ENHANCING MANGROVE RESTORATION THROUGH INNOVATIVE AND SUSTAINABLE DESIGN SOLUTION FOR SRI LANKA

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Abstract: Mangrove forests are critical for coastal protection, biodiversity, and carbon storage, but they suffer substantial risks from coastal development and climate change. This study critically evaluates previous mangrove conservation initiatives and emphasizes the need for innovative ways to improve present methods. Based on sustainable design principles, the research proposes identify a path to develop a product for increasing the mangrove restoration challenges, to focus to the product's design, assesses. The success and limitations of prior protection techniques, and investigates the integration of environmentally friendly materials and sophisticated design elements. This study seeks to improve mangrove restoration efforts and encourage their preservation by offering a novel strategy that combines sustainable materials and current technologies. The findings offer practical recommendations for enhancing mangrove protection and underscore the potential for continued innovation in this field.

Keywords: *Mangroves Ecosystem, Restoration, Sustainable solution, Re-usability, Circular Economy*

1. Introduction

Mangrove ecosystems are among the most resilient and ecologically vital areas globally, playing a crucial role in sustaining coastal biodiversity and supporting the livelihoods of surrounding communities. In Sri Lanka, these coastal forests are instrumental in safeguarding natural habitats from erosion, storm surges, and rising sea levels, while also providing essential homes for a wide array of marine and terrestrial species. Despite their significance, mangroves face severe threats from human activities, climate change, and natural disasters, jeopardizing their continued existence and the critical services they offer. The devastating impact of the 2004 Indian Ocean tsunami starkly underscored the vulnerability of Sri Lanka's mangrove forests, revealing the extent of damage and highlighting the urgent need for restoration efforts (Kodikara et al., 2017). In response to the extensive destruction and degradation caused by both natural disasters and human activities, the Sri Lankan government and various NGOs have initiated restoration projects to revitalize these crucial ecosystems. This global trend toward mangrove restoration underscores the increasing recognition of their importance. However, achieving effective restoration requires addressing the specific ecological challenges and ensuring the sustainability of these efforts. There is a lack of literature on this research topic and narrowing to the material solution, as no prior studies have been conducted using this specific material, and this research aims to fulfill this gap.

2. Background

2.1 BACKGROUND ON MANGROVE ECOSYSTEM IN SRI LANKA

Figure 01, Impact with Mangroves (Author creation)

Figure 02, Impact without Mangroves (Author creation)

Mangrove ecosystems are integral to the coastal ecosystems worldwide, particularly in Sri Lanka. They provide substantial ecological services, including stabilizing shorelines and offering habitat and breeding sites for marine biodiversity.

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Additionally, mangroves act as natural safeguards against disasters such as cyclones, tsunamis, low-intensity storms, and wave surges. Renowned as the most valuable and interesting marine resources, mangroves contribute significantly to both ecological stability and economic sustainability. (Kotagama, S. W., & Wijesundara, S. 2007). The research will discuss in detail information about the diversity of mangroves, distribution of mangroves in coastal regions and economic and ecological benefits derived from mangroves.

2.2 IMPORTACE FOR THE COASTAL BIO DIVERSITY

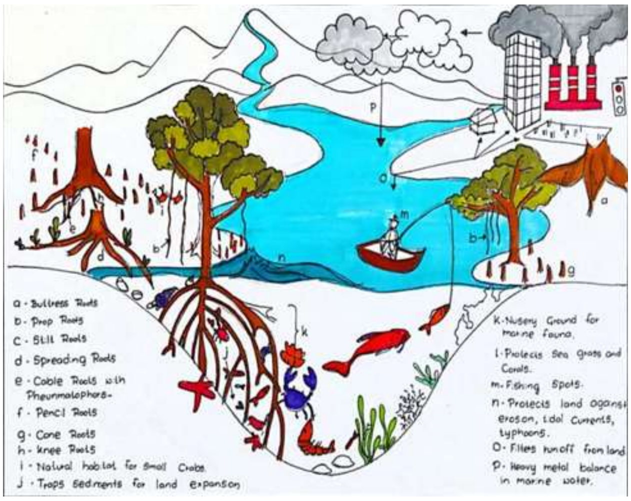

Figure 03, Importance of Mangrove Eco System *(Author creation)*

In Sri Lanka, mangroves are an important component of the coastal biodiversity because they offer a variety of marine and terrestrial species with necessary habitats. These distinct ecosystems serve as havens for a variety of wildlife. Many commercially significant fish and crabs find their natural home in the mangrove woods, which act as nurseries for immature fish and crabs until they are old enough to migrate to coastal regions. This crucial function highlights the significance of mangroves for birds, numerous aquatic plants, reptiles, and the larger ecological network in addition to marine life. (Kusum et al., n.d.).

2.3 CHALLENGES FACED BY MANGROVE ECO SYSTEM IN SRI LANKA

Anthropogenic activities and environmental changes pose a serious threat to mangrove ecosystems, even though their substantial contributions to the ecological and economic stability of Sri Lanka. Over exploitation, pollution, and coastal development are the main human-caused factors destroying these vital habitats. Furthermore, these problems are made worse by climate change, since increasing sea levels and harsher weather put additional strain on the fragile ecosystem (Kodikara et al., 2017). Mangrove plants are particularly vulnerable to high sea waves, salinity, crab and insect infestations, and variable tides. These plants are essential for protecting coastal areas and maintaining marine life. In addition to impeding the growth of new plants, these causes cause a notable drop in biodiversity and habitat loss.

2.4 RESEARCH PROBLEM AND OBJECTIVES

Figure 04, Failures in mangrove conservation efforts (Kodikara et al., 2017)

Image 1 : Dried plant, 2 : An uprooted plant, 3: Plant root attacked by a crab, 4 :Plant covered by algae that caused its death,
5 / 6: Insect attacks, 7: Uprooted plant, 8: Drying & Quality seed plants.

The purpose of this research is to find at what factors affect mangrove restoration projects in Sri Lanka and whether they succeed or fail. The main goals are to evaluate the efficacy of existing restoration and reintroduction techniques and to comprehend the ecological conditions necessary for mangrove persistence. The study will also look at socioeconomic issues that affect mangrove protection and pinpoint roadblocks that prevent efficient conservation measures. The goal of the research is to improve the resilience of Sri Lanka's mangrove ecosystems by addressing these issues and offering evidence-based recommendations that can improve present practices.

2.5 SIGNIFICANT OF THIS STUDY

The understanding of mangrove ecosystem management and restoration in Sri Lanka would be greatly advanced by this study. The research will shed important light on the ecological needs of mangroves and the efficacy of current techniques by analyzing the variables determining the success or failure of restoration operations. These understandings are critical for creating more focused and successful conservation plans that will guarantee the ecological well-being of mangrove ecosystems and greatly enhance the results of restoration initiatives. As the significant of this study, There is no any proper research done under identify the path to product design solutions. Because of that there is a lack of research done in Sri Lankan Context, and this research will be an supportive design solution to fill the gap to protect mangrove plantations.

3. Literature Review

3.1 CURRENT STAGE OF MANGROVE CONSERVATION

The catastrophic 2004 Indian Ocean tsunami, which claimed an estimated 230,000 to 280,000 lives, including over 35,000 in Sri Lanka alone, That caused to interest among Southeast Asian governments, NGOs, and coastal communities in restoring mangrove ecosystems. Also according to the Most of the mangrove restoration projects in Sri Lanka have failed. Among the 23 Restoration project sites that covered about 2000 Hectares, Only 200-220 or Under 12%, were even marginally successful. Only three sites or about 13%, were successful to any degree at all, and each of these was under 50% As an investment of over 13 Million in USD in these projects (Kodikara et al.,2017).

3.2 SRI LANKAN MANGROVE CONSERVATION SELECTIONS

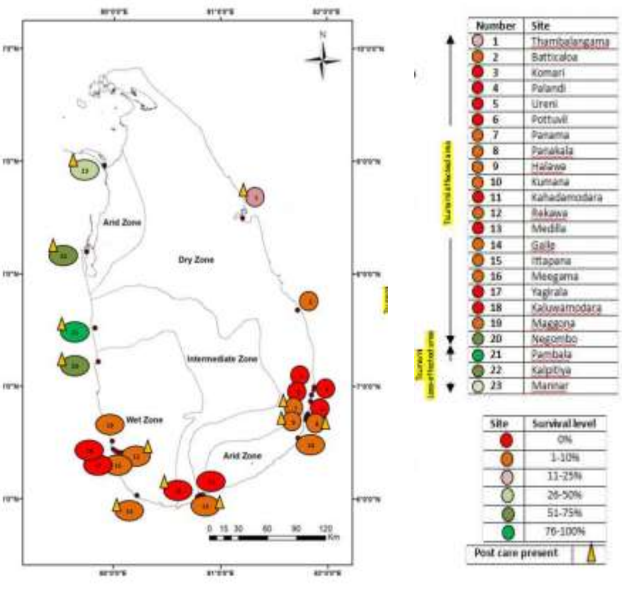

Figure 05, Failed restoration sites and growth rates

(Kodikara et al.,2017)

The study of Sri Lankan mangrove conservation highlights the significant obstacles that restoration projects face, especially when looking at locations with slow growth rates. While some sites show survival rates between 1 and 10%, eight sites have reported a 0% survival rate. The Southern and South-eastern provinces are the majority of these low-growth rate sites, which are distinguished by significant sea wave activity (Kodikara et at.,2017). These places are known for having high failure rates because the immature mangrove plants are often uprooted by the strong waves that constantly disturb them.

3.3 IDENTIFYING THE CONSERVATION ZONES

An important factor in improving growth rates and the general health of an ecosystem is the establishment of conservation zones, which are usually defined as green belts. Lagoon zones are surrounded by a conservation belt that is carefully established as illustrated in Figure 06, typically covering an area of 10 meters in width. This belt serves as a supportive and protective barrier that lessens wave energy, stabilizes the shoreline, and lessens sedimentation. The mangrove growth is more stable in the belt since it encompasses both the nearby land and the lagoon. The green belt promotes the deposition of organic materials and offers a habitat that is favourable to the emergence and growth of mangrove species (T. Kapurusinghe, personal communication, April 28, 2023).

Figure 06, Mangrove Conservation Belt in a lagoon Sri Lanka *(Author creation)*

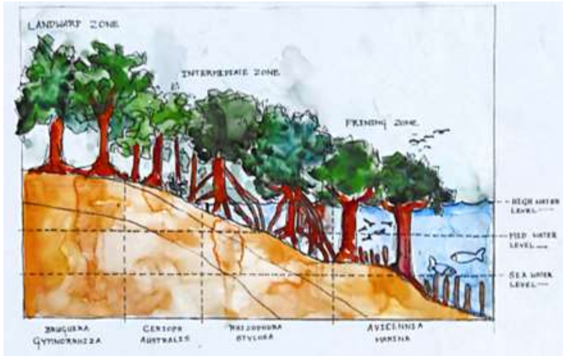

Figure 07, Mangrove Conservation Zones *(Author creation)*

Mangrove ecosystems can be divided in to three zones as illustrated the Figure 07. The Fringing Zone, dominated by Avicennia marina, which thrives in high salinity and tidal areas and plays an important role in erosion control. The Intermediate Zone, where Rhizophora mucronata stabilizes sediments in moderate salinity conditions; and the Landward Zone, which is home to Bruguiera species that adapt to lower salinity and less frequent flooding. Each zone supports distinct mangrove species that are best adapted to specific environmental circumstances, which is critical for the general health of the ecosystem.

3.4 TYPES OF PLANT SELECTIONS FOR THE CONSERVATIONS

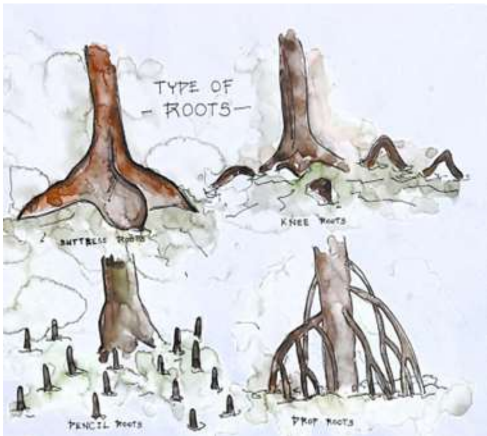

Figure 08, Types of mangrove roots for the plant selection
(Author creation)

The safeguarding of mangroves places a strong emphasis on choosing species that are compatible with the salinity, tidal inundation, and sediment types of the area. The following species are frequently given priority for conservation in Sri Lanka: Bruguiera gymnorrhiza, which grows in lower salinity conditions and has viviparous propagules that germinate on the parent tree, making it easy for the stems to disperse and establish in difficult environments; Avicennia marina, which is found in intermediate salinity zones and whose snorkel-like roots facilitate oxygen exchange in wet soils; and Rhizophora mucronata, which anchors coastal soil and supports small marine life in high salinity zones (Chathuranga et al., 2024).

3.5 MANGROVE RESTORATION EFFORTS AND PRACTICES

Restoration practices refer to the various techniques and approaches used to rehabilitate degraded mangrove ecosystems and enhance their ecological functions. These practices often involve innovative methods and materials aimed at improving mangrove growth, resilience, and integration into the surrounding environment. Successful restoration relies on principles of sustainable design, which include using eco-friendly materials and incorporating advanced technology to support the natural growth and health of mangroves.

In Global Context Several experimental strategies have been used worldwide to assist with mangrove restoration. Image 1:Shows an experiment PVC planter covers were initially used to protect Mangroves from debris. However, these protectors proved oneffective as they restricted the roots, access to CO_2, leading to plant mortality (Schmitt & Duke, 2015). Image 2:

The concrete Mangrove seed planter dome restricts root growth and soil interaction, preventing the plants prom developing in to a full eco system, and author said the method of using seedlings in concrete balls needs further clarifications (Schmitt & Duke, 2015). Image 3: mangrove tree planters concrete and this is an ongoing experimental research that can directly plant the seed, some how the cost is high and still need further clarification to get the knowlade how it's create the eco system and habitat with the roots and sediment(Perricone et al., 2023), image 4: Terra pods with wave breakers which were still in a conceptual level idea (Lee & Lee, 2016) andauthor said these concrete structures that resemble oversized toy jacks, protect shores across the world from life-threatening waves—but they are not environmentally friendly or sustainable (Inhabitat, 2016) .

Figure 09, 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

In Sri Lanka, some Mangrove restoration efforts use Fishing nets, plastic barrels, and environment harmful materials have been used to rehabilitation initiatives to protect the mangrove roots. Given the submerged and sediment-rich environment of the mangroves, this technique might seem reasonable, but it has resulted in a number of problems. The plastic barriers have a tendency to collect trash and obstruct water flow, which can encourage the spread of illnesses and pests. These circumstances not only damage the mangroves but also provide a breeding habitat for dangerous organisms that endanger humans and other creatures.

Figure 10, Restoration methods founded by the Sri Lankan local communities
(Save Rathgama Lagoon Sanctuary - Sri Lanka, 2021.)

3.6 CONTEMPORARY PRACTICES AND SUSTAINABLE METHODS

Increasing the Re-plantation rate of mangroves involve 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 a 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 hush helps stablize planting site and improve soil conditions (Jayawardane et al., 2015; Kusumo et al., 2018).2018). As a researcher after studying these practices, Identified that clay plays a significant role in enhancing the success of mangrove restoration efforts.

3.7 IDENTIFICATION OF NEW SOLUTIONS FOR MANGROVE RESTORATION

As discussed in section 3.6, clay has been identified as an optimal solution for mangrove restoration because it naturally occurs in the ecosystem's sediments. In exploring suitable materials for restoration, research focused on the qualities that need for the Eco system, leading to the discovery of bisque ware as a particularly beneficial material. In Sri Lanka, the porcelain tableware industry produces significant amounts of bisque ware waste Explore the table 01 below, a low-fired clay that fired to 800’C material often discarded due to damages incurred during production (M.Ruwan, personal communication, August 11, 2022).

This material is typically dumped without a proper solution, despite its high porosity and calcium content, which are valuable qualities for brackish water planting (Wang & Wu, 2013). The porosity of bisque ware can enhance water retention and nutrient availability, essential for plant growth in mangrove restoration efforts. The clay industry in the region has historically thrived due to the availability of high-quality clay deposits and skilled labor. While the demand for traditional clay products has declined, the industry has adapted by producing decorative pottery and other items. Repurposing bisque ware waste for mangrove conservation can reduce waste and leverage its beneficial properties. The high porosity of bisque ware, combined with its calcium content, provides an optimal substrate for mangrove planting, promoting ecological and economic sustainability in Sri Lanka (Author findings; Shinozaki et al., 2018).

Table 01, 06 month of Bisque Damages in 2022 *(Author Creation)*

Month	Total Bisque Issued	Damaged Bisque ware	Damaged percentage
January 2022	4 31 261	16 540	3.69%
February 2022	4 00 534	13 737	3.31%
March 2022	5 21 341	19 584	3.62%
April 2022	3 23 801	13 109	3.89%
May 2022	4 63 031	18 261	3.79%
June 2022	4 34 098	15 177	3.37%
Total	2 104 066	96 408	

3.8 THEORETICAL FRAMEWORK

According to the gathered data The theoretical framework address the critical challenges in mangrove restoration, including the main factors and heading the conceptual framework by considering strengthening the effectiveness of restoration efforts

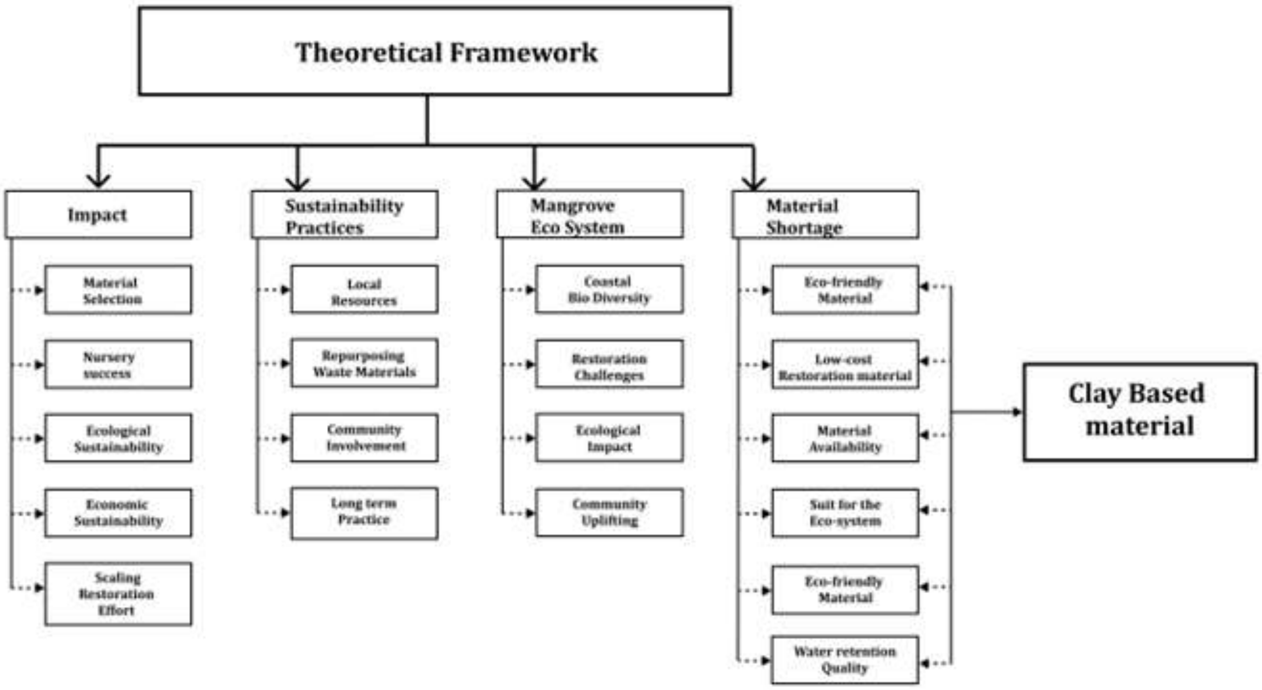

Figure 11, Theoretical Framework
(Author Creation)

3.9 CONCEPTUAL FRAMEWORK

The conceptual framework integrates the challenges and addresses them for mangrove ecosystem restoration, focusing on the impact of material shortages and sustainable solutions.

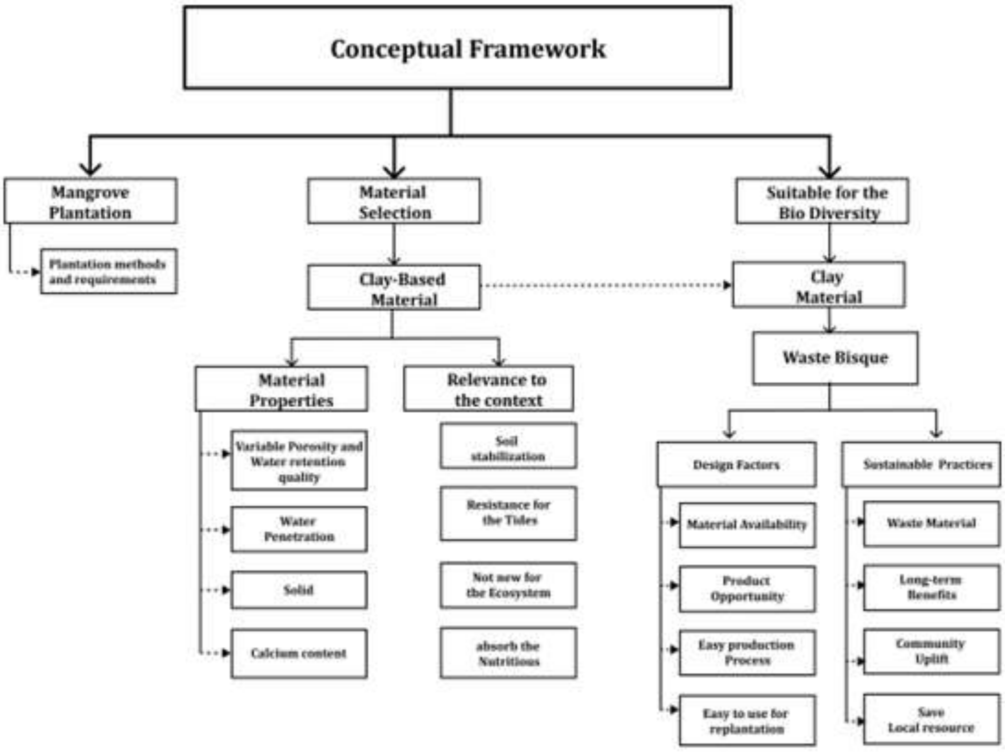

Figure 12, Conceptual Framework
(Author Creation)

4. Methodology

4.1 RESEARCH APPROACH
There is a notable lack of literature exploring the combination of bisque and clay for ecological restoration purposes. This research adopts and experimental approach to address the issue of the material shortages in mangrove restoration. The use of bisque ware, a high-porosity byproduct of porcelain manufacturing, as an aggregate material in conjunction with clay for mangrove restoration represents a substantial research gap. Because of its high calcium content and frequent disposal, bisque pottery offers a special chance to develop a novel material intended for brackish water situations. We can create a novel composite material that combines clay and bisque pottery, utilizing both materials' porosity and calcium content to promote plant growth and aid in restoration efforts. This novel method has the potential to greatly increase the efficacy of mangrove restoration initiatives in addition to providing a long-term solution for trash management.

4.2 THEORITICAL AND CONCEPTUAL FRAMEWORK
Both Theoretical and conceptual frameworks are incorporated to guide the research process. The theoretical framework address the selections of materials and methods by highlighting the significance of addressing material shortage and promoting sustainable practices in mangrove restoration. By addressing the existing and available knowledge, The conceptual framework is developed based on the theatrical frame work factors by addressing the new material intervention and considering product design solutions. Together, these frameworks provide the research design, material development, and experimental conditions to consider alignment with the core goals of ecological sustainability and restoration effectiveness.

4.3 DATA COLLECTION METHODS
For data collection, the author employed both quantitative and qualitative methods. Questionnaires were distributed to mangrove restoration teams to gather qualitative insights, while quantitative data was collected regarding waste materials. The author used grounded theory to explore data from both the Material findings and mangrove restoration communities. This approach enabled the systematic analysis of bisque ware waste types and quantities, identifying its potential for enhancing mangrove restoration. By examining waste characteristics and contextual applications, the author uncovered opportunities to repurpose bisque ware, revealing innovative ways to benefit both environmental restoration and industry practices.

4.4 LIMITATIONS
This experimental project faces several limitations. To obtain the most accurate results, the new material must be tested in real-world conditions with continuous assessments. Additionally, the author’s examination was limited to bisque ware from the porcelain tableware sector in Sri Lanka, which may not fully represent other sources or types of bisque waste. These constraints highlight the need for broader testing and validation to ensure the findings are applicable across various contexts.

4.5 MATERIAL DEVELOPMENT

For the material development phase, the experiment was done with various combinations of bisque ware and clay to determine the optimal mix. The bisque ware will be combined with clay 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 for further details look the section 5.2. This process aims to identify the most effective material combination for enhancing plant growth and stability in mangrove restoration projects.

5. ANALYSIS

5.1 WHY CLAY IS USE AS A BEST MATERIAL FOR THE ECO SYSTEM

Clay as a material shows an optimal material for mangrove ecosystem restoration due to it is propoties and suitability for brackish water environment, as discussed in section 3.6 and 3.7. Natural qualities such as water retention, Adopt to the salinity water conditions and creating stable substrate that supports mangrove seeding growth. As an important fact clay compatibility with other materials such as bisque ware, improve the structural and functional qualities that can control the shape and form of the design withing the limitations, Furthermore clay's abundance and low environmental footprint make it a sustainable and cost-effective solution for addressing material shortages in restoration projects .

5.2 MATERIAL EXPERIMENT

Figure 13, Material Development Process *(Author Creation)*

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 cm² 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

As the above process, This step-by-step firing process ensured that each batch was treated under the same conditions, allowing for a clear comparison of the effects of temperature and material composition on the physical properties of the final products.The study explored various combinations of bisque ware and clay to determine the optimal mix for enhancing material properties suitable for mangrove restoration. The combinations tested were:

Table 2, Tested sample ratios and firing temperatures *(Author Creation)*

Bisque ware	Roofing Clay	Firing temperatures			
20%	80%	500°C	650°C	750°C	850°C
50%	50%	500°C	650°C	750°C	850°C
60%	40%	500°C	650°C	750°C	850°C
80%	20%	500°C	650°C	750°C	850°C

The rationale behind using these ratios was to evaluate how varying proportions of bisque ware, known for its high porosity and calcium content, affect the resulting material's properties. The lower percentages of bisque ware (20% and 40%) were anticipated to yield materials with moderate porosity and strength, while higher percentages (50%, 60%, and 80%) were expected to enhance porosity and water absorption, potentially improving the material's suitability for brackish water environments. The aim was to identify a balance that provides both structural integrity and beneficial characteristics for plant growth.

5.3 MATERIAL QUALITIES

The analysis of samples fired at different temperatures reveals distinct qualities across the firing ranges:

Table 3, Sample qualities *(Author Creation)*

500°C Fired Samples	These samples showcase an earthy colour and a rustic charm, with the lowest shrinkage rate among all temperatures, making them ideal for precise shaping. They have good water absorption while maintaining structural integrity. This low firing temperature is cost-effective, saving on fuel and other costs. The material's unique visual appeal and affordability make it suitable for various applications.
650°C Fired Samples	Compared to the 500°C samples, those fired at 650°C exhibit increased strength and a different colour. The material has improved fired clay qualities but experiences higher shrinkage and water absorption. This temperature enhances the material's durability but may limit its application due to these changes.
750°C Fired Samples	Samples fired at 750°C show a significant increase in strength and a reduction in shrinkage compared to lower temperatures. However, they also have a high water absorption rate, with some samples absorbing up to 8 ml of water in less than 10 minutes. The darker hue and uniform appearance make these samples suitable for applications where strength is crucial, though their high water absorption may restrict their use.
850°C Fired Samples	The highest firing temperature results in exceptional strength, transforming the clay into high-fire material with a significantly darker colour and uniform appearance. These samples experience substantial shrinkage and have very high water absorption rates, with some draining 8 ml of water in under 5 minutes. While the high strength and unique properties may be advantageous for specific applications, the increased production costs and high water absorption rate must be considered

5.4 POTENTIAL APPLICATIONS

With the various firing temperatures 500°C, 650°C, 750°C, and 850°C—reveal distinct characteristics in colour, strength, shrinkage, and water absorption. Among these, the 500°C fired sample, particularly with a 50:50 clay-to-bisque ratio, has demonstrated the most favorable qualities. The 500°C fired sample stands out for its exceptionally low shrinkage, which facilitates precise casting and molding, making it ideal for creating detailed forms. This low shrinkage contributes to ease of production and consistency in shape, which is especially beneficial for applications requiring exact dimensions. Additionally, the material's weight remains manageable, and its low firing temperature imparts a desirable decadence quality, giving the finished product an attractive rustic appeal.

The 500°C sample also exhibits a breakable strength, which can be advantageous for applications involving plant growth. This property allows the material to break or disintegrate as needed, enabling better filtration and root growth. The presence of calcium in the material further enhances its filtering ability, making it suitable for horticultural applications where soil or water filtration is required. Overall, the 500°C fired sample with the specified clay-to-bisque ratio proves to be a versatile and effective choice, balancing ease of production, aesthetic quality, and practical functionality for specific applications.

5.5 EFFECT OF DEVELOPED MATERIALS FOR MANGROVE CONSERVATION

The 500°C fired clay with a 50:50 clay-to-bisque ratio is particularly advantageous for mangrove cultivation. Its low shrinkage and manageable weight ensure easy casting into various forms, including seedling pots. The breakable strength of this material allows it to disintegrate over time, facilitating the expansion of mangrove roots into surrounding soil. This property is critical for mangroves, as their extensive root systems need to penetrate the substrate to stabilize and thrive. Additionally, the calcium content in the clay enhances its filtering ability, ensuring better water quality around the roots, which is vital for the healthy growth of mangroves. This combination of structural and functional qualities makes the 500°C fired clay an ideal medium for supporting the initial stages of mangrove growth and ensuring their successful establishment.

5.6 OPPORTUNITIES

Figure 14 - Beneficiaries *(Source:Author Creation*)

The invention of a successful product for mangrove restoration presents significant opportunities across multiple sectors. It benefits the porcelain tableware industry with innovative, eco-friendly designs and supports the clay community by sustaining traditional crafts and boosting economic growth. Increased production and transportation needs create jobs for daily workers, transporters, and local businesses. Conservation teams, investors, and restoration professionals gain reliable tools for efficient mangrove planting and maintenance. The product fosters employment in sapling collection, sorting, and nursery work, while enhancing site management and research efforts. Local economies benefit from increased Eco tourism, supported by hotel and food providers (Seacology, n.d.). Government and organizational involvement ensures policy support and resource allocation, and restored mangrove ecosystems improve conditions for fishing communities and local wildlife, promoting biodiversity and environmental health.

6. Conclusion

In conclusion, this research has examined the mangrove ecosystem in Sri Lanka, identifying current failures and their causes while assessing Sri Lankan restoration efforts. It highlighted the shortcomings of existing solutions and introduced new findings that address these gaps. Specifically, repurposing bisque ware and clay materials offers optimized qualities for mangrove planting. The 500°C fired sample with a 50:50 clay to bisque ratio proves to be highly effective due to its qualities, which facilitates precise casting and molding, and its breakable strength, which supports root expansion and substrate stabilization. Additionally, the material's calcium content improves water filtration around the roots, fostering healthier mangrove growth. Implementing these findings in Sri Lanka not only enhances the efficiency of mangrove restoration but also provides economic and ecological benefits across various sectors. The porcelain tableware industry, clay communities, transporters, conservation teams, and local communities will all benefit from this innovative approach, which integrates waste management with environmental sustainability. However, as this is an experimental study, continuous long-term assessments are necessary to validate and optimize the effectiveness of these findings in real world conditions.

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