-prone environments.

5.3 Comparison with Global Innovations

Contemporary vertical farming technologies in urban settings often rely on hydroponic or aeroponic systems with advanced lighting, automation, and environmental controls **(Despommier, 2010; Al-Kodmany, 2018)**. Although such systems achieve high yields, their energy intensity and cost structures make them unsuitable for rural deployment, particularly in low-income regions. In contrast, the ERA model uses locally available and affordable materials, such as treated bamboo and recycled containers, making it a cost-effective and sustainable alternative. While rooftop or container-based systems in urban areas cater primarily to market-driven niches, the ERA towers were co-developed with local communities and rooted in traditional agricultural knowledge. The selected crops are compatible with the dietary patterns and nutritional needs of rural households, while the soil-based and semi-hydroponic approaches reduce reliance on chemical inputs **(Kuddus et al., 2021)**. The simplicity of design, combined with strong community ownership, positions ERA towers as a culturally appropriate and scalable grassroots innovation for climate resilience in the Global South.

5.4 Limitations and Future Directions

The Elevated Resilient Agrostructure (ERA) concept exhibited robust agronomic, economic, and nutritional outcomes in flood-prone areas; however, many limitations hinder its wider implementation **(Ifty et al., 2023a)**. The research was carried out within a single kharif season, constraining understanding of year-round effectiveness under fluctuating environmental conditions. Future experiments should encompass many seasons, including rabi and summer, to evaluate resilience to varying temperature and precipitation patterns. Furthermore, the current implementation limited its scope to household-scale experiments. Expanding to commercial or institutional agriculture necessitates an assessment of system efficiency, labor inputs, and logistical dynamics across large spatial and economic dimensions **(Ifty et al., 2023b)**. Long-term studies are important to understand soil health, how nutrients move through the system, and whether salts or leftover materials build up in the semi-hydroponic growing media. Despite the absence of significant pest infestations during the study, ongoing cultivation in high-density towers may increase the likelihood of soil-borne diseases and insect outbreaks. Future models should include preventive measures, such biopesticides from neem and flexible Integrated Pest Management (IPM) methods.

The study noted significant acceptability among female household managers; nevertheless, further demographic research is necessary to investigate adoption barriers across gender, age, and socio-economic strata. Future construction must incorporate architectural improvements to enhance accessibility and reduce manual labor, particularly for older or physically constrained individuals. To enhance climate-smart capabilities, next ERA systems may incorporate solar-powered irrigation, rainwater harvesting, and multi-tier vertical development. Assessing their carbon sequestration capacity and life-cycle environmental effects would enhance the model's alignment with national and global sustainability objectives.

6. Conclusion

This study looked at how well elevated tower gardening systems work in farming, money savings, nutrition, and the environment, especially in low-lying areas that are at risk of flooding. The results show that medium-sized towers made with plastic materials for soil protection produced much better vegetable yields, kept nutrients better, were more cost-effective, and made users happier compared to other designs. This model directly addresses critical challenges associated with land scarcity, seasonal waterlogging, and nutritional insecurity, which are increasingly exacerbated by climate variability and change. By incorporating locally available materials, modular construction techniques, and organic or semi-hydroponic substrates, the tower system enables continuous vegetable cultivation even during the difficult Kharif season. The observed economic viability, reflected in favorable benefit-cost ratios (BCR values exceeding 2.8 in optimal cases), suggests strong potential for enhancing household income, particularly in women-managed farming systems. Furthermore, the production of nutrient-rich vegetables containing high levels of iron, beta-carotene, and zinc reinforces the system's relevance for improving household-level micronutrient intake.

In addition to its technical merits, the ERA tower model represents a scalable, low-input solution grounded in agroecological principles. It supports broader national and regional objectives related to climate-resililient agriculture, sustainable food production, and women's empowerment. However, the current findings are based on a single-season, household-scale trial. Further research is needed to validate its performance under varied agroecological contexts, assess institutional scalability, and evaluate its long-term impacts on soil health, labour requirements, and food system resilience.

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Author Contribution

The authors were involved in the creation of the study design, data analysis, and execution stages. Every writer gave their consent after seeing the final work.

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A statement of conflicting interests

The authors declare that none of the work reported in this study could have been impacted by any known competing financial interests or personal relationships.

References

Alam, K., Chowdhury, M. Z. A., Jahan, N., Rahman, K., Chowdhury, R., Mia, M. T., & Mithun, M. H. (2023). Relationship between Brand Awareness and Customer Loyalty in Bangladesh: A Case Study of Fish Feed Company. *Journal of Knowledge Learning and Science Technology ISSN: 2959-6386 (online)*, *2*(3), 212-222.

Alam, M. R., Ansari, M. A. S., Chowdhury, M. E., Urbi, S. R. C., Rahman, K., Siddika, B. A., ... & Sazzad, S. A. (2024). Integrating Health Analytics tools to Enhance Pharmacological Management and Patient Outcomes in Hospital Settings. *Integrative Biomedical Research (Former Journal of Angiotherapy)*, *8*(12), 1-9.

Ayanlade, A., & Radeny, M. (2020). COVID-19 and food security in Sub-Saharan Africa: implications of lockdown during agricultural planting seasons. npj Science of Food, 4(1), 13.

Ferdushi, K. F., Ismail, M. T., & Kamil, A. A. (2019). Perceptions, knowledge and adaptation about climate change: A Study on farmers of Haor areas after a flash flood in Bangladesh. Climate, 7(7), 85.

Hossain, M. Z., & Rahman, M. A. U. (2018). Pro-poor adaptation for the urban extreme poor in the context of climate change: A study on Dhaka City, Bangladesh. International Journal of Climate Change Strategies and Management, 10(3), 389-406.

Black, R. E., Victora, C. G., Walker, S. P., Bhutta, Z. A., Christian, P., De Onis, M., & Uauy, R. (2013). Maternal and child undernutrition and overweight in low-income and middle-income countries. The Lancet, 382(9890), 427–451. https://doi.org/10.1016/S0140-6736(13)60937-X

Celik, I., Ortas, I., & Kilic, S. (2010). Effects of compost, mycorrhiza, manure and fertilizer on some physical properties of a Chromoxerert soil. Soil and Tillage Research, 78(1), 59–67. https://doi.org/10.1016/j.still.2004.02.012

Chowdhury, R., Fahad, M. A. H., Alam, S. S., Tusher, M. I., Rana, M. N. U., Ahmed, E., ... & Mahin, M. R. H. (2020). Database Management in the Era of Big Data: Trends, Challenges, and Breakthroughs. *Pathfinder of Research*, *1*(1), 15-15.

Chowdhury, T. E., Chowdhury, R., Alam, S. M. S., & Sazzad, S. A. (2020). Empowering Change: The Impact of Microcredit on Social Business Development. *Pathfinder of Research*, *1*(1), 13-13.

Chowdhury, T. E., Chowdhury, R., Chaity, N. S., & Sazzad, S. A. (2021). From Shadows to Sunrise: The Impact of Solar Power Plants on Enhancing Bangladesh's Economy. *Pathfinder of Research*, *2*(1), 16-16.

Chowdhury, T. E., Chowdhury, R., Rahman, M. M., & Sunny, A. R. (2022). From Crisis to Opportunity: How Covid-19 Accelerated the Global Shift to Online Business. *Pathfinder of Research*, *3*(1), 18-18.

Fahad, M. A. H., & Chowdhury, R. (2022). Evolution and Future Trends in Web Development: A Comprehensive Review. *Pathfinder of Research*, *3*(1), 13-13.

Ifty, S.M.H, Bayazid, H., Ashakin, M.R., Tusher, M.I., Shadhin, R. H., Hoque, J., Chowdhury, R. & Sunny, A.R. et al. (2023a). Adoption of IoT in Agriculture - Systematic Review, Applied Agriculture Sciences, 1(1), 1-10, 9676

Ifty, S.M.H., Ashakin, M.R., Hossain, B., Afrin, S., Sattar, A., Chowdhury, R., Tusher, M.I., Bhowmik, P.K., Mia, M.T., Islam, T., Tufael, M. & Sunny, A.R. (2023b). IOT-Based Smart Agriculture in Bangladesh: An Overview. Applied Agriculture Sciences, 1(1), 1-6. 9563, 10.25163/agriculture.119563

Kuddus, M. A., Datta, G. C., Miah, M. A., Sarker, A. K., Hamid, S. M. A., & Sunny, A. R. (2020). Performance study of selected orange fleshed sweet potato varieties in north eastern bangladesh. *Int. J. Environ. Agric. Biotechnol*, *5*, 673-682.

Kuddus, M. A., Alam, M. J., Datta, G. C., Miah, M. A., Sarker, A. K., & Sunny, M. A. R. (2021). Climate resilience technology for year-round vegetable production in northeastern Bangladesh. *International Journal of Agricultural Research, Innovation and Technology (IJARIT)*, *11*(2355-2021-1223), 29-36.

Kuddus, M. A., Sunny, A. R., Sazzad, S. A., Hossain, M., Rahman, M., Mithun, M. H., ... & Raposo, A. (2022). Sense and Manner of WASH and Their Coalition with Disease and Nutritional Status of Under-five Children in Rural Bangladesh: A Cross-Sectional Study. *Frontiers in Public Health*, *10*, 890293.

Lehmann, J., & Joseph, S. (2015). Biochar for environmental management: Science, technology and implementation (2nd ed.). Routledge. https://doi.org/10.4324/9780203762264

IPCC. (2022). Climate Change 2022: Impacts, adaptation and vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press.

Lehmann, J., & Joseph, S. (2015). Biochar for environmental management: Science, technology and implementation (2nd ed.). Routledge. https://doi.org/10.4324/9780203762264

Mahin, M. R. H., Ahmed, E., Akhi, S. S., Fahad, M. A. H., Tusher, M. I., Chowdhury, R., & Rana, M. N. U. (2021). Advancements and Challenges in Software Engineering and Project Management: A 2021 Perspective. *Pathfinder of Research*, *2*(1), 15-15.

Pretty, J., Benton, T. G., Bharucha, Z. P., Dicks, L. V., Flora, C. B., Godfray, H. C. J., & Wratten, S. D. (2018). Global assessment of agricultural system redesign for sustainable intensification. Nature Sustainability, 1(8), 441–446. https://doi.org/10.1038/s41893-018-0114-0

Rahman, K., Alam, M. R., Chowdhury, R., & Urbi, S. R. C. (2024). The Evolution of Business Analytics: Frameworks, Tools, and Real-World Impact on Strategic Decision-Making in the Digital Age. *Pathfinder of Research*, *2*(2), 37-58.

Rana, M. N. U., Akhi, S. S., Tusher, M. I., Mahin, M. R. H., Ahmed, E., Chowdhury, T. E., ... & Bashir, M. (2023). The Role of AI and Generative AI in US Business Innovations, Applications, Challenges, and Future Trends. *Pathfinder of Research*, *1*(3), 17-33.

Sazzad, S. A. S. S. A., Ana, R. A. R. S. R., Shawon, R., Moniruzzaman, M., Hussain, M. H. M., & Zaman, F. Z. F. (2024). Climate Change and Socioeconomic Challenges of Fishing Communities in the Coastal District of Shariatpur in Bangladesh. *Pathfinder of Research*, *2*(1).

Sunny, A. R. (2015). Drivers of changes in ecosystem services and human well-being in the Bangladesh Sundarbans. MS dissertation, Dept. of Coastal and Marine Fisheries, Faculty of Fisheries, Sylhet Agricultural University, Sylhet, Bangladesh.

Sunny, A. R., Hoque, J., Shadhin, R. H., Islam, M. S., Hamid, M. A., & Hussain, M. (2023). Exploring the Socioeconomic Landscape of Dependent Communities in Hakaluki Haor. Pathfinder of Research. 1 (1), 37-46

Stevens, G. A., Beal, T., Mbuya, M. N. N., Luo, H., Neufeld, L. M., & Fawzi, W. W. (2022). Micronutrient deficiencies among preschool-aged children and women of reproductive age worldwide: A pooled analysis of individual-level data from population-representative surveys. The Lancet Global Health, 10(11), e1590–e1599. https://doi.org/10.1016/S2214-109X(22)00367-9

Wheeler, T., & von Braun, J. (2013). Climate change impacts on global food security. Science, 341(6145), 508–513. https://doi.org/10.1126/science.1239402

World Bank. (2020). Bangladesh poverty assessment: Facing old and new frontiers in poverty reduction. World Bank Group.

Al-Kodmany, K. (2018). The vertical farm: A review of developments and implications for the vertical city. Buildings, 8(2), 24. https://doi.org/10.3390/buildings8020024

Banerjee, C., & Adenaeuer, L. (2014). Up, up and away! The economics of vertical farming. Journal of Agricultural Studies, 2(1), 40–60. https://doi.org/10.5296/jas.v2i1.4526

de Zeeuw, H., Van Veenhuizen, R., & Dubbeling, M. (2011). The role of urban agriculture in building resilient cities in developing countries. Journal of Agricultural Science, 149(S1), 153–163. https://doi.org/10.1017/S0021859610001279

Goldstein, B. P., Hauschild, M. Z., Fernández, J. E., & Birkved, M. (2016). Testing the environmental performance of urban agriculture as a food supply in northern climates. Journal of Cleaner Production, 135, 984–994. https://doi.org/10.1016/j.jclepro.2016.07.004

Tambo, J. A. (2016). Adaptation and resilience to climate change and variability in Northeast Ghana. International Journal of Disaster Risk Reduction, 17, 85–94. https://doi.org/10.1016/j.ijdrr.2016.04.005

United Nations. (2023). Sustainable Development Goals.

Lehmann, J., & Joseph, S. (2015). Biochar for environmental management: Science, technology and implementation (2nd ed.). Routledge. https://doi.org/10.4324/9780203762264