ECO-INNOVATIVE PRODUCT DESIGN SOLUTION FOR ENHANCING MANGROVE HABITAT AND SYSTEM RESTORATION IN SRI LANKA

URESHA E.D.T.[1]* & RANASINGHE W.M.N.D.[2]
[1,2]University of Moratuwa, Sri Lanka
[1]*thiranuresha@gmail.com*, [2]*dilshanir@uom.lk*

Abstract: This study presents the design and preliminary evaluation of Aqua Nest, an eco-innovative and biodegradable mangrove seedling protector developed from recycled porcelain bisque waste. The research applies a Design-for-Environment (DfE) framework to address high seedling mortality in Sri Lanka's coastal restoration projects, focusing on stability, biodegradability, and ecological integration. The protector was designed to enhance root anchoring, allow natural water flow, and support early stage habitat formation while gradually decomposing into nutrient rich sediment. Two full scale prototypes were fabricated and tested for 21 days at a Koggala lagoon site in southern Sri Lanka. Qualitative field observations confirmed structural stability, seed retention, and early ecological interaction, including algal growth and colonisation by small aquatic organisms. The findings are preliminary and qualitative, intended to demonstrate feasibility rather than provide statistical validation. However, the results indicate that Aqua Nest can offer temporary protection and promote microhabitat formation during early mangrove establishment. By repurposing ceramic industry waste into a functional coastal restoration product, this study introduces a circular design model linking material innovation with ecological resilience and community based sustainability.

Keywords: *Sustainable Product Design, Design-for-Environment (DfE), Mangrove Ecosystem Restoration, Sustainability Systems Development, Circular Economy*

1. Introduction

Mangroves are among the most productive ecosystems in Sri Lanka, providing shoreline protection, biodiversity support, and carbon sequestration (Kotagama & Wijesundara, 2007). Despite significant national and international investment, many restoration efforts have shown low long term survival rates, with fewer than 12% of replanted mangroves surviving (Kodikara et al., 2017). Key causes include seedling instability, strong tidal activity, sediment movement, and inadequate structural protection during early growth. Conventional materials such as PVC barrels, concrete pods, and plastic coverings offer temporary stability but often harm ecosystems, obstruct root development, and contribute to non-biodegradable waste.

Recognising this gap, the present research positions product design as an ecological intervention, integrating design thinking into coastal ecosystem restoration. The study adopts a Design-for-Environment (DfE) framework, which emphasises sustainable material selection, circular resource use, and the minimisation of environmental impact throughout a product's life cycle. Within this framework, Aqua Nest was developed as a biodegradable mangrove seedling protector made from recycled porcelain bisque clay composites, merging industrial waste reuse with eco engineering principles.

By integrating material innovation, functional prototyping, and field based validation, this study demonstrates how eco innovative product design can address one of Sri Lanka's most persistent environmental challenges high seedling mortality in mangrove restoration. The paper documents the design, development, and preliminary field evaluation of seedling protector (Aqua Nest), highlighting its potential contribution to restoration ecology and sustainable community production. The research also acknowledges its qualitative scope and the need for extended quantitative assessment to confirm long term performance and ecological outcomes.

2. Background

2.1 IMPORTANCE OF EFFECTIVE MANGROVE RESTORATION

Mangrove ecosystems are among the most productive and valuable components of Sri Lanka's coastal landscape. They provide vital ecological services such as shoreline stabilisation, biodiversity protection, carbon sequestration, and disaster mitigation (Kotagama & Wijesundara, 2007). Despite several decades of restoration efforts, mangrove replantation projects in Sri Lanka have shown low long term success rates. Only a small percentage of the 2,000 hectares of re-planted mangroves have survived, largely due to inadequate structural protection, poor site selection, and physical stress from waves and tides (Kodikara et al., 2017). Addressing seedling instability and high early stage mortality is therefore crucial to ensuring ecological resilience and restoration effectiveness.

*Corresponding author: Tel: +94 717645412 Email Address: thiranuresha@gmail.com
FARU Journal: Volume 12 Issue 01 DOI: DOI: https://doi.org/10.4038/faruj.v12i1.338

2.2 CHALLENGES FACED BY MANGROVE ECO SYSTEM IN SRI LANKA
Mangrove seedlings in Sri Lanka face multiple stressors: strong tidal currents, fluctuating salinity, erosion, and predation by crabs and insects (Wickramasinghe et al., 2022). Traditional methods such as using plastic barrels, fishing nets, and concrete planters often fail to stabilise seedlings and may even damage the surrounding ecosystem by impeding water flow or releasing harmful residues. These unsustainable practices highlight a need for eco-engineered, biodegradable structures that can ensure both seed stability and environmental safety. Recent research supports a transition towards biodegradable composite protectors that combine functionality with ecological integration (Sasanpour et al., 2021; Pereira et al., 2022).

2.3 RESEARCH PROBLEM
Although the importance of mangrove restoration is well recognised, there remains no widely adopted, biodegradable, or scientifically optimised protector for mangrove seedlings in Sri Lanka. Current community level restoration practices rely on basic and non biodegradable materials such as black polythene covers, plastic barrels, roofing tiles, and fishing nets to shield young plants from waves and crab damage. While these temporary measures provide limited physical support, they often block water circulation, trap debris, and eventually contribute to plastic waste accumulation in lagoons.

As a result, these methods fail to ensure stable root development or long term ecological compatibility. This study therefore addresses the need for a locally manufacturable, biodegradable protector the Aqua Nest developed through sustainable product design and material innovation. By re-purposing porcelain bisque waste blended with natural clay, the proposed design seeks to enhance seedling stability, promote healthy root anchoring, and restore ecological balance without introducing synthetic waste into the coastal environment.

2.4 AIM AND OBJECTIVE
Research Aim To design, develop, and preliminarily evaluate a biodegradable mangrove seedling protector (Aqua Nest) manufactured from repurposed porcelain bisque waste and clay as a product design solution to reduce early seedling loss in Sri Lankan restoration sites.

Research Objectives.

- Identify functional and environmental requirements for early stage seedling protection in brackish conditions.
- Optimise a bisque–clay material system that balances porosity, strength, and controlled biodegradation.
- Prototype and conduct preliminary field trials to observe stability, seed retention, and early ecological interactions under natural tidal conditions.
- Assess scalability considerations and outline the scope for future cost benefit and life-cycle evaluations.

2.5 HYPOTHISIS
This study proposes that the Aqua Nest, a biodegradable seedling protector developed through product design principles, can offer preliminary functional and ecological benefits during early mangrove establishment. It is expected to improve seedling stability and root anchoring under tidal conditions while showing early signs of ecological compatibility through biofilm formation and habitat interaction.

2.6 PRELIMINARY FIELD CONTEXT AND EMPIRICAL SCOPE
This study is qualitative and preliminary, based on short term prototype testing that demonstrates feasibility rather than measurable impact. Quantitative assessment is still required to evaluate seedling survival, material degradation, and ecological performance through 6–12 months of extended monitoring, with full biodegradation expected within about two years. The design's scalability also depends on the reliable supply of bisque ware waste. Future work should therefore include controlled survival trials, a basic cost benefit and life cycle evaluation, and long term ecological monitoring to confirm that the Aqua Nest performs sustainably and without unforeseen environmental effects.

3. Literature Review

3.1 CURRENT STAGE OF MANGROVE CONSERVATION
Mangroves play an essential role in maintaining coastal resilience and biodiversity, yet restoration projects worldwide continue to face high failure rates due to poor survival and ecological adaptation. Following the 2004 Indian Ocean tsunami, Southeast Asian nations, including Sri Lanka, intensified restoration efforts. However, only about 12% of the country's 2,000 hectares of replantation projects have succeeded, with most failures concentrated in southern coastal zones exposed to heavy wave activity (Kodikara et al., 2017). These results underline the need for design-based interventions that can mitigate early stage mortality and improve seedling establishment under dynamic tidal conditions.

3.2 MANGROVE CONSERVATION ZONES PROJETCS IN SRI LANKA
Effective mangrove restoration in Sri Lanka depends on establishing clearly defined conservation belts, which serve as the primary target zones for this research. These protective green belts, typically about 10 metres wide, are created along lagoon margins to absorb wave energy, reduce shoreline erosion, and minimise sediment displacement (T. Kapurusinghe, personal

communication, April 28, 2023). They form stable ecological buffers that support the early growth of mangroves by improving water retention and promoting the deposition of organic matter. Within these belts, appropriate species selection is crucial for achieving long term restoration success. Commonly prioritised species include Rhizophora mucronata, which stabilises high salinity zones and supports marine biodiversity; Avicennia marina, known for its pneumatophores that enable oxygen exchange in waterlogged soils; and Bruguiera gymnorrhiza, which thrives in low salinity areas and consolidates the shoreline (Chathuranga et al., 2024; Wickramasinghe et al., 2022). Understanding the environmental conditions of these conservation belts directly guided the design of the Aqua Nest. The wall height, porosity, and anchoring geometry, in particular, were carefully defined to ensure that the protector integrates effectively within these natural restoration zones and complements existing ecological processes.

Figure 01, Mangrove Conservation Belt in a Lagoon Sri Lanka (Authors' creation)

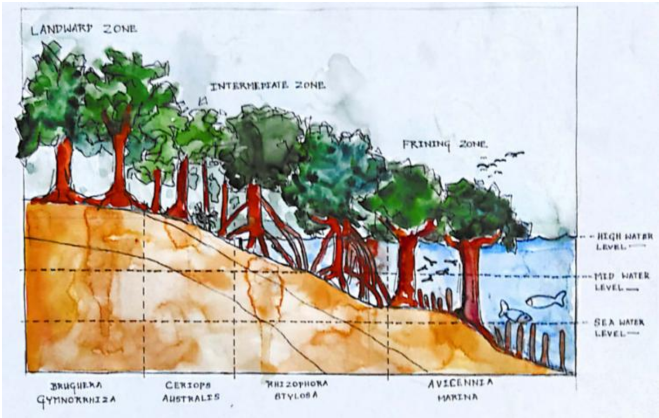

Figure 02, Cross section of the Mangrove Conservation Zones (Authors' creation)

3.3 EXISTING MANGROVE RESTORATION EFFORTS AND PRACTICES

Figure 03, Existing product developments for the mangrove re-plantation
(Schmitt & Duke, 2015; Perricone et al., 2023; Lee & Lee, 2016)
Image 1 :PVC Planter cover, 2 :Mangrove seed planter Concrete , 3 :Mangrove Tree planters concrete 4 :Mangrove planter pod as a wave breaker

Conventional restoration methods such as plastic barrels, concrete planters, and fishing nets—provide temporary protection but often disrupt water flow, block oxygen exchange, and contribute to plastic pollution (Schmitt & Duke, 2015; Perricone et al., 2023). Concrete based planters, though more durable, restrict root expansion and increase production costs (Lee & Lee, 2016). In Sri Lanka, locally improvised methods using roofing tiles and netting have yielded inconsistent results and introduced non biodegradable waste into lagoon ecosystems. These shortcomings indicate a need for biodegradable, low cost, and environmentally adaptive designs that integrate material science and ecological engineering principles (Sasanpour et al., 2021; Pereira et al., 2022).

3.4 CONTEMPORARY PRACTICES AND SUSTAINABLE METHODS

Increasing the Re-plantation rate of mangroves involves several strategic approaches such as selecting suitable planting sites, employing proper techniques, and providing ongoing maintenance. Root covering methods, like plastic barrels, covering by roofing tiles and fishing nets, have been used to protect plants but often cause issues such as trapping algae or failing to stabilize the plant. However, these approaches have often been problematic. Planting rate increasing materials are essential for the successful restoration of mangroves. Some of the materials found in the context such as clay and husk are now being used in Sri Lankan nurseries to improve the growth rates. As clay promotes water retention and root aeration, while coconut husk helps stablize planting site and improve soil conditions (Jayawardane et al., 2015; Kusumo et al., 2018). As a researcher after studying these practices, identified that clay plays a significant role in enhancing the success of mangrove restoration efforts.

3.5 MATERIAL INNOVATION IN ECO-DESIGN AND BIODEGRADABLE SOLUTIONS

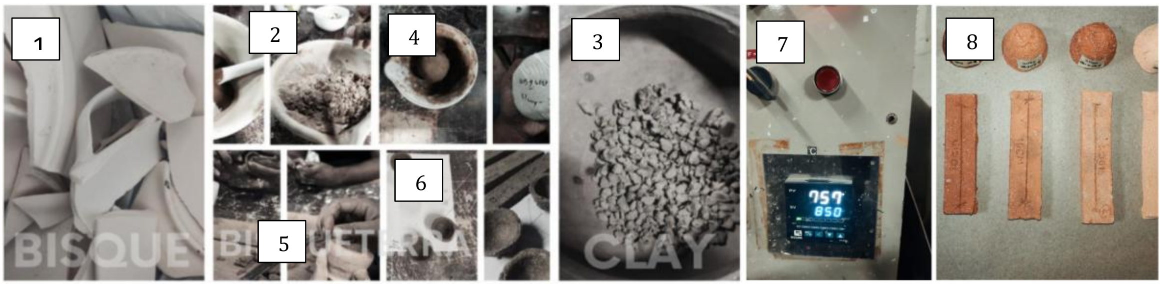

Figure 04, Material Development Process *(Uresha & Ranasinghe, 2024)*
Image, 1,3: Samples were prepared by first crushing bisque ware and clay into powders, 2: Mixing them with water 4: Create a pulp, 5,6: Mixture was then moulded into three distinct sample types- 10 cm^2 slabs for shrinkage measurement, 20 ml capacity pots for assessing porosity and water absorption, and solid 2 cm thick slabs for evaluating strength. 7: Firing, the kiln was allowed to cool down before proceeding with the next set. 8: Fired Samples.

The research explored sustainable material alternatives for mangrove restoration, focusing on re purposing bisque ware waste. Various ratios of bisque ware and clay were tested at firing temperatures of 500°C, 650°C, 750°C, and 850°C to assess their physical and functional properties. Among these, the 50% bisque ware and 50% clay composition fired at 500°C exhibited the most favorable characteristics. This mixture retained an earthy colour with minimal shrinkage, making it ideal for precise shaping and molding. Additionally, the material demonstrated good water absorption while maintaining structural integrity, which is essential for supporting mangrove seedlings in brackish water environments (Uresha & Ranasinghe, 2024).

The 500°C fired sample was found to be the most energy efficient, reducing fuel consumption while preserving the material's beneficial properties. Its manageable weight and ease of casting make it suitable for producing seedling pods and substrate supports, offering a practical solution for large scale restoration efforts. The material's fragility ensures that it can gradually disintegrate, allowing mangrove roots to penetrate and establish themselves in the soil. This property is crucial for enhancing plant stability and survival rates, as mangroves require strong root systems to succeed in challenging coastal conditions. This finding supports the feasibility of developing scalable, sustainable materials within existing Sri Lankan manufacturing contexts.

3.6 THEORETICAL FRAMEWORK FOR DESIGN DEVELOPMENT

The research adopts a Design-for-Environment (DfE) framework that positions product design as an ecological intervention rather than a purely technical activity. DfE integrates environmental considerations into all stages of the design process from material selection and production to use and end of life degradation (Graedel & Allenby, 2010; Vezzoli & Kohtala, 2018). Within this framework, the Aqua Nest is conceived not only as a protective device but also as part of a closed ecological cycle in which its decomposition contributes nutrients back into the mangrove substrate. The framework encourages systems thinking, where social design approach, material, and ecological factors are addressed collectively to improve both environmental and community outcomes (Brezet & van Hemel, 2021).

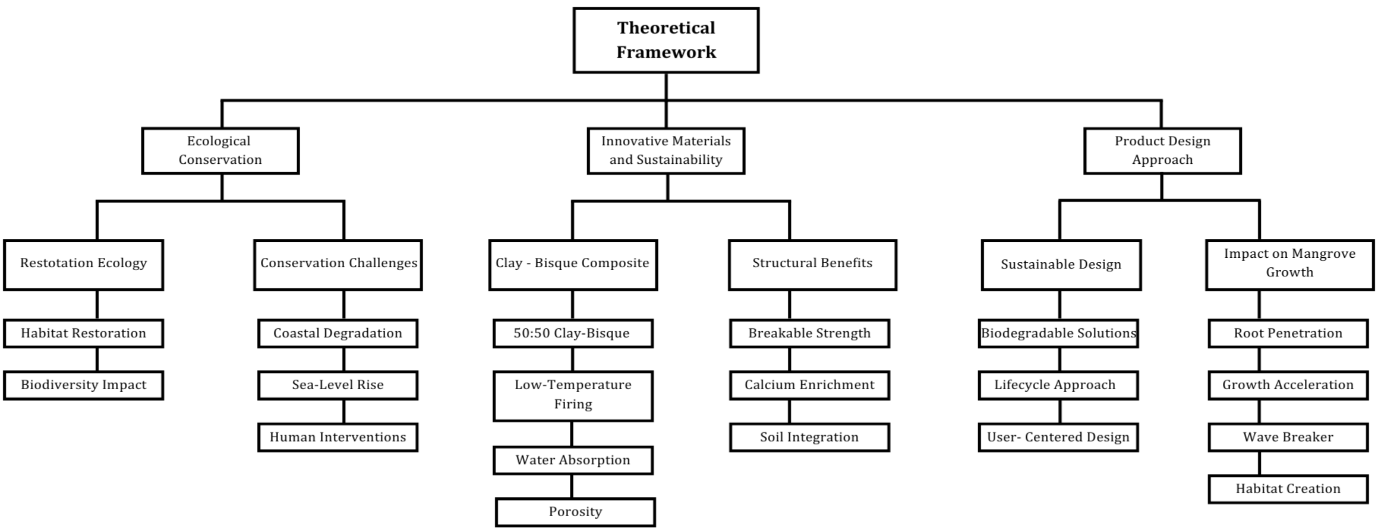

Figure 05, Theoretical Framework (Authors' Creation)

3.7 CONCEPTUAL FRAMEWORK FOR DESIGN DEVELOPMENT
The conceptual framework integrates restoration ecology, material innovation, and Design-for-Environment principles. It identifies seedling stability, root anchoring, biodegradability, and ecological integration as core design priorities. The Aqua Nest embodies these through a circular design approach that repurposes ceramic waste into a biodegradable protector, supporting mangrove growth while reducing carbon and material waste in coastal restoration.

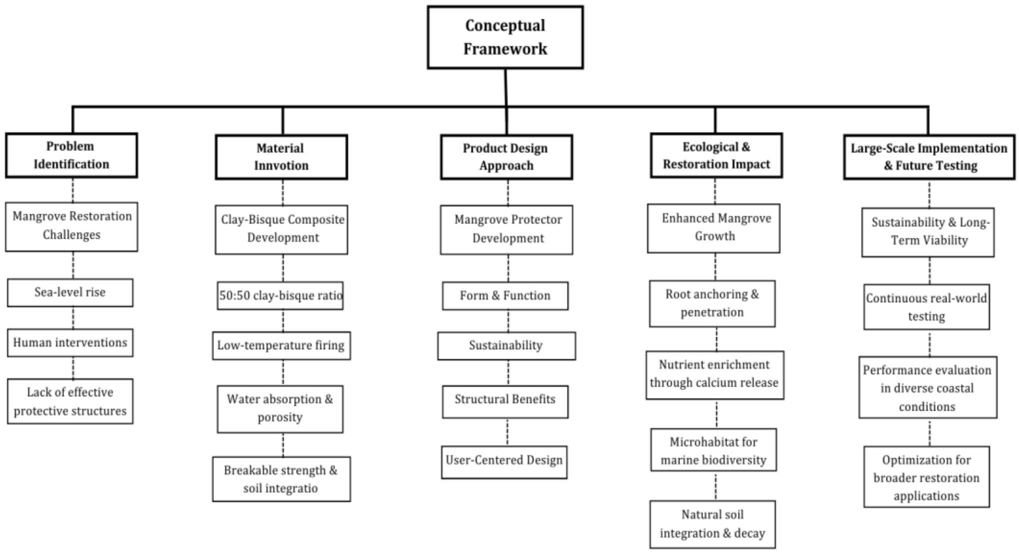

Figure 06, Conceptual Framework *(Authors' Creation)*

4. Methodology

4.1 RESEARCH APPROACH
This study follows a design research methodology guided by the principles of Design for Environment (DfE) and sustainable product innovation. It adopts an experimental and qualitative research approach to explore how design can directly contribute to ecological restoration through material and functional testing. The research positions product design as an ecological intervention, integrating environmental responsibility into every stage of the design process—from problem identification to material selection, prototyping, and contextual evaluation. The goal is not only to produce a functional artefact but also to generate new design knowledge applicable to coastal restoration contexts. The framework aligns with DfE principles outlined by Vezzoli and Kohtala (2018) and emphasises circular material use, minimal environmental impact, and community based scalability.

4.2 DESIGN METHODOLOGY
The study employed an iterative, human and environment centred design process structured around four key phases:

Contextual Research
Secondary data on mangrove degradation, restoration challenges, and local material availability were reviewed. Interviews with community members and environmental officers provided insight into real world restoration practices.

Ideation and Concept Development
Sketching and digital modelling were used to explore multiple form concepts that enhance seedling stability, water flow, and anchoring.

Material Experimentation
Laboratory tests were conducted to develop a biodegradable composite from porcelain bisque waste and clay, exploring ratios and firing temperatures to achieve controlled porosity and degradation.

Prototype Evaluation
Scaled prototypes were field tested to evaluate functional performance and ecological compatibility in natural brackish water conditions.
This structure follows a Research through Design (RtD) approach, where making and testing serve as primary means of knowledge generation.

4.3 MATERIAL DEVELOPMENT

For the material development phase, the experiment was done with various combinations of porcelain bisque ware and red clay to determine the optimal mix in the following ratios: 20% bisque ware to 80% clay, 40% bisque ware to 60% clay, 50% bisque ware to 50% clay, 60% bisque ware to 40% clay, and 80% bisque ware to 20% clay. These mixtures will then be fired at temperatures of 500°C, 650°C, 750°C, and 850°C. Additionally, several shapes were developed and tested to evaluate design qualities, penetration efficiency, and water absorption, ensuring the final structure effectively supports seedling stability and enhances mangrove restoration efforts. This process aims to identify the most effective material combination for enhancing plant growth and stability in mangrove restoration projects.

4.4 PROTOTYPE DEVELOPMENT AND TESTING

The product development methodology focused on designing an eco friendly mangrove protector that enhances seedling stability while supporting the surrounding ecosystem. The Aqua Nest form was engineered to withstand tidal forces and erosion, ensuring structural strength while allowing gradual biodegradation. A porous bisque clay composite was developed to optimize water retention, aeration, and root penetration, promoting healthy growth. Design parameters such as size, wall thickness, and weight were refined for efficient manufacturing, transport, and field deployment, while the perforated geometry enabled controlled water flow that prevents sediment blockage and maintains ecological balance. Its non toxic, biodegradable composition supports marine biodiversity by offering shelter for small aquatic organisms and encouraging natural sediment movement, thus contributing to mangrove ecosystem resilience. Building on these design principles, two full scale Aqua Nest prototypes were fabricated through slip casting, each approximately 180 mm in diameter with distributed openings for tidal circulation and root extension. 21 days field trial at a Koggala lagoon site in southern Sri Lanka, conducted under moderate tidal conditions and compared with unprotected control seedlings, assessed stability, seed retention, and ecological response through qualitative observation and photographic documentation.

4.5 PRELIMINARY FIELD CONTEXT AND EMPIRICAL SCOPE

Preliminary evaluation relied on direct qualitative observation during the 21 days field trial. Site inspections were carried out every three days to document prototype stability, seedling condition, and surface responses under natural tidal movement. Photographs and field notes were used to record visible changes such as root emergence, algae formation, and the presence of small aquatic fauna around the Aqua Nest units. Both prototypes remained stable throughout the period, showing no displacement under moderate wave activity.

5. Analysis and Discussion

5.1 DESIGN CONSIDERATIONS

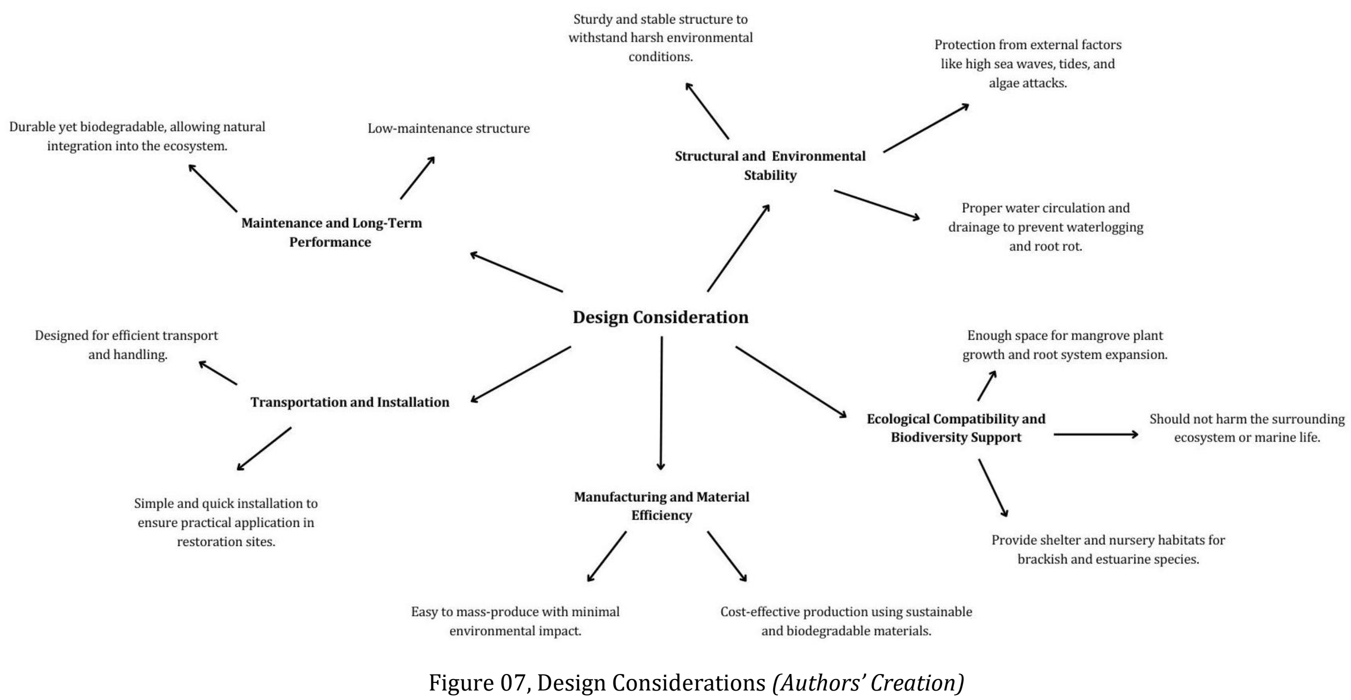

Figure 07, Design Considerations *(Authors' Creation)*

The Aqua Nest project was analysed through the DfE framework, positioning the product as an eco-innovative intervention for mangrove restoration. The design aimed to minimize ecological disruption while supporting natural regeneration processes. By combining circular design thinking with environmental systems awareness, the prototype aligns with global sustainable product development practices (Bhamra, 2021; Vezzoli & Kohtala, 2018). The form was intentionally modelled to respond to coastal hydrodynamics stabilising seedlings while allowing water circulation and sediment flow. Its hollow, perforated geometry supports aeration and root penetration, balancing structural resilience with material degradability. This approach reflects DfE principles of designing with ecosystems rather than for them, enabling nature to complete the product's functional cycle through biodegradation and sediment assimilation (Graedel & Allenby, 2010).

5.2 DESIGN DEVELOPMENT AND PROTOTYPE OUTCOMES

The development process progressed through ideation, form refinement, prototyping, and field evaluation. During ideation, multiple concepts were explored to address mangrove restoration challenges ensuring seedling stability, supporting root expansion, and maintaining ecological balance. Inspired by natural seed pods and coral forms, the structure was conceived to integrate visually and functionally with coastal habitats while resisting tidal forces.

Figure 08, Prototype Developments *(Authors' Creation)*

In the form refinement stage, sketches were translated into 3D models to optimize geometry, perforation layout, and manufacturability. Iterations focused on balancing weight, buoyancy, and erosion resistance while enabling water flow and root penetration. The final design achieved a stable form that facilitates seedling protection and early habitat formation.

Each prototype was produced using a porous bisque clay composite made from recycled porcelain waste, selected for its strength, porosity, and biodegradability. Two full scale Aqua Nest units (180 mm in diameter) were slip cast and tested at a Koggala lagoon in southern Sri Lanka under moderate tidal exposure. Both maintained positional stability, resisted displacement, and showed no material cracking. Laboratory observations confirmed adequate porosity for oxygen exchange and gradual degradation. These outcomes demonstrate the technical and ecological feasibility of reusing ceramic waste for coastal restoration, consistent with previous studies on biodegradable marine materials (Pereira et al., 2022; Sasanpour et al., 2021).

5.3 PRELIMINARY FIELD OBSERVATIONS

Field trials were conducted at Koggala Lagoon, Galle District, in southern Sri Lanka, over a 21 days observation period. Two Aqua Nest units were deployed alongside unprotected control seedlings to evaluate their functional performance under natural brackish tidal conditions.

Figure 09, Prototype Testing and Refine (Authors' Creation)

Throughout the test period, both prototypes maintained positional stability against moderate wave activity. No seed displacement occurred within the protectors, whereas several unprotected control seedlings were uprooted or washed away. After approximately 14 days, early root anchoring was observed through the perforations in the protector walls. The surface of both units developed a thin algal layer, and small brackish water insects and crustaceans including copepods and juvenile shrimps began inhabiting the openings, suggesting early ecological compatibility.

These short term qualitative observations indicate that the design successfully provided a micro habitat and initial structural protection. However, the 21 days duration was insufficient to assess full seedling maturity or material degradation. Future studies should include extended monitoring over six to twelve months to capture long term seedling survival, structural performance, and ecological interactions under variable environmental conditions. Based on laboratory ageing tests and the material's composition, the Aqua Nest is expected to undergo complete natural degradation within approximately two years, progressively enriching the surrounding sediment with calcium and clay minerals.

While these results demonstrate early performance, quantitative data such as measured survival percentages, growth rates, and degradation metrics will be required in future research to validate and statistically support these initial findings.

5.4 EXPECTED ECOLOGICAL OUTCOMES

Building on field observations and material analysis, the Aqua Nest is conceptually projected to follow four ecological phases: stabilisation, colonisation, integration, and dissolution. Initially, the structure buffers tidal energy, reduces seed displacement, and maintains oxygenated conditions for early root penetration. As microorganisms and small aquatic fauna colonise its porous matrix, a biofilm develops, enhancing nutrient exchange and ecological anchorage. Over time, the biodegradable bisque clay material gradually releases calcium and silicate minerals, enriching the sediment and supporting mangrove root growth. Eventually, the protector disintegrates and assimilates into the substrate, leaving a stable root network and restored sediment balance. This hypothesised pathway reflects eco-engineering models in which biodegradable scaffolds initiate habitat formation before natural systems achieve self sustaining stability (Sasanpour et al., 2021).

The following stages describe this ecological sequence in greater detail.

Stage 01: Planting the Seed in Protector (Aqua Nest)

The Aqua Nest provides a stable environment for mangrove seeds, protecting them from strong sea waves and tidal movements. This ensures that the seeds remain in place, allowing for proper germination without being displaced by water currents.

Stage 02: Growing the Plant with a Strong Main Root

As the seed develops, the steady environment of the Aqua Nest supports the formation of a strong main root. The structure shields the young plant from external disturbances, allowing it to establish a firm foundation in the aquatic ecosystem.

Stage 03: Anchoring Prop Roots on the Protector

As the mangrove matures, it begins to develop prop roots that extend outward. The Protector's textured surface and porous material aid in root anchoring, ensuring better stability and reducing plant mortality.

Stage 04: Providing Shelter and Algae Food

The porous nature of the Aqua Nest encourages algae and biofilm formation, which in turn attracts small aquatic creatures such as shrimp, crabs, and juvenile fish. These organisms find shelter in the hollow spaces, contributing to the ecosystem's natural food chain.

Stage 05: Eating Calcium and Growing Roots

The bisque material in the Aqua Nest is rich in calcium, which leaches into the water over time. This provides essential nutrients for both plant growth and marine organisms, further promoting the symbiotic relationship between flora and fauna within the habitat.

Stage 06: Decaying and Creating a New Habitat

Over time, the Aqua Nest naturally decomposes, enriching the surrounding soil with organic material. This process creates a fertile ground for new mangrove seedlings to grow, contributing to long term habitat restoration and ecosystem sustainability.

5.5 SOCIO-ECONOMIC AND ENVIRONMENTAL RELEVANCE

Beyond its ecological function, the Aqua Nest embodies a circular economy approach that links industrial waste recovery with community driven environmental restoration. Sri Lanka's ceramic sector produces substantial bisque ware waste, which can be repurposed as a raw material for ecosystem rehabilitation rather than discarded. By integrating this waste stream into the production cycle, the design converts an industrial by product into an ecological asset.

The slip casting technique enables decentralised fabrication near coastal areas, reducing transport emissions and creating local employment opportunities. Involving coastal communities in the manufacturing and deployment processes fosters environmental stewardship and provides income diversification for households engaged in fishing or craft based livelihoods.

Economically, the design's simplicity supports scalable, low cost implementation through mould reuse and locally available materials. Environmentally, each unit contributes to sediment stabilisation and biodiversity enhancement before naturally degrading without residue. These social, economic, and ecological benefits collectively align with the United Nations' Sustainable Development Goals for responsible consumption and production (Brezet & van Hemel, 2021). Long term implementation will, however, depend on maintaining consistent waste supply chains and quality assurance through collaboration between ceramic manufacturers, researchers, and conservation agencies.

5.6 STUDY LIMITATIONS, ECONOMIC FEASIBILITY, AND ECOLOGICAL RISKS

This study was limited to short term qualitative testing; quantitative data on seedling survival rates, degradation kinetics, and ecosystem response are required for long term validation. Extended monitoring over 6–12 months is recommended to assess seasonal variations and material behaviour under diverse salinity conditions.

Economic Feasibility and Scalability:
A preliminary cost assessment (2024) estimated the production cost of a single Aqua Nest unit at approximately LKR 240, including raw materials, labour, and firing. These figures, derived from small-batch production, are indicative and subject to variation with changes in energy prices, transportation, and raw material availability. The primary material recycled bisque waste is currently a low-cost industrial by product but may increase in value if large scale demand develops. Despite these uncertainties, the slip casting process enables decentralised, low cost manufacturing using existing ceramic facilities, supporting community participation and circular economy principles.

Potential Ecological Risks:
Although designed to be environmentally compatible, the long-term ecological impacts of the Aqua Nest require continued observation. Potential risks include unintentional attraction of non native species, alteration of local sediment dynamics, or imbalance in microfaunal populations. These factors warrant careful ecological monitoring to ensure that artificial structures integrate harmoniously into natural systems without disrupting existing biodiversity.

6. Conclusion

The Aqua Nest project demonstrates the potential of sustainable product design to address environmental and social challenges through practical innovation. By transforming recycled porcelain bisque waste into a biodegradable mangrove protector, this study presents a circular design solution that enhances seedling stability, supports early ecological integration, and reduces industrial waste. Preliminary field observations confirmed the prototype's ability to remain stable under tidal conditions and promote root anchoring and habitat formation. Although the findings are qualitative and based on short term testing, they provide a strong foundation for extended field monitoring and quantitative validation. The approach also shows promise for low cost, community based production, linking local livelihoods with restoration activities. Overall, Aqua Nest highlights how design-for-environment principles can contribute to sustainable coastal restoration and strengthen climate resilience in Sri Lanka.

7. References

Bhamra, T. (2021). Thirty years of design for sustainability: An evolution of research, policy and practice. Design Science,7 , e20. https://doi.org/10.1017/dsj.2021.13

Brezet, H., & van Hemel, C. (2021). Ecodesign: A promising approach to sustainable production and consumption. United Nations Environment Programme. https://wedocs.unep.org/handle/20.500.11822/33379

Chathuranga, H. N., Senanayake, F. R., Yintoo, A. Y., Zoysa, D., & Min, T. T. (2024, July 22). Ascertainment of photosynthetic biomass accumulation rates of individual trees as a proxy to measure the primary ecosystem services production in the early growth phase of selected mangrove plant species in Shwe Thaung Yan coastal area, Myanmar. International Conference on Mangroves for Sustainability (ICMS), Beragala, Sri Lanka.

Graedel, T. E., & Allenby, B. R. (2010). Industrial ecology and sustainable engineering. Prentice Hall.

Jayawardane, L., Kodituwakku, K. A., Ranaweera, K. K. D. S., & De Silva, D. (2015). Effect of clay on growth and biomass of mangrove seedlings in brackish water. Journal of the National Science Foundation of Sri Lanka, 43(2), 141–147. https://doi.org/10.4038/jnsfsr.v43i2.7946

Kodikara, K. A. S., Mukherjee, N., Jayatissa, L. P., Dahdouh-Guebas, F., & Koedam, N. (2017). Have mangrove restoration projects worked? An in-depth study in Sri Lanka. Restoration Ecology, 25(5), 705–716. https://doi.org/10.1111/rec.12492

Kotagama, S. W., & Wijesundara, S. (2007). Mangrove conservation in Sri Lanka. National Science Foundation of Sri Lanka.

Kusumo, A., Ong, J. E., & Dahdouh-Guebas, F. (2018). The role of soil characteristics in the success of mangrove rehabilitation. Wetlands Ecology and Management, 26(3), 233–243. https://doi.org/10.1007/s11273-017-9575-4

Lee, S.H., & Lee, W.K. (2016). TetraPOT. Inhabitat. https://inhabitat.com/tetrapot-uses-mangroves-to-grow-a-greener-sea-defense-system/tetrapot-by-sheng-hung-lee-1/

Pereira, M., Alves, R., & Silva, A. (2022). Designing biodegradable composites for coastal and marine applications. Journal of Cleaner Production, 363, 132492. https://doi.org/10.1016/j.jclepro.2022.132492

Perricone, M., Rossi, F., & Gagliano, A. (2023). Sustainable design strategies for coastal protection: Evaluating biodegradable and low-impact materials for marine restoration. Ocean & Coastal Management, 239, 106643. https://doi.org/10.1016/j.ocecoaman.2023.106643

Sasanpour, F., Rahbar, M., & Sadeghi, S. (2021). Eco-engineering with biodegradable structures for mangrove and wetland restoration. Ecological Engineering, 165, 106223. https://doi.org/10.1016/j.ecoleng.2021.106223

Schmitt, K., & Duke, N. C. (2015). Mangrove management, assessment and monitoring. In Encyclopedia of Earth Sciences Series. https://www.researchgate.net/publication/281836109

Uresha, E. D. T., & Ranasinghe, W. M. N. D. (2024). Enhancing mangrove restoration through innovative and sustainable design solutions for Sri Lanka. FARU 2024 Conference Proceedings, University of Moratuwa.

Vezzoli, C., & Kohtala, C. (2018). Design for environmental sustainability: Life cycle design of products. Springer. https://doi.org/10.1007/978-1-4471-7472-1

Wickramasinghe, S., Wijayasinghe, M., & Sarathchandra, C. (2022). Sri Lankan mangroves: Biodiversity, livelihoods, and conservation. In Coastal Ecosystems of the Tropical Indo-Pacific (pp. 297–329). Springer. https://doi.org/10.1007/978-981-19-0519-3_13