A knowledge-based Framework for an aesthetically pleasing Waste-Driven Wall Finish Panel Toward a Sustainable Building Practice in Saudi Arabia

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Abstract

This study demonstrates the significance of integrating sustainable development principles into urban design in Saudi Arabia, aligning with the nation's Vision 2030 goals toward creating a sustainable society. The investigation concentrates on establishing a knowledge framework for producing visually appealing wall panels from recycled materials, a critical component of addressing future energy and environmental challenges. A sequential transformative mixed methods design was implemented, commencing with an inductive qualitative approach to establish an initial framework through logical argumentation and analytical literature review. This framework was subsequently refined using a deductive quantitative approach, which included the Delphi method and an immersive case study to achieve expert consensus. The framework was further refined during the final phase, which involved an exploratory follow-up to establish complementarity between qualitative and quantitative findings. The results indicate that the circular economy principles in Saudi Arabia can be strengthened by using recycled materials to create aesthetically appealing wall panels. The anticipated results offer valuable insights and practical guidance to architects and designers, leading to a more environmentally conscious and sustainable approach to construction in the region.

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General Abstract

This study emphasizes the need to incorporate sustainable practices into urban planning in Saudi Arabia, therefore helping the country's Vision 2030 goals for a greener future. The research focuses on developing a framework for constructing beautiful wall panels using recycled materials, which is critical for solving energy and environmental issues. By integrating several research methodologies, the study creates an initial framework that is subsequently refined with expert feedback. The findings suggest that employing recycled materials for these wall panels not only improves their beauty but also helps to create a more sustainable and environmentally responsible approach to building in Saudi Arabia. This study's findings provide architects and designers with practical suggestions to assist them in creating more sustainable construction practices in the region.

Dedication

In honor to my dear mother, whose prayers strengthened me in my moments of weakness. Her consistent faith in me has been a guiding light throughout this journey.

To my dear father, who passed on the first year of my Ph.D., and to my elder brother Muhamed, who left us a year later, You both stated me as a "doctor" long before I earned the title. Your love, faith in me, and aspirations for the future have been my driving force. I carry your memories with me every day, and this accomplishment is as much yours as mine.

I also dedicate this work to my siblings, Mona, May, Maha, Noha, Khaled, Ahmed, Nourah, and Kolod. Your presence in my life has been a source of strength and encouragement, and I am grateful for your unwavering support.

To my husband and my precious daughters, my princess, Al Jawhara, Fatima, and Munirah, this journey would not have been possible without you by my side. Thank you for your love, support, patience, understanding, and endless encouragement. This success is a testament to our shared strength and commitment.

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I am eager to express my gratitude to all who participated in my research. Your efforts were crucial in successfully completing this study, and I sincerely appreciate your willingness to offer your time and knowledge generously.

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Chapter 1 Introduction

1.1 Introduction

According to Hans Carl von Carlowitz (1712), regarding the unregulated use of forests, "the concept of sustainability occurs in times of shortages or disastrous incidents" (Kundak, 2006). However, according to the Brundtland Report (1987), Sustainable development is "development that meets present needs without compromising future needs," Wood (2005) claimed that "development" itself is contrary to sustainability; thus, "human development must take place minus overwhelming the natural ecosystems that we depend on." Whereas most definitions of sustainability are insignificant (Dobson, 1996), some are specific. "Sustainable" is usually applied to characterize a technology with minimal environmental effects on one environmental challenge, usually quantified based on decreased resource usage or even pollution discharges as a percentage or fraction. According to Ostrom (2015), sustainability should discuss the complex interactions among social-ecological systems. Moreover, the definition is based on a sequence of assumptions and choices of the applicable values and prime concerns used in trade-off decisions. Preferences and values drive decisions regarding trade-offs amongst optional building designs. Nevertheless, most value possibilities are not precisely demonstrated, though they are absolute both in the development and ordinary design practice (Dobson, 1996; 1998). Hence, to comprehend the total results of the building, there is a need to consider all the human health and ecological factors involved, mainly for a specific site and project. Sustainable architecture's objective is to build a well-designed building plus a site environment conducive for its occupants, efficient in natural resources usage, common undesirable effects on the atmosphere, durable, and cost-effective (Cao, Dia, & Liu, 2016).

The research aspiration is to assess the sustainable practices of the construction industry in Saudi Arabia. The study tries to pinpoint and analyze the chief sustainability implementation practice, explicitly discussing the merits of recycling and the challenges hindering higher recycling rates.

1.2 Overview

Sustainable buildings, i.e., green buildings, are designed, constructed, and operated in a resource-friendly manner. Its sole purpose is to minimize environmental and human health impacts and decrease energy consumption (Akadiri, Chinyio, & Olomolayie, 2012). The sustainable building concept is of great concern and is debated internationally. In the past two decades, sustainable buildings have been emphasized significantly, particularly in Saudi, because of their environmental, social, and economic impacts (Alyami, Kwan, & Rezgui, 2013). Consequently, sustainable building investment in Saudi Arabia is the third-highest investment worldwide (Alardhi, Alaboodi, & Masri, 2020). Additionally, Saudi Arabia's vision of 2030 has been put forward to achieve a sustainable society by driving a circular economy where the kingdom can increase waste management efficiency. Especially where municipal waste is expected to hit 1.26 kg/capita by 2050 (AlHumid et al., 2019), such a vision can be achieved by increasing investments in advanced technology worldwide to be used in waste recycling. Part of the challenge of meeting this vision is identifying and developing technologies that appropriately incorporate recycled plastics. Furthermore, energy-efficient building materials typically need low maintenance, last longer, and warrant general thermal and structural performance maintenance over time, obtaining minimal energy demand and causing fewer CO2 discharges (Dobson, 1996). Therefore, plastics for construction are introduced at this point. They are resource and energy-efficient and have long-term quality performance. In addition, plastics keep the buildings warm and dry for comfortable living and working

spaces, all while being cost-effective for the entirety of the lifecycle of the building (Wood. et al., 2015). However, recycling plastics may cause a reduction in the product's properties (Ignatyev et al., 2014). Yet, additives such as fibers, compatibilizers, stabilizers, pigments, and fire retardants enhance the properties of recycled plastic that can outperform conventional materials (Dehghani, Ardekani, Al-Maadeed, Hassan, & Wahit, 2013). However, oil prices have increased the need to minimize synthetic fiber usage in polymer composites made from petroleum materials, which has pushed researchers to look for ways to incorporate natural fibers into modern polymer composites (Ghori et al., 2018). Natural fibers as bio-filters, in comparison to synthetic fibers-based polymer composites, are gaining popularity due to their low cost, low density per unit volume, comparable specific strength, cost-effectiveness, and renewability (Jawaid & Khalil, 2011).

1.3 Biocomposites as a building material

In recent years, numerous efforts have been made to develop high-performance recycled bioplastics composite for consumer electronics, automotive, and other durable consumer goods (DiGregorio, 2009). Their manufacture could be more energy-efficient than petroleum-based and recyclable alternatives (Karana, 2012). The promising features of biopolymer composites emphasize the potential to employ such material in building industries (Binhussain & El-Tonsy, 2013; Dehghani et al., 2013). Nevertheless, users perceive architecture via multiple senses, and the materials used in a building directly influence how users perceive the space (Pallasmaa, 2024; Wastiels et al., 2012). Thus, selecting materials for a building system requires a full assessment of their particular characteristics (Y.Ljungberg). The technical properties and aesthetic qualities of materials should be considered when evaluating them for building applications (Goto et al., 2019). The building industry has begun employing several

biocomposite materials due to their exceptional thermal insulation and sound absorption performance (Ahmad et al., 2022). Meanwhile, Manu et al. (2022) highlighted constraints in the market availability and manufacturing quantities of finished biocomposite materials compared to polymer composites. The primary issue with recycled biocomposites is the challenge of distinguishing them because of their unappealing visual quality. Dehn (2014) highlights that end-users may not consistently react favorably to waste-driven items due to their appearance. Karana (2012) also illustrates the possible lack of attention to aesthetics in initiatives for sustainability, mainly when focusing on efficiency. Scientists in the construction industry have been investigating the potential of recycled biocomposites to enhance thermal, mechanical, and cost-effective elements of building construction (Nourbakhsh & Ashori, 2010). Nevertheless, research into the aesthetic desirability of recycled biocomposite materials is lacking.

1.4 Bridging the gap

"When I'm working on a problem, I never think about beauty. But when I've finished, if the solution is not beautiful, I know it's wrong." - R. Buckminster Fuller

Recognizing the role of aesthetics for materials is emphasized as a critical component of fostering social sustainability (Y. Ljungberg). Designers are able to influence consumer pleasure and purchase habits by manipulating sensory qualities (Zuo, 2010). Nonetheless, specific procedures are necessary to produce distinct sensory impressions, which have the potential to influence the way in which materials are perceived, thereby facilitating the harmonization of aesthetic appeal and functionality (Karana et al., 2009). Thus, creating an aesthetically pleasing wall panel that meets user demands requires a

comprehension of the complex interplay between materiality, design, and user context (Rognoli, 2010). At the level of material properties, the intersection of Architectural design and science highlights the interdisciplinary character of this project. Science and architectural disciplines possess rationales that align with their particular concerns and requirements concerning building materials (Salama, 2008). Hence, disciplinary boundaries may prove inadequate when it comes to attaining ideal solutions for visually appealing wall panels. Thus, it is crucial to establish a knowledge framework that integrates heterogeneous knowledge using a transdisciplinary approach to address this disparity, as illustrated in **Figure 1-1** . Transdisciplinary, as promoted by Nicolescu (2002), highlights the development of new, integrated knowledge to meet complex global issues. This strategy incorporates actively exchanging knowledge and forming shared understanding among multiple stakeholders (McGregor, 2004). Utilizing a transdisciplinary knowledge framework in building science is mandatory for coordinating various research methodologies to create visually appealing finish panels.

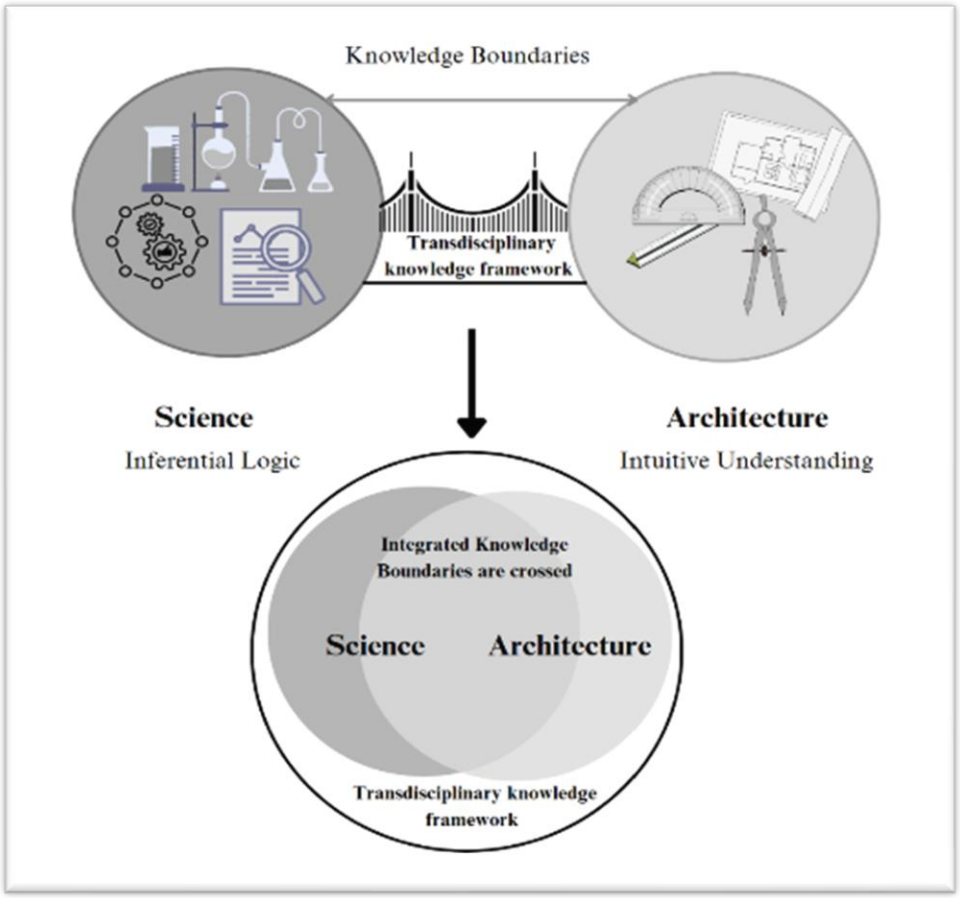


FIGURE 1-1 TRANSDISCIPLINARY KNOWLEDGE FRAMEWORK

Considering the above, this study seeks to provide an overview of how recycled biopolymer can replace the conventional/vernacular finish materials used in Saudi Arabia's market by developing a knowledge framework as a road map to create durable, beautiful, and inexpensive wall panels.

1.5 Research Approach

1.5.1 The Problem Statement

According to (Manu, 2022), despite several advantages, biocomposites are still not as frequently employed as conventional materials in the building sector. One of the primary reasons is the lack of aesthetic appeal. The user's perception of a product's design besides the material function offers a substantial buying incentive. Thus, understanding the available knowledge and associated challenges to producing an aesthetically appealing biocomposite is required.

1.5.2 The Purpose Statement

This study aims to demonstrate the practical application of recycled biopolymer composites in creating an aesthetically pleasing wall finish panel as a sustainable alternative to conventional finish materials in Saudi Arabia towards a circular waste system. However, numerous factors must be addressed in product design, such as manufacturing properties, functional properties, and sensory and aesthetic traits (Zuo et al., 2016). Thus, the research investigation aims to create a knowledge-based framework to facilitate the integration of diverse knowledge sources in architectural and science practices for producing an aesthetically pleasing wall panel by the intersection between material, process, and product. The refined framework is then integrated into a design matrix as a manufacturing guideline and design tool for customers and architects for customization freedom. The success of this investigation will open the gate for future research to test the materials' aesthetic aspects and performance to compete with other materials in the Saudi market for sustainable building practice and to facilitate the transition from a linear to a circular waste system.

1.5.3 Goals and Objectives of the Research

1.5.3.1 Research Goal

This research aims to close the waste management loop and create a roadmap to achieve a circular economy in Saudi Arabia by creating a wall finish panel out of polymer and agricultural waste that is standardized by achieving a beautiful design that fulfills clients' desires.

1.5.3.2 Research Objectives

The following research objectives will assist in meeting the research goals.

- Developing a knowledge-based framework of procedures to produce an aesthetically pleasing wall panel.
- Implement the framework into a design matrix for the manufacturer as a guideline throughout the panel manufacturing process.
- Creating design selection tools to achieve individuality among users.
- Demonstrate the possibility of developing beautiful, panelized wall finishes derived from biopolymer waste.

1.5.4 Research questions

The central question of developing a knowledge framework to produce waste-driven finish wall panels for the Saudi Arabian cladding system market lies in whether it contributes to creating an aesthetically pleasing wall panel that competes with traditional applications in the Saudi market. The research question for this proposal has six sub-questions, which are shown below:

- What type of waste could be recycled at a low cost in Saudi Arabia?
- What issues are associated with recycled plastic when added to the material flow stream in Saudi Arabia?
- What should be the appropriate consistency content and proportion of biopolymer composite?

- What is the production process, pretreatment temperature/fabrication methodology?
- What is the process of creating a beautiful wall panel?
- Does the developed Framework contribute to the creation of a beautiful wall panel?

1.5.5 Research Methods

The primary objective of this research is to construct a knowledge framework that facilitates the potential of biopolymer composite finish material as a substitute for the conventional one utilized in the cladding system of buildings in Saudi Arabia. In order to accomplish this, a sequential transformative mixed methods design with inductive (qualitative) and deductive (quantitative) methods has been employed (Creswell & Plano Clark, 2011). (Refer to **Figure 1-2 & Table 1-1**)

Table 1-1 key aspect of research methodology

Mixed Methods Design	Theoretical Lens	Timing	Integration	Methodological Rationale
Sequential Transformative Design	Explicit advocacy lens	Sequential Beginning with the qualitative phase	Data Analysis stages. Phase I, II, and III (separated). Interpretation stage. Phase IV (merged)	Development, complementarity, and expansion

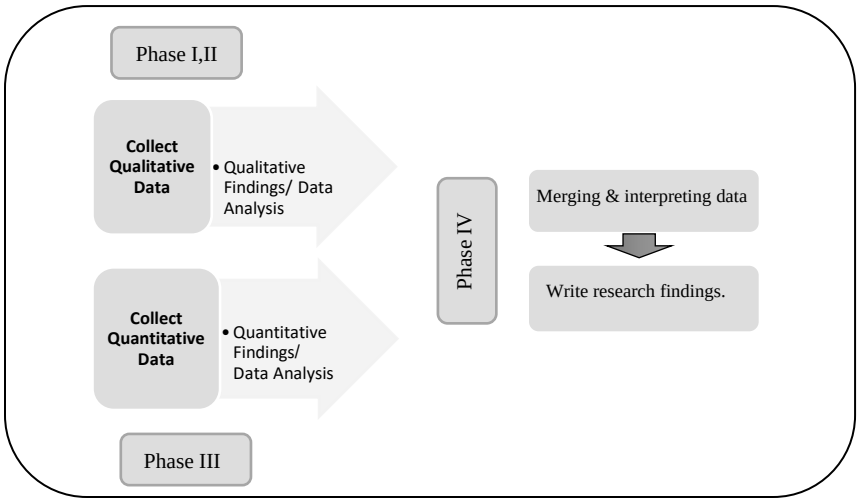


Figure 1-2 sequential transformative

The research unfolds in distinct phases aligned with the methodology chosen to address the research questions. Upon completion of each procedure, a revised version of the Framework was generated. In the initial inductive phase, an analytical literature review and logical argumentation shape the Framework, detailing configurations, and procedures in three key sections: material, process, and outcome. In the second phase, a qualitative immersive case study approach employs the aesthetics theory and initial Framework procedures in the production of wall panel samples. The Framework's refinement is then guided by the substantial knowledge gathered from the immersive case study. In the third deductive phase Delphi approach used which involves experts, contributing to a consensus on the refined Framework. The final exploratory follow-up phase involves data analysis and interpretation through complementarity, emphasizing how recycled waste enhances aesthetic qualities in finish panels.

1.5.6 Research Scope

This research focuses on developing a knowledge framework to design a wall finish panel that fits the Saudi cladding system market. The raw material selected to create the biopolymer composite panel was based on a marketing analysis of the waste in Saudi Arabia. The polymer type is polyethylene terephthalate (PET), and the fiber waste is derived from the palm stem.

1.5.7 Research Limitations

The study's primary objective is to document the development process of producing waste-driven wall panels through a descriptive knowledge framework. Nevertheless, numerous experiments are necessary to assess the products' aesthetics and physical, chemical, and mechanical performance. However, that is postponed for future research due to the constraints imposed by time and instruments, as well as the scope of the study.

1.5.8 THE SIGNIFICANCE OF THE STUDY

The architectural industry in Saudi Arabia is witnessing a growing interest in sustainable building practices, driven by the need to minimize resource consumption, reduce carbon footprint, and address environmental concerns. This presents a significant opportunity to adopt recycled plastics in the building industry. In 2015, the building materials global market was worth approximately $800 billion (Dwivedy, 2018). Today, the Gulf Co-operation Council (GCC) region comprises Bahrain, Kuwait, Oman, Qatar, Saudi Arabia, and the United Arab Emirates, accounting for around 3% of the global construction materials market. Plastic construction materials in various forms are expected to grow sales by 10% between 2021 and 2026. In addition, between 2021 and 2026, Saudi Arabia is expected to dominate the GCC Building & Construction Plastic Market. Recycled bioplastics could be used as interior or exterior finish panels when applied to building enclosures such as walls. In addition, offering the product in various appealing textures and colors will maximize market penetration. In this context, developing aesthetically pleasing exterior wall panels incorporating recycled materials is essential to promoting sustainability and circular economy principles within the construction sector. By investigating the knowledge that resides at the intersection between material, process, and outcome, this research seeks to provide a descriptive framework that can guide designers, architects, and developers in creating environmentally friendly and visually appealing wall panels.

Literature review Chapter 2

2.1 Introduction

This chapter covers fundamental knowledge on constructing a visually appealing waste-driven wall panel framework through a literature review. This chapter begins with exploring the current state of sustainable building practices and circular economy initiatives in Saudi Arabia. They are followed by an explanation of plastic composition and its recycling issue globally. Then, an analysis of the Aesthetic definition and its prominent role in leading the recycling invites toward a circular economy globally and in Saudi Arabia. This study will then examine the Recycling challenge and opportunity in Saudi Arabia. The author will then go on to a deep analysis of Saudi's recycling market. Finally, this literature will end up with a material selection for the proposed project.

2.2 Sustainable building practices

Sustainable architecture is to create a well-designed structure and site that is efficient with natural resources, durable, and cost-effective (Cao, Dia, & Liu, 2016). Nonetheless, the most demanded materials on a global scale are building materials such as steel, cement, glass, aluminum, bricks, etc. (Andrady, 2015). Those materials require a significant amount of energy to produce (Andrady, 2015). Hence, when used in large quantities, these substances may negatively impact the environment and the energy supply (Reddy, 2004). On the other hand, reducing nonrenewable natural resource use, reusing items after consumption, and recycling waste are crucial for sustainable development and limiting environmental consequences (Manrich & Santos, 2009). Therefore, maximizing our energy sources is essential to creating low-cost, low-impact, environmentally friendly, and long-lasting building alternatives (Reddy,

2004). According to Reddy (2004), recycling waste should promote more effective resource sharing, particularly energy resources, with less environmental impact and more sustainable practice (Manrich & Santos, 2009).

Global MSW production is estimated at 2.01 billion tons per year (Silpa Kaza, 2018), with an expected increase to 2.59 billion tons by 2030 (Hadidi et al., 2020). Plastic is the second-largest waste after food worldwide (Silpa Kaza, 2018). Its disposal causes severe environmental issues worldwide (Abdel-Shafy & Mansour, 2018). The Plastic Solution Fund (2019) pointed out that plastic threatens the environment by emitting carbon monoxide and other hazardous gases, which, in turn, aggravate the greenhouse effect and hinder collective efforts to avert a climate change crisis. In development, the awareness of this problem today leads to a critical field of research.

2.2.1 PLASTIC

Promoting plastic recycling demands an understanding of plastic's nature, composition, and underlying causes for its enormous popularity. According to Mason et al. (2018), plastic is a synthetic polymer composed of different types based on their chemical components. Plastic types are named based on the polymerized chemical monomers during manufacturing (Mason et al., 2018). In other words, polymer comes from Greek words where poly means (many), and meros means (parts) (Chanda & Roy, 2006). Thus, a polymer consists of a minor, simple chemical unit called (a monomer) that appears to repeat itself many times through a process called (polymerization), forming chemical molecules (Andrady, 2015). The poly is usually written in front of the repeating unit's name. (Chanda, 2018) For instance, Polyethylene (PE) is made by polymerizing Ethylene gas, where a repetition of substantial units of the Ethylene monomers forms a large molecule chain. (Andrady, 2015)

In the post-industrial age, different types of plastic are being produced daily with other peculiar properties to suit different uses. However, the growth of the world population increases the demand for plastic production. The huge dependence on plastics refers to the fact that they are lightweight, cheap, disposable, and durable, as described by Dvorak, Hopewell, and Kosior (2009). Consequently, plastic dumping and accumulation in landfills around the world have increased. Hence, a global issue arises worldwide since plastics are considered undegradable materials, as Hahladakis, Lacovidou, Purnell Velis, and Weber (2018) reported. MacInnes (2019) explained that as a result, the majority of their waste ends up in landfills or oceans, which, in turn, becomes a contaminating material. It is estimated by the Ocean Conservancy (2019) that more than 165 million metric tons of plastic waste are being disposed of in the oceans yearly. This high level is unfortunate since recycling plastics can reduce the volume of waste in landfills and the oceans, decrease the use of oil in producing plastic, and lower energy consumption associated with plastic products.

2.2.2 THERMOPLASTIC

MacInnes (2019) distinguished two types of plastic in his research paper titled "Plastics," namely thermoplastic and thermoset. Both can undergo the process of heating, shaping, and cooling similarly. The latter differs from the former in the reheating stage, where it decomposes instead of being softened (Manrich & Santos, 2009). Therefore, only thermoplastic polymers can be recycled (2014). The flexibility of thermoplastic resulted in its widespread use in all its shapes, such as polyvinyl chloride, polyurethane, polycarbonates, and polystyrene, as Fitzpatrick (2017) explained.

Furthermore, Hahladakis, Velis, Wber, Lacovidou, and Purnell (2018) reported that thermoplastic forms 50% of the plastic mass. Additionally, Bharsakale, Gawande, Renge, Tayde, and Zamare (2012) pointed out that about 80% of the plastic used by humans is thermoplastic, making it imperative to find

solutions to recycle it. MacInnes (2019) explained that once plastic waste is dumped into the environment, it releases harmful chemicals that find their way back to humans, which, in turn, causes cancers and defects. Not only that but Hahladakis et al. (2018) added that burnt waste, such as thermoplastic, emits carbon monoxide and dioxide into the atmosphere, which acts as a contaminating material in the environment. Similarly, Hanan et al. (2011) highlighted that the effects of climate change, global warming and their emission of gases, water scarcity, and the rapid population increase had aggravated this problem. Consequently, thermoplastic recycling creates economic and environmental value by converting plastic found in waste into reusable materials, as per Baldwin, Cornell, Rader, and Sadler (1995). Although recycling technology was introduced as the way forward to achieve and ensure a sustainable environment, it can degrade the materials' mechanical properties (Ignatyev et al., 2014). Yet, embedding fibers inside the matrix of recycled plastic will result in an improved product (Nourbakhsh & Ashori, 2010). Biopolymer composite is a solution to the unsustainable raw material production, product creation, and disposal of Plastic (Manu et al., 2022).

2.2.3 BIOPOLYMER COMPOSITES

Composites are different structural material mixtures made by mixing two or more component materials with astonishingly varied properties and property control (Christian,2016). Biopolymer composites are a term for reinforced biopolymers (Manu et al., 2022). They were "bio" simply because of their component source, not their biodegradability (Ebnesajjad, 2012). Thus, Biopolymer composites (biocomposites) are composite materials manufactured by employing a natural substance as reinforcement and a natural or synthetic polymer as the matrix (Manu et al., 2022). The reinforcement and matrix operate synergistically, providing superior qualities to their natural counterparts (S.J.Christian, 2016). The reinforcement material contributes significantly to stress transmission and biocomposite strength, while

the matrix offers functional properties and protects the reinforcement material (Ghori et al., 2018). Christian (2016) further asserts that natural fiber in biopolymer composites is continuously added to a polymer matrix at a discontinuous level to enhance the existing composite's tensile strength and stiffness. Preparing this composite form aims to obtain an end-product with durability performance and good mechanical behavior imparted by polymer and natural fibers, respectively (Ghori et al., 2018). Natural fiber reinforcements affect electrical conductivity, thermal properties, degradability, morphological characteristics, crystallinity, and production cost of the biopolymer composites (Al-Kaabi et al., 2004; Dehghani et al., 2013; Ghori et al., 2018). Natural fiber polymer composites offer critical features that might be used in today's industries, where stringent sustainability standards are driving the demand for more eco-friendly materials (Al-Kaabi et al., 2004). In several sectors, conventional materials may be substituted by composite materials based on the improvement in the desired attribute (Sandak et al., 2019). Natural fiber-reinforced polymer composites find their most common uses in the transportation, aircraft, and building sectors (Hosseini, 2020). The following paragraph will provide insight into the use of biocomposites in architecture, highlighting the potential of the proposed waste-driven wall panel as a viable product for architecture and design applications.

2.3 Biocomposites in Modern Architecture: A Green Revolution in Building Materials

Biocomposites are widely used in many architectural applications, such as new construction, historical restoration, furnishings, and decoration installations (Hosseini, 2020). Various polymers, reinforcements, and additives may be used to manufacture the desired characteristics in Biocomposite products. The combinations of these essential elements provide a wide variety of options for the product's intended use in terms of cost, durability, strength, and other properties like fire resistance. Consequently, considering the component, additive, and manufacturing procedures is essential based on the application

of the product. **Table 2-1** below highlights the parameters that must be considered when developing a wall finish panel for interior and exterior applications, according to the American Composites Manufacturers Association's (2016) guidelines.

TABLE 2-1 WALL FINISH APPLICATION REQUIREMENTS

Wall finish application	Challenge	Consideration
Exterior	Exposure to extreme weather conditions	The design must withstand weathering factors such as heat without degradation or structural damage.
	Continuous exposure to UV radiation can cause discoloration and deterioration of certain materials.	UV resistance must be added to the composite to preserve appearance and structure.
	Materials may expand and contract due to temperature variations, causing structural issues.	Use appropriate installation techniques to account for heat fluctuations.
	Exterior panels may experience wind and mechanical stress.	Ensure that the composite's mechanical strength is adequately supported to withstand external forces.
Interior & Exterior	Both exterior and Interior applications must comply with fire safety regulations.	A fire retardant must be added to the composite to comply with the building code requirements.
Interior	Interior panels are often selected based on their visual attractiveness.	Choose materials that provide diverse design options, hues, and textures to fulfill the required interior aesthetics.
	Interiors may need Acoustic modification to reduce noise.	Select materials that provide favorable acoustic characteristics.
	Interior panels are exposed to dirt, stains, or spills.	Simple maintenance and cleaning aspects should be considered to ensure hygiene and long-lasting durability.

2.3.1 Sustainable Materials and Consumer Influence

Since the start of the twenty-first century, the development of sustainable manufacturing materials has become a global objective. Increasing numbers of architects and designers are turning to recycled biocomposites as a sustainable, long-lasting material option that can withstand a prolonged period while providing innovative and practical solutions (Association, 2016). According to the American Composites Manufacturers (Association, 2016), Biopolymer composites have unique characteristics that make them desirable, sustainable materials for builders, architects, and product manufacturers. They feature reduced heat conductivity, less shipping and installation weights, and a lower carbon impact than other materials. However, when mixing multiple materials in product design, considering manufacturing costs, functions, aesthetic, economic, and environmental issues is essential (Zuo et al., 2016). Yet, the current global recycling system interest is determined by the economic and cost-benefit with less attention to the environmental issues (Hopewell et al., 2009). Customers are thus the most robust revenue generator and the driving force behind corporate sustainability (Andrady, 2015). Customers in today's market are no longer only recipients of a company's wares (Andrady, 2015). They are becoming more involved with the company to make demands and provide input on the things they buy (Andrady, 2015). Aesthetic considerations, cost, and product function are the primary considerations when consumers choose which materials to utilize (Goto et al., 2019). It has been shown that when a product is aesthetically pleasing, consumers are more likely to identify and value its functionality and use (Hekkert et al., 2003).

2.3.2 AESTHETIC

Aesthetics comes from the Greek word "aisthetikos," which means "perception and understanding through the senses" or "sense-based knowledge. "Its characteristics extend beyond visual and physical traits and include the human perception and experience of a multi-layered world.

"I touch the wall with my eyes." Juhani Pallasmaa

Pallasma, in his book "The Eyes of the Skin: Architecture and the Senses," proposed reconsidering the integrity of the senses in our experience of architecture. He highlights the significance of sensory experience, where architecture enhances our experience to see ourselves as spiritual beings engaging with the world instead of inhabiting the world. He links perception to memory, emotion, and imagination. These phenomenological conditions develop when one sense stimulates another; as Pallasmaa expresses, 'the eye invites tactile feelings.' Therefore, architects must be conscious of these many sensory inputs as people perceive a building and its materials via their senses (Wastiels et al., 2012). Ultimately, various positive emotional experiences should be made available to the consumer for the material's perception to evoke feelings of desire (Karana, 2012).

1.4.3.1 Biopolymer Composite & Aesthetics

Utilizing waste-derived materials is one of the most effective methods to contribute to sustainable building design (Sauerwein et al., 2017). Therefore, a strong focus is on introducing low-cost, new, and enhanced aesthetics for materials to promote sustainability in human society (Ljungberg, 2007). However, the move from traditional fuel-based plastics, firmly embedded in society, to sustainable alternatives has been prolonged (Karana, 2012). This issue is aggravated by environmentally conscientious clients who

don't utilize products accordingly. (Sauerwein et al., 2017). Hosey (2012) argues that sustainability has lost emphasis on aesthetics via its focus on efficiency. Aesthetics is what prevents people from utilizing waste-driven products since sustainable architecture concentrates on environmental effects rather than aesthetics, as stated (Hosey,2012). Compared to the aesthetic potential of synthetic composites, biocomposites in their natural state are aesthetically unattractive, and trim work has been made to improve this feature (Karana, 2012). As a result, only a limited number of non-structural finish biocomposite materials have been brought to market compared to synthetic plastic, and even then, only in relatively small quantities (Manu et al., 2022).

The significance of materials in defining a product's value and meaning is a point that scholars in materials and design acknowledge (Karana et al., 2009). Products that enjoy widespread acceptance may convey multiple meanings (Karana et al., 2009). Consumers consider a product's visual appeal alongside its practical qualities (Goto et al., 2019). Individuals pursue things that complement their sense of self and establish a connection with them (Zuo, 2010). People often rely on certain sensory characteristics to attribute specific meanings to materials and objects (Zuo, 2010). Sensorial qualities refer to the interaction between materials and users via the five senses: sight, touch, smell, taste, and hearing (Zuo, 2010). They consist of physical attributes such as smoothness, coldness, and flow and visual characteristics like mattes, transparency, and gloss (Zuo et al., 2014). According to Kagan (2011), the aesthetics of sustainability is a subset of aesthetics that focuses on processes and relationships and is based on "sensibility to patterns. "Therefore, aesthetic evaluations of biocomposites should account for their inherent connection to the natural world since this is one of their primary selling points (Manu et al., 2022). Nonetheless, biocomposite designers either replicate characteristics of other natural materials via patterns and colors or emulate a conventional material, which may confuse material identity (Friedel,

2017). Biocomposites need to stand out from the crowd visually so that people can understand that they are made from natural ingredients without being confused with other, more conventional building materials (Manu et al., 2022).

Unity-in-variety is one of the aesthetic foundations that might be followed to improve biocomposite materials in product design (Sauerwein et al., 2017). A form of unity amid the various constituents is generally required to comprehend an object and consider it pleasurable. Thus, pleasure may be found in discovering the diversity between a material's visual and tactile properties, as stated by (Sauerwein et al., 2017)—nevertheless, excessive unity results in a loss of interest and boredom (Hekkert, 2006.

Finally, according to Post et al. (2016), product designs that exhibit an ideal balance between type and unity are aesthetically valued. Hence, biocomposites might be appealing and distinguishing by changing the material's physical and perceptual features (Karana et al., 2009).

2.4 The Case of Saudi Arabia (KSA)

2.4.1 Recycling challenge and opportunity in Saudi Arabia

Economic and technological issues constrain the development of recycling systems worldwide (Ignatyev et al., 2014). Consequently, producing high-quality products with low processing costs requires an excellent understanding of the current challenges, resources, and technology available. Therefore, when preparing to develop and operate a sustainable recycling program, consideration should be given to the market prices of recyclable products, market requirements, and future demand trends (Willems et al., 2022). Thus, analyzing the waste plastic markets in KSA is essential to close the loop and reach the

circular economy's goal. In this case, investigating the existing market of recyclable products with an economic value is the most critical stage of any market analysis (Alhumoud, 2005). Thus, Igor et al. (2014) suggest considering several factors, such as the volume and logistics of the waste material and the recycling cost for an effective recycling stream. In the following section, I will study the recycling market in KSA by reviewing the current systems' technology, challenges, and opportunities to recycle plastics and agricultural waste.

2.4.2 Market analysis of recyclable materials waste and technology in (KSA)

2.4.2.1 MSW in Saudi Arabia

According to ("Deploying Municipal Solid Waste Management," 2020) and ("Municipal Solid Waste Management Practices and Opportunities in Saudi Arabia, "2019), the Kingdom of Saudi Arabia currently produces approximately 14 million tons of MSW per year, averaging 1.4 kg per capita per day, more than the global average of 1.2 kg/capita/day. Abu Seif and Hakami (2015) asserted that the population of Saudi Arabia is about 29.4 million. Cekirge and Ouda (2013) reported that the rapid population increase, and urbanization generate a municipal solid waste of 1484 tons per year. In a recent study by Zafar (2013), the waste generation reached nearly 15 million tons annually. In other words, an individual consumer generates from 1.5 to 1.8 kg of waste daily. Zafar (2013) highlighted that about six million tons of waste are generated annually within three large cities: Riyadh, Jeddah, and Dammam. In addition, Ahmad, Alamoudı, Demirbas, and Sheıkh (2016) highlighted that Dammam, Riyadh, Jeddah, and Mecca account for most of the waste generation. In other words, waste produced by the four cities forms 10% of the total waste generated in the country, as Heidrich and Huang (2007) described. The escalating waste generation in the country, as emphasized by Parikh and Parikh (1997), poses environmental threats and depletes natural resources. With an annual landfill demand of approximately

2.8 million square meters, recycling plastic, which constitutes 5-17% of municipal solid waste (MSW) in landfills, can significantly reduce the volume of waste reaching local landfills and extend their lifespan (Alhumoud, 2005)

2.4.2.2 Plastic stream in Saudi Arabia

Rising demand for plastic increases plastic waste. According to (Muzammil et al., 2016), in their study "Solid waste management in Saudi Arabia: A review," plastic is the second most abundant stream in MSW, accounting for around 5-17 percent. According to the Gulf Petrochemicals and Chemicals Association (GPCA), by 2022, the polymer industry is anticipated to increase with a compound annual growth rate (CAGR) of 3% to 34.5 million tons (Tan, 2017). The production of thermoplastic in the Gulf Co-operation Council (GCC) region, which comprises Bahrain, Kuwait, Oman, Qatar, Saudi Arabia, and the United Arab Emirates, accounts for 7.4 percent of the world's total in 2013 (GPCA, 2013). Their production capacity grew by 14% compared with 4.8% per annum worldwide (GPCA, 2013).

Regarding that, Abu Seif et al. (2015) reported that Saudi Arabia's sorting and recycling of general waste, including plastic waste, is only between 10-15%. Subsequently, Khan and Zakariya (2013) asserted that managing such a vast amount of waste became problematic and challenging to the government in Saudi Arabia. Abu Seif et al. Parikh and Parikh (1997) also added that the increased waste generation process in Saudi Arabia poses a threat by polluting the environment and decreasing natural resources. Especially since the annual landfill demand is approximately 2.8 million per square meter, recycling plastic, which is about 5-17% of MSW in the landfill, will reduce the volume of waste arriving at local landfills, thereby extending the landfill's life (Alhumoud, 2005).

Accordingly, Saudi Arabia's vision of 2030 has launched the recycling project as one of its top goals for the near future. It was announced in October 2017 that as part of the Saudi Vision 2030, the Public

Investment Fund (PIF) created The Saudi Recycling Company, a government-owned enterprise tasked with waste management and recycling projects in Saudi Arabia (Napco, 2017). The Saudi Recycling Company would work in partnership with private sector companies to support and operate these domestic recycling projects (Napco, 2017)

A few small-scale projects have been implemented in the Eastern Province of Saudi Arabia, although current KSA practices for recovering resources from solid waste are ineffective (Muzammil et al., 2016). Napco National is one of a few companies in Saudi Arabia that recycle plastics and contribute to the circular economy. They have invested in Jeddah and Dammam facilities and waste collecting, sorting, and cleaning equipment to recycle post-industrial plastic and agricultural waste (Napco, 2017). Napco utilizes closed-loop mechanical recycling to direct collected waste into the same user or applications needing recovered resins of equivalent grade (Napco, 2017). Abu Seif et al. (2015) in their paper titled "Household Solid Waste Composition and Management in Jeddah City, Saudi Arabia: A Planning Model," and Pariatamby and Tanaka (2014) in their article titled "Municipal Solid Waste Management in Asia and the Pacific Islands" explained the process of closed mechanical loop recycling taking place in Jeddah by firstly, dividing the city into four sampling zones. Secondly, waste samples were collected from dumpsites and segregated at the source based on their types in color-coded bins. Thirdly, waste is sorted into categories, weighed, and recorded in tables. Finally, the plastic waste will be converted to be reused through what is known as "mechanical loop recycling," in which each plastic waste is recycled based on its origin separately to maintain its value, as Napco National explains (2017). Napco's closed-loop mechanical recycling is a good start toward creating a circular economy. Yet, minimal resources addressed plastic recycling in Saudi Arabia. However, municipal plastic waste is

enormous compared to any other country in the region, as Khan et al. (2013) verified that it is at its starting point.

2.4.2.3 Cost consideration

It would be challenging to encourage recycling activity without financial incentives (Alhumoud, 2005). In 2015 Saudi Arabia was the world's eighth-largest plastics producer, accounting for two percent of global polymer sales (admin, 2014). They are leading the production of plastic in Gulf countries, which accounted for 67 percent of GCC polymer output in 2016 (DUBLIN, 2016). The country's production of polymers expanded by 11 percent per annum over the past decade and continues to grow (admin, 2014). Nonetheless, plastic consumption in KSA is the highest among the GCC countries at 61 percent (admin, 2014). They consumed 95 kg per person (admin, 2014). The country's increased production and consumption of plastic have proven promising outcomes of recycling plastics (Nizami et al., 2017). Ali, Rahman, Redhwa, and Siddiqui (2006) noted that the rate of economic return would surpass 14 percent if they were recycled. Napco National (2017) verified that by saying recycling plastic scraps to regenerate resins will, indeed, create a considerable value. Nonetheless, the current market choice between recycled and virgin plastic in production is based on cost and quality (Hopewell et al., 2009).

As for cost, a significant challenge recycling practices face is the high logistics costs, which combine the costs of collecting recyclable materials, transportation, and performing relevant pretreatment operations, as Alhumoud (2005) stated. Yet, although the collection, separation, and cleansing of waste are difficult and expensive, facilities to clean, sort, and recycle plastic, such as "Napco," already exist in KSA, reducing the processing cost. (Alhumoud, 2005; Napco, 2017).

Another critical factor in the economic appeal of recycling is the expense of virgin polymers, which can be seen as ideal replacements for recycled polymers from a financial perspective (Hopewell et al., 2009). Since recycled polymers often have inferior quality compared to virgin polymers, their price is limited by their cost (Hopewell et al., 2009). Therefore, the recycling cost must be substantially lower than the cost of local or imported virgin materials to accept recycled products in the GCC market. (Alhumoud, 2005). However, the price of oil, the primary feedstock for plastic production, affects the cost of virgin polymers (Hopewell et al., 2009). Oil's price has climbed dramatically since 2005, when it was roughly $25 per barrel, and now ranges from $50 to $150 per barrel (Hopewell et al., 2009). As a result, while higher oil prices raise the cost of collection and reprocessing increases to some degree, recycling has become more economically appealing, as highlighted by (Hopewell et al., 2009). Finally, the environmental costs of polymer production, such as CO2 emissions, should be considered and compared to recycling results (Hopewell et al., 2009).

As for quality, many standards and guidelines consider recycled materials to be lower quality than virgin materials, so purchasing products made of recycled materials will be regarded as an environmentally friendly investment (Hopewell et al., 2009). Meanwhile, the quality of such recycled products should be high enough to make such a company profitable (Alhumoud, 2005). Thus, converting plastic waste into long-lifetime material using the appropriate additives and technology grants economic and environmental benefits towards sustainable development (Alhumoud, 2005). As discussed previously in the sustainable building practice section, bio-based composite is the way forward for successful recycling technology of polymer waste. The biopolymer composite might save energy compared to petroleum-based alternatives and could be recycled (Karana, 2012). Simultaneously, such an approach will reduce the natural resources and energy and lower CO2 emissions (Ignatyev et al., 2014). In addition,

to develop a particular technology to produce a biopolymer composite, it is essential to understand that mixing more than one polymer type will typically make a weak product and cause contamination to the composite matrix (Hopewell et al., 2009). Thus, choosing one appropriate polymer type is necessary to close the loop and implement a practical recycling project. Controlling the supply of recyclable products is a problem that many private sector businesses and communities face worldwide. (Alhumoud, 2005) As a result, the volume of polymer and fiber on the KSA market should be considered to ensure a continuous flow of the recyclable material.

2.4.2.4 Polymer Volume

The GCC report demonstrates that the GCC countries' greatest plastic consumption by volume is in the packaging division, with a market share of 44% (GPCA, 2013). The Saudi Arabian plastic packaging market was worth USD 7.64 billion in 2018 and is expected to grow to USD 10.64 billion by 2024, with a CAGR of 5.6 percent between 2019 and 2024 (DUBLIN, 2016). The growth of the food industry in the country increases the packaging demand (Research, 2019). To this extent, Saudi Arabia has become one of the largest markets in the Middle East for the packaging industry (Research, 2019). Moreover, the current pandemic crisis has boosted the demand for packaging and plastic use (Research, 2019). According to the Saudi Arabian Ministry of Commerce and Industry, the beverage and soft drink industries are currently among the nation's most mature businesses (Research, 2019). The 2017 Global Packaging Trends Report concludes that between 2017-2020 drinks bottle is the most significant growth category among other types of plastics (Research, 2019)

The resins that are most typically utilized in the manufacture of consumer bottles are polyethylene terephthalate (PET) and HDPE (Dwivedy, 2018). However, the demand for PET bottles was about 24 million tons globally in 2017, higher than HDPE (Dwivedy, 2018). Middle East is considered

the third largest region globally in PET bottle consumption (The 2017 Global Packaging Trends Report). Additionally, since 2006, the consumption of PET has been the strongest among other types of polymers in GCC countries, growing by 11.6% per annum, higher than the global growth of 5.3% per annum (GPCA, 2013). KSA has the largest share of PET consumption in the middle east and Africa (Tan, 2017).

Consequently, PET waste is the highest among other types of plastics in the country (Research, 2019). PET demand is increasing during the holy month of Ramadan and haj by distributing water to the Holy Mosque (Nizami et al., 2017). In his study "Plastic waste carbon footprint generation in KSA, "Islam Muhammad (2018) delineates that the waste from water bottles alone in KSA is more than eight hundred thousand tons. About 300,000 tons are recycled, with the rest destined for landfills (Nizami et al., 2017). Furthermore, water bottles independently produce around 26 million tons of CO2 in Saudi Arabia annually (Islam et al., 2018). The high volume of this type of plastic necessitates a recycling initiative (Dwivedy, 2018). In addition to the volume, PET uses little energy during recycling (Dwivedy, 2018).

Furthermore, it is much easier to eliminate volatile contaminants while recycling PET polymer compared to other polymer types (Dwivedy, 2018). Over the projected period of 2021-2026, the Middle East and Africa PET resin market is expected to expand at a substantial rate, with a CAGR of over 4.5 percent. During the forecast era, the demand is projected to be driven by a growing focus on recycling (Research, 2019). The recent PET marketplace and the prospects prove a high flow of the material (Islam et al., 2018). Thus, PET bottle recycling is a viable long-term project for Saudi Arabia, as it reduces the need for raw materials (Nizami et al., 2017). These characteristics make it a promising closed-loop polymer (Dwivedy, 2018), especially in the Saudi market. Therefore, PET is the appropriate polymer type for developing this study's proposed exterior wall panel.

2.4.2.5 Fiber Volume

Natural fibers are a widely available, highly accessible substance found in nature. They exhibit several exceptional material qualities, including high strength, particular stiffness, biodegradability, and cheap cost per unit volume (Alkoaik et al., 2019). The wide variety of natural fibers like sisal, kenaf, jute, oil palm, flax, and hemp typically generate a spectrum of the probability of designing composites for a particular application or with specific material properties (Al-Kaabi et al., 2004). Parameters like aspect ratio and filler concentration, plus the degree of an interfacial adhesion amid the matrix and the filler, can all be invoked to produce the composite with ideal properties (Dehghani et al., 2013). Besides, natural fibers are used as fillers or reinforcing materials, mainly for polymer-based matrices, decreasing waste disposal challenges and reducing the use of fossil fuels (Ghori et al., 2018).

Nonetheless, Saudi Arabia has a harsh climate, with summer temperatures reaching 50°C in the shade and winter temperatures as low as 0°C or much below (Salman et al., 2018). Subsequently, few plant species can thrive in such a harsh environment (Misachi, 2017). The vast majority of this region is practically devoid of vegetation except for a few desert plants, such as the date palm tree (Misachi, 2017). The date palm is the most significant fruit widely grown in (KSA) since it accounts for 75 percent of the country's fruit output. KSA is one of the world's leading palm tree production countries (Elfeky & Elfaki, 2019). According to Almadini et al. (2021), More than two-thirds of Saudi Arabia's permanent cultivated land is planted with date palms, with an estimated 25 million trees generating about 1 million tons of dates per year, about 15% of global output. In addition, the number of date palm trees in Saudi Arabia is continuously rising, reaching more than 28 million in 2018 (Alkoaik et al., 2019). Yet, the date palm needs specific care over its lifespan (Faiad et al., 2022). Offshoots and dead or faulty fronds must be removed annually, creating 20 kg of waste per date palm (Faiad et al., 2022). As a result, Saudi Arabia

produces 200,000 tons of biomass waste annually (Faiad et al., 2022). This massive amount of waste is often disposed of by burning, resulting in severe environmental pollution and health issues (Alkoaik et al., 2019). On the contrary, this enormous waste could give the country a tremendous chance to design profitable, sustainable applications rather than dispose of them (Faiad et al., 2022).

Additionally, date palm trunk and leaf fibers have better mechanical strength and modulus than E-glass and several aluminum alloys (Ghori et al., 2018). These features of date palm fibers turn them into a possible alternative to synthetic fibers in polymer composite in structural and semi-structural applications (Ghori et al., 2018). Composite production might offer new markets for DPL waste that is generally thrown away (Dehghani et al., 2013). Significantly, the manufacturing costs will be drastically lowered due to the lower price of one ton of palm, which accounts for between $100 and $150 (DOHA, 2017). Thus, adapting PET polymer and DPL to produce a panelized wall system in Saudi Arabia will create a massive value to the market and circler economy.

2.4.3 Exploration of Sustainable Wall Panel Materials in the Saudi Market

The utilization of sustainable wall panel materials has become increasingly prevalent in the Saudi construction sector as a result of the increasing focus on green building approaches. This section examines multiple types of sustainable wall panel materials that are currently accessible in the Saudi market.

2.4.3.1 Granite

Granite is a natural stone used as a wall cladding material. It is rarely favored in residential buildings due to the stone's hardness, darker color, and visible texture (Idris, 2004). Yet, commercial structures often utilize it (Idris, 2004).

2.4.3.2 Natural Limestone

Limestone is typically used in buildings' exterior cladding for appearance and does not fulfill any structural functions (El-Aal et al., 2021). The standard application of a limestone facade, as stated by (El Hanandeh, 2015), is by adding an EPS-backed limestone cladding with a thickness of 30–50 millimeters to a concrete wall with a thickness of 100 millimeters, then cement plaster with a thickness of 25 millimeters is used to mount the stone.

2.4.3.3 Terracotta

The production of terracotta panels involves extruding a clay mixture into a fabrication and then molding it into various geometrical forms using two layers of material (Watts, 2011). The panels are then strengthened with minimal amounts of aluminum to create louvered screens (Watts, 2011). In addition, these panels include grooves and holes that enable them to be hung from clips that are linked to the building (Alhefnawi, 2021). This helps keep the panels from getting heavy (Alhefnawi, 2021). Terracotta has high thermal efficiency but is rarely used in residential buildings and is primarily found in schools in Saudi Arabia (Alhefnawi, 2021).

2.4.3.4 Wood–plastic composites (WPC)

Bio-based materials, such as wood–plastic composites (WPC), have attracted the attention of the building and construction industry (Friedrich & Luible, 2016). It is featured by providing thermal insulation and heat preservation properties (Seven Trust, 2021). WPC cladding systems used in the Saudi market are imported from China and constructed using recycled high-density polyethylene and solid wood fibers (Seven Trust, 2021).

2.4.3.5 EIFS

The External Insulation Finishing System (EIFS) is an exterior wall cladding system (Totten & Pazera). According to (Ghosh, 2015), the system comprises an EPS (Expanded Polystyrene) insulating board that is attached to the wall and kept in place by mechanical fasteners. One side of the insulation is coated with an adhesive layer of cement and reinforced with fiberglass mesh. The systems involve specific fittings such as starting strips and corner beads to link them to the building structures. Primers and topcoats are applied on top of the reinforcing layer.

2.5 The Potential of Recycled PET/Palm Fiber in Wall Panel Application in KSA

Integrating biocomposite materials into indoor and outdoor wall panel applications requires a thorough assessment of critical factors for user safety and comfort. Addressing safety characteristics such as compliance with building codes, fire resistance, consideration of climatic conditions, and improving user experience via aesthetics and noise reduction in acoustic panels are all crucial aspects to consider. The subsequent paragraphs will address the prospective utilization of biocomposite wall panels to fulfill the specifications of interior and outdoor buildings.

2.5.1 CODE COMPLIANCE

Each building type is subjected to regional code-compliant regulations and standards for use, area, occupancy, materials' wind load, structural, and fire rating requirements. Thus, architects must examine the regional building code requirements for the building type they are designing to apply the panel properly and assure the users' safety. According to (SBC, 2018), biopolymer composites' wall panels can be applied to any building type with any height if they meet the following requirements:

- Thermal barrier.
- Fire resistance, if required, for the assembled wall type

- The potential heat indicated in MJ/m^2 of the wall assembly's insulation shall not be exceeded.
- The insulation's flame spread and smoke-developed index shall be tested, except for a fabricated panel with a minimum of 0,5 mm aluminum facings and a total thickness of 6.3 mm or less.
- Materials intended to be installed in more than one thickness, minimum and maximum thickness of the exterior wall shall be tested on ignition.
- If the fiber-reinforced polymer (FRP) is installed on a building with a hight of 12m or less above grade, compliance with the previous regulations is waived when the following criteria are met:
- A fire separation distance of 1.5 m or less.
- Fire separations more than 1.5 m must pass NFPA268 tests to ensure they do not sustain exterior wall igniting.
- The external combustible wall covering must be backed by the outer wall and not extended over it.
- Where the fire separation distance is 1'5 m or smaller, FRP cannot exceed 10% of the wall area. Where the fire separation distance is larger than 1.5 m, fiber-reinforced external wall covering is unrestricted.
- The FRP panel must have a flame spread index of 200 or less. The flame spread index criteria do not apply to coatings with a thickness of less than 0,9 mm applied directly to the fiber-reinforced polymer.
- fire blocking.

2.5.2 Safety Features (Fire Resistance)

Using biocomposite materials as wall panels required compliance with relevant fire safety regulations. Including a fire retardant in the composite is crucial for reducing fire risk (Binhussain & El-Tonsy, 2013). However, designing fire barriers should be considered when the wall panel is used for exterior application (Sandak et al. (2019). Sandak et al. (2019) state that biocomposite panels shouldn't adhere directly to the wall structure. To enhance the effectiveness of fire suppression systems, ventilated

facade systems that are sealed with vapor-permeable membranes should integrate biocomposites (Sandak et al. (2019). This system offers an air plenum layer beneath the cladding to facilitate the interchange of moisture and vapor (Sandak et al. (2019). Therefore, in the event of a fire, the air contained in the plenum could potentially contribute to its advancement. Consequently, the chimney effect behind the cladding may cause flames to propagate upwards along the upper portion of the facade rather than toward the building itself (Sandak et al. (2019). Therefore, while biocomposite materials may present fire hazards in the construction industry, they can be utilized securely by installing appropriate fire-retardant and fire-barrier systems. This approach effectively addresses concerns and guarantees improved fire safety.

2.5.3 Climate Resistance

Saudi Arabia has a harsh climate, with summer temperatures reaching 50°C in the shade and winter temperatures as low as 0°C or much below. Integrating recycled PET/DPF composite as an exterior wall alternative offers a revolutionary prospect for pursuing sustainable building practices. Nonetheless, the intense solar UV light exposure and elevated temperatures of the region pose substantial obstacles to the durability and effectiveness of recycled materials utilized in the construction sector and must be thoughtfully considered. The current section explores the substantial capabilities of the biocomposite under consideration, investigating its thermal, creep, and UV light resistance.

1.4.3.1 Thermal resistance

Employing recycled date palm fiber (DPF) with PET to form an exterior wall panel exhibits potential in dry and hot weather conditions because of their unique thermal property. **Table 2-2** highlights the findings of studies investigating the performance of DPF/recycled polymer composites in heat degradation concerning fiber proportion and surface treatment.

TABLE 2-2 THERMAL PROPERTY OF PALM FIBER INTEGRATED INTO THE POLYMER COMPOSITE

Fiber& composite property	Research studies illustrate the thermal properties of recycled palm fiber and polymer			
	(Al-Kaabi et al., 2004)	(Binhussain & El-Tonsy, 2013)	(Dehghani et al., 2013)	(Raza et al., 2022)
Fiber to polymer Ratio	Random	1:1	5 WT.% 10 WT.% 15 WT.%	Not specified
Composite's Thermal degradation	Not specified	340 C^O	430 C^O	424 C^O / 386 C^O / 282-383 C^O For four samples
Fiber's Thermal degradation	25C^O	250 C^O	300 C^O	255 C^O
Treatment	untreated	untreated	Treated with NaOH	untreated

Natural fiber-reinforced composites have greater thermal stability than fibers alone (Raza et al., 2022). The results of Raza et al. (2022) research indicate that the initial degradation temperature of the insulating composite rose to 282 °C, while the raw fibers began to decompose at 255 °C. The result of the Binhussain & El-Tonsy (2013) study also illustrates a rise in the thermal degradation of DPL reinforced composite to 340°C compared to fiber alone, starting at 250 °C. Furthermore, the composite reinforced with alkaline-treated DPF exhibits superior mechanical and thermal properties, as demonstrated in the study of Dehghani et al. (2013). In his investigation, the composites undergo thermal degradation at a high temperature, opposing the composites examined by Al-Kaabi et al. (2004), Binhussain & El-Tonsy (2013), and Raza et al. (2022). The fiber proportion simultaneously influences the thermal stability of biocomposites. As shown in **TABLE 2-2**, the study by Dehghani et al. (2013) illustrates that thermal degradation of the composite containing 5 WT.% fiber begins at 430 °C. It decreases immediately with fiber addition to 424 °C and 386 °C with the addition of a 10,15 WT.%, respectively. Yet, in Binhussain & El-Tonsy (2013) study, the thermal degradation started at 340 °C, which could be due the fiber to polymer ratio of 1:1. Nonetheless, (Raza et al., 2022) study reveals diverse ranges of thermal deterioration of the composite between 282 and 383 °C, which may be due to the random addition of fiber. He mixed a

random quantity of fiber with the polymer once and then made several samples that, in the end, showed varying densities.

1.4.3.2 Creep resistance

The preceding analysis of Dehghani et al. (2013), Al-Kaabi et al. (2004), Binhussain & El-Tonsy (2013), and Raza et al. (2022) research findings investigated how additives, treatment methods, and fiber types affected the thermal performance of DPF composites. The DPF composite addressed in the research of Dehghani et al. (2013) has superior mechanical and thermal performance compared to previous studies due to using a unique treatment technique, incorporating additives, and investigating various fiber proportions. Adapting the Dehghani et al. (2013) approach for wall panel formation is promising for external applications. Nevertheless, utilizing the composite material for exterior purposes requires a tendency to withstand creep.

Although the result of the Dehghani et al. (2013) study did not explicitly state an improvement in creep resistance, the Dynamic Mechanical Analysis (DMA) results revealed surprising details about the material's behavior. The results showed no noticeable variations across formulations below the glass transition temperature (Tg), suggesting a stable glassy state. However, when the temperature grew, Tan δ values, which measure the ratio of the material's viscous to elastic response, started increasing and peaked at about 80°C. Between 80 and 120 °C, Tan δ values decreased, probably because of cold crystallization of the polymer. This temperature range corresponds to probable structural transitions, possibly related to the glass transition or other viscoelastic processes.

Moreover, the connection between peak intensities of Tan δ curves and impact strength indicates that adding palm fiber enhances energy dissipation under stress conditions. The observed temperature-dependent changes in Tan δ and correlation with impact strength indicate a promising potential for the

PET/palm fiber composite in exterior applications, especially in regions with extreme temperatures. However, creep is not an issue with the suggested wall finish since it is a finished non-structural panel and is not significantly affected by spikes at or above Tg. In other words, biocomposites are generally not employed in load-bearing or structural applications where they will be subjected to prolonged exposure at or above the Tg of the resin matrix.

1.4.3.3 Thermal comfort

The internal air temperature is a fundamental aspect that directly affects the comfort of the occupants. Proper insulation is necessary to mitigate the risk of excessive heat or cold to ensure the user's comfort. Researchers in the construction and architecture field have conducted several lines of research on this matter. They have examined the effect of bicomposites in the building's construction to enhance its thermal performance. Abdou et al. (1996) analyzed the thermal properties of fiber-reinforced plastic panels in their study on the thermal performance of a prefabricated building envelope system. They analyzed two full-scale panels measuring four by four feet, one with a thickness of one inch and the other with three inches. The outcome indicates outstanding R values for the panels under review. Moreover, the R-value increased as the panel thickness reached three inches. These findings demonstrate the potential for using biopolymer composite as a wall panel system in buildings responsible for energy efficiency. Similar studies by; (Augaitis et al., 2020, Hassanin et al., 2018; Mohamed et al., 2021; Muthuraj et al., 2019) have proved the viability of producing thermally insulating materials from biobased composites. In addition, (Alkoaik et al., 2019; Raza et al., 2022). Research indicates that producing insulation materials from date palm waste is a potential strategy for generating eco-friendly and cost-effective alternatives to high-priced and harmful petroleum-based insulation products.

1.4.3.4 UV light resistance

Prolonged exposure to ultraviolet (UV) light is a significant concern for the durability of an exterior wall application and requires a comprehensive evaluation. Al-Azzawi (2015) examined the performance of recycled PET (r-PET) samples when exposed to UV and accelerated weathering. The research suggests that despite slight discoloration, gloss changes, and the formation of minor cracks, the fundamental properties of r-PET remain mostly unchanged even after extended exposure to extreme weather conditions. The study's results on the molecular structure and mechanical properties of r-PET and its ability to withstand degradation caused by UV radiation provide evidence that r-PET biocomposites might be a feasible and environmentally friendly substitute for external wall panels. Concerning the discoloration issue, the use of additives may improve the characteristics of the material and decrease the perceived issue of UV light exposure (Ebnesajjad, 2012). Utilizing UV radiation blockers might potentially address the problem of color fading (Mason et al., 2018). Additionally, coating the panel with an opaque Gelcoat can protect it from ultraviolet light. Gelcoating is the most prevalent of these methods because it offers the desired surface quality and a 10-20-mil (0.25 0.51 mm) thick protective coating.

1.4.3.5 Conclusion

Based on the previous discussion, the success of reinforcing recycled PET with natural fibers depends on factors such as the proportions and treatment of the natural fibers, the additives, and the processing techniques used to meet the desired properties for the intended application. Bio-composites fabricated from recycled PET and date palm fibers exhibit strong potential as external or internal wall materials, even in extremely hot environments, due to their resistance to heat, creep, and UV radiation. However, extensive testing and analysis will be conducted in future research to improve these properties for outstanding durability and expanded application in buildings.

2.5.4 User Comfort (Noise Control and Aesthetics)

1.4.3.1 Acoustic panel insulation

Buildings must have adequate acoustic qualities to attain desirable sound levels. Date palm fiber-reinforced biocomposites have exceptional acoustic characteristics, making them a desirable option for constructing wall panels. The distinctive cellular structure of date palm fibers enhances acoustic performance by naturally absorbing sound, as Salih et al. (2013) assert.

In their work, Salih et al. (2013) utilized palm fibers obtained from several portions of date palm trees to strengthen unsaturated polyester resin in producing composites. The researchers examined the acoustic insulation properties concerning fiber length and varying volume fractions. The findings indicate that increasing the volume percentage of Date palm fibers improved the composites' acoustic insulation properties. Conversely, as the fiber length increased, these properties decreased. Another investigation was conducted by Taban et al. (2021), who used date palm fiber to produce acoustic insulation panels suitable for building insulation. They manufacture panels of varying thicknesses (25, 35, 45, and 55 mm) and densities (125 and 175 kg/m3). The results of the sound absorption coefficient suggest that panels measuring 55 mm in thickness and having a density of 175 kg/m3 demonstrate superior sound-absorbing capabilities. As a result, increasing the panels' thickness and density increases the acoustic property of the panel.

The results discussed above highlight the effectiveness and cost-efficiency of utilizing reinforced date palm composites for acoustic insulation panels, providing a viable alternative to standard panels made of synthetic fibers. This environmentally friendly solution aligns with the need for sustainable materials, giving an innovative option for the construction market.

1.4.3.2 Aesthetics

The potential of biocomposites to enhance thermal performance, mechanical integrity, and aesthetics in wall panel materials could increase their utility in the construction market. Reinforced composite wall panels offer architects and designers an innovative approach to preserving structural integrity while expressing creativity; this might lead to better aesthetics and more practical environments. However, aesthetics is increasingly regarded as significant factors by the market, alongside functionality and durability. This illustrates the significance of aesthetic and other sensory characteristics in shaping consumers' perceptions regarding products and their subsequent purchasing decisions.

According to the American Composites Manufacturers Association (2016), biocomposites provide a potential new way to improve the visual appeal of building materials because of their low cost and ease of molding into complex forms. They also can capture very complicated patterns with no loss of detail using affordable molds. Moreover, they can be formed to any size, shape, and texture. Despite their promise, existing research has failed to address these materials' visual and tactile features adequately. Therefore, the proposed framework in this study provides a road map to enhance biocomposite aesthetics by manipulating the tactile and visual properties that will influence the intersection between material and process. This approach enables customization and adaptability in the design of Biocomposites, allowing for the rebranding of an unattractive variant into one that is more appealing.

2.6 A Review of Processing Challenges and Strategies in PET-Palm Fiber Composites

Polyethylene terephthalate (PET) is one of the world's largest recycled polymers by volume (Ebnesajjad, 2012). Employing natural fibers as fillers or reinforcement in biocomposites offers various benefits, such as low density, low cost, and availability compared to synthetic fibers (Al-Kaabi et al.,

2004). Nonetheless, recycling and combining PET (polyethylene terephthalate) with palm to create materials pose unique processing challenges. Navigating these complexities is crucial for advancing sustainable practices in material development.

2.6.1 BONDING ISSUE

The performance of biopolymer composites is significantly impacted by the fiber's characteristics and the qualities of the interface between the natural fiber and the polymer (Singh et al., 2021). One significant limitation of using natural fibers as reinforcement is the weak bonding between hydrophilic natural fibers and hydrophobic polymers at the interface (Dehghani et al., 2013). Adequate bonding requires a deep understanding of the chemical composition of the surface being bonded, the procedures for applying the binding agent, and techniques for preparing the surface (Singh et al., 2021).

Numerous studies suggest that chemical treatment may enhance the performance of date palm fibers (Ghori et al., 2018). Alkaline treatment by sodium hydroxide (NaOH) increases surface roughness by reducing fiber diameter, thereby increasing the aspect ratio. This type of treatment led to the development of a rough surface that resulted in better fiber–matrix interface adhesion and increased mechanical strength (Dehghani et al., 2013). Al-Kaabi et al. (2004), in their study "Natural Fiber Reinforced Composites from Date," did a scanning electron microscopy examination of the composite they produced without fiber pretreatment. The result reveals poor bonding between the fiber and matrix as well as an unsmooth fiber surface covered with dust. The inadequate adhesion between the fiber and polymer matrix resulted in poor mechanical properties for the composite they created. Another study by Binhussain et al. (2013) also resulted in a low mechanical property on the final product due to untreated fiber. Thus, treating the DPL reduces their limits and improves their compatibility with the polymer in the

composites, as proved in (Dehghani et al., 2013) study where the pretreatment of DPL with 5% sodium hydroxide (NaOH) produces a clean and smooth fiber surface and enhances the final product property.

Furthermore, a coupling agent can improve the interfacial adhesion between the fiber and the polymer in the polymer matrix (Dehghani et al., 2013). However, the coupling agents' application technology affects the composite's bonding property. According to Ghori et al. (2018), the internal pretreatment coupling method is more effective than the pretreatment method. In a study by Binhussain et al. (2013), a coupling agent was used as a pretreatment for the polymer, which resulted in an ineffective surface topography and reduced mechanical strength. In contrast, the study of Dehghani et al. (2013) used internal pretreatment where the compatibilizers were added during the blend mixing, which improved the interfacial adhesion and enhanced the composite's mechanical properties.

To sum up, surface treatment procedures, coupling agents, and compatibilizers affect the compatibility of date palm fibers with PET matrix and can overcome bonding limitations (Dehghani et al., 2013).

2.6.2 Processing thermal issue

The lower processing temperature of natural fibers, which decomposes at high temperatures between 100 and 250 °C, is considered a significant limitation when combined with PET, as its melting point reaches 245°C (Al-Kaabi et al., 2004; Dehghani et al., 2013). Therefore, producing reliable natural fiber-reinforced polymer composite products requires a deep understanding of fiber deterioration at processing temperatures (Al-Kaabi et al., 2004). Applying date palm fibers (DPF) as a filler in polymeric matrices across industry sectors represents a valuable technological innovation. DPF is composed of micro cellulose fibrils embedded in the molecular chains of lignin, which have been identified as the most

important structural elements in fibers due to their stability and high mechanical properties. On the other hand, date palm fiber (DPF) has a more desirable chemical composition and mechanical strength than other natural fibers (Ghori et al., 2018). The thermal stability of DPF is higher than other natural fibers, where the start of thermal degradation ranges from 240-250 °C, as stated by (Al-Kaabi et al., 2004; Dehghani et al., 2013; Raza et al., 2022). However, fiber surface treatment is required to enhance the fiber thermal stability and overcome the high processing temperature of PET. According to Magagula et al. (2022), the composites reinforced with fibers undergoing surface treatment demonstrated reduced weight loss and enhanced heat stability (Magagula et al., 2022). The alkaline modification is a widely used chemical treatment approach because of its simplicity, effectiveness in modifying the surface, and cost-effectiveness. The alkaline modification process increases the fiber's thermal degradation stability by partly extracting lignin and eliminates waxes and other compounds covering the fiber's outer surface. Dehghani et al. (2013), in their study "Mechanical and thermal properties of date palm leaf fiber reinforced recycled poly (ethylene terephthalate) composites," compared the thermal stability of treated and untreated fiber and showed significant differences. The thermal degradation of the untreated fiber starts at 250°C, while that of the treated fiber degrades at around 300°C.

The above discussion demonstrates that date palm fibers could be used as reinforcement for composites made from thermoplastic polymers despite the high processing temperatures required for this material.

2.7 Framework's potential in the body of knowledge of recycled biopolymer waste

The study presents an innovative approach by addressing the lack of attention devoted to aesthetics in prior studies on recycling biopolymer composites. By merging aesthetics and sustainability this endeavor contributes to the current body of knowledge in two keyways. First, it illuminates the

significance of aesthetics, emphasizing its role in the acceptance and adoption of sustainable materials within the construction industry. Second, it presents a comprehensive knowledge framework that synthesizes material process and product considerations, providing a structured approach to the development of aesthetically pleasing and environmentally friendly wall panels. Furthermore, this research expands the existing body of knowledge in architecture and material science by bridging the gap between these disciplines and emphasizing the importance of aesthetics alongside performance. By recognizing the interconnectedness of architectural design and material selection, it encourages the adoption of sustainable materials while considering aesthetic preferences. The proposed framework is a critical tool that will support the effective implementation of sustainable materials and encourage the growth of research considering the aesthetics and performance of any recycled materials.

2.8 Chapter Summary and Conclusion

In conclusion, the literature review provided an extensive review of sustainable building practices in Saudi Arabia, emphasizing the increasing significance of environmentally friendly construction materials and technology in the country. Considering the rising focus on environmental responsibility, the need for inventive resolutions has grown exceedingly crucial. Investigating sustainable wall panel materials in the Saudi market has uncovered the possibility of using recycled PET and palm fiber to produce aesthetically pleasing and eco-friendly alternatives. Despite the prevalence of current building materials in the market, sustainable alternatives that are aesthetically pleasing and align with sustainability goals and waste reduction may be provided. The significance of producing an aesthetically pleasing wall panel using recycled PET and palm fiber lies in its capacity to transform the building industry in Saudi Arabia. By prioritizing environmental considerations and conforming to worldwide sustainability trends, this initiative has the potential to establish novel benchmarks for the industry.

Incorporating recycled materials minimizes waste and demonstrates a dedication to sustainable practices, in line with the Saudi government's objectives for a more environmentally friendly future.

Significantly, establishing a framework act as a guide for the effective implementation of this large undertaking. An organized framework will provide direction for all stages of the project, starting from the original ideation to the development of materials, implementation of production processes, and final entry into the market. It will provide a systematic approach to guaranteeing that every part of the project is in line with sustainability goals while also satisfying the requirements of the competitive Saudi market.

The initiative to produce visually appealing wall panels using recycled PET and palm fiber supports worldwide sustainability objectives and establishes Saudi Arabia as a leader in embracing inventive and environmentally friendly building materials. The suggested Framework is an essential instrument that will facilitate the effective execution of this sustainable project and drive the development of the construction sector in the area.

Approach/ Methodology Chapter 3

3.1 Introduction

The research is structured in a framework of epistemological thought that recognizes the complex interactions among diverse fields of knowledge. It acknowledges the significant influence of user experience and sensory perception on the aesthetic qualities of wall panels by employing descriptive theories derived from different knowledge domains. The study aims to explore several realms of interdisciplinary interaction in which diverse forms of knowledge intersect through a transdisciplinary approach. Incorporating descriptive and explanatory theories is crucial for developing a knowledge framework for fabricating aesthetically appealing wall panels. To fully comprehend the principles and methodologies that influence the processes of the wall panel design, it is critical to possess established knowledge of explanatory theories, where scientific and architectural principles determine aesthetics and material quality considerations. On the contrary, descriptive theories offer a deeper comprehension of the experiential and subjective elements integrated into the design domain. The study promotes an integrated approach to knowledge development to provide readers with the essential information required to make decisions concerning designing visually appealing wall panels. This will be achieved by synthesizing knowledge from various disciplines within specific domains.

Therefore, this chapter explains the rationale for integrating explanatory and descriptive theories within a mixed-methods design. It outlines and defines the domains of knowledge and methodology associated with the framework's construction over three phases, beginning with the creation of the initial framework and ending in its refinement.

3.2 Knowledge

Knowledge is an intersection of experience, values, contextual information, expert insight, and intuition. It is a structure for evaluating and incorporating new experiences and information. (Matthew & Sternberg, 2009). While information is descriptive and refers to the past and present, knowledge is fundamentally predictive. It offers the foundation for predicting the future with confidence based on information (Alipour et al., 2011). Knowledge is cognitively generated and eventually leads to its approach to organizational domains, which are methodically integrated into documents, roles, processes, practices, and norms (Cooper et al., 2005).

3.2.1 Domains of Knowledge

Green (2021) states that the common architectural knowledge domains are Priori, Explicit, Tacit, Procedural, and Posteriori Knowledge.

•Priori Knowledge is design theories and principles defined and used throughout the brainstorming and pre-design phases.

•Explicit Knowledge in architectural design is obtained via formal education and other regulated ways (books, media, webinars, etc.)

•Tacit Knowledge is created by explicit instruction and direct experience gained through experimental design and learning.

•Procedural Knowledge is the outcome of the owner's expertise and experience in design.

•Posteriori Knowledge is the expertise and experience gained over years of architectural practice.

Integrating diverse knowledge sources in architectural and martial science practices to produce a beautiful wall panel requires a roadmap to propose structure, processes, and information to assist in implementing the wall panel design. However, to determine the information source and type, it is necessary to understand the framework structure and analyze the research methods and their associated knowledge domains.

3.3 Knowledge Framework structure

In the realm of material perception, individuals naturally give precedence to perceptual and experiential factors, thereby assigning considerable importance to the aesthetic and emotional experience (Zuo, 2010). The significance that we attribute to the materials we come into contact with is intricately linked to the sensory characteristics of those materials (Zuo, 2010). Significantly, manufacturing procedures play a role in creating particular sensory encounters, profoundly influencing how we perceive materials (Karana et al., 2009). Recognizing that the sensorial qualities and experiences of individuals affect the aesthetic perception of a material, it becomes evident that the manufacturing process of basic materials significantly influences the manipulation and improvement of these sensory attributes (Karana et al., 2009). Through deliberate manipulation of the manufacturing process, it is possible to shape the sensorial properties of the material, thereby exerting an influence on the meaning that is ascribed to it. Concerning the development of visually appealing wall panels, the proposed framework in the study aims to explain the complex interactions between material, process, and outcome **Figure 3-1**. According to this knowledge framework, the intended result, a visually appealing product, influences the interaction between the material and the manufacturing process. This emphasizes the significant consequences that deliberate material manipulation can have on the overall aesthetic quality of the end product.

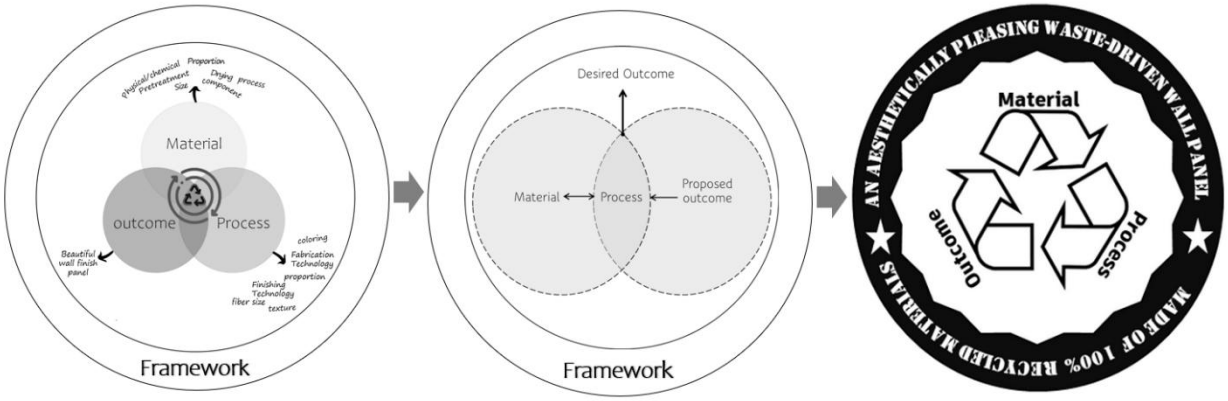


FIGURE 3-1 FRAMEWORK STRUCTURE

3.4 Framework development process

The development process was conducted in four phases, each using the appropriate method to capture knowledge and answer the research question, as shown in **Figure 3-2**.

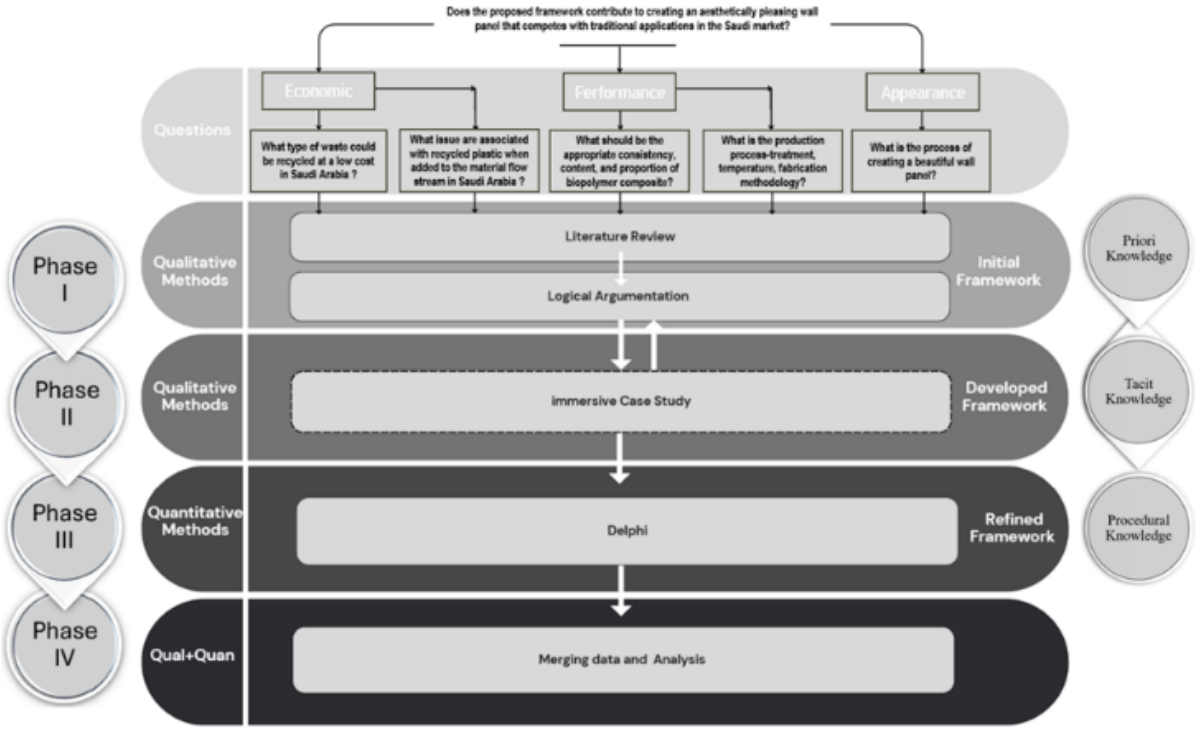


FIGURE 3-2 FRAMEWORK DEVELOPMENT PROCESS

3.4.1 PHASE I (INDUCTIVE)

The inductive approach in this study aims to develop the initial Framework to achieve a beautiful wall panel that competes with the conventional cladding system in the Saudi market by employing literature review and logical argument.

3.4.1.1 SOURCES OF RELEVANT KNOWLEDGE

Knowledge development in phase I was captured through priori knowledge. A" priori" is a Latin phrase that means "before" (Stull, 1984). A priori knowledge, as explained by Rowe (1982), is knowledge learned before engaging in a specific design problem. It refers to the data gathered in the early design

stage, processed, and utilized to control decision-making (Rowe, 1982). The priori knowledge was obtained through a qualitative approach, including literature review and logical argumentation. The literature review helps to understand the issues related to the design problem. Logical argumentation, on the other hand, was gathered to analyze studies of the primary function and proof of conceptual characteristics.

3.4.1.2 LITERATURE REVIEW

In the first part of this phase, a literature review was carried out to determine the current level of knowledge related to the application of recycled biocomposite waste in architecture. The topics illustrated in this section are the following:

- Sustainability and the related recycling issues
- Biocomposite and aesthetics
- The case of Saudi Arabia.
- Recycling pet-palm challenges: processing and environmental considerations

3.4.1.3 LOGICAL ARGUMENTATION

The second part of the qualitative study is a Logical Argumentation. According to (Groat, 2013), The logical argumentation method tends to combine previously diverse components into unified frameworks with considerable and sometimes new explanatory power. The logical argumentation in this research is the focal point of building up a design framework to develop the waste-driven finish panel. The Framework was mapped by analyzing previous methods for developing Biopolymer composites.

3.4.2 Phase II (Inductive)

In the second phase, the initial framework was examined and developed using the qualitative immersive case study approach.

3.4.2.1 Sources of relevant knowledge

Integrating theoretical considerations with practical experience when developing a product is standard practice. Experience-based knowledge that cannot be expressed is called tacit Knowledge (Matthew & Sternberg, 2009). According to Matthew & Sternberg (2009), cognitive processes use tacit knowledge to gain a new experience, improve practical learning processes, and pursue particular objectives.

3.4.2.2 Immersive Case Study

Although the previous analytical literature review and the Logical Argumentation methods provided a tentative plan to create the finish panel composite, combining them with other research methods is necessary to test the initial Framework, look at the problems, and solve them from different perspectives to Develop the proposed Framework. Thus, immersive case study research was conducted using an exploratory approach to address the research gap. According to Yin (2009), the exploratory case study provides researchers with the appropriate hypotheses and propositions for future investigation. Using a case study approach may help researchers better understand interventions in which the outcomes are not well defined.This part is divided into two stages. The preliminary stage comprises the material components, which include examining the pretreatment technique, grinding, and preparing the raw material. The following stage is the fabrication procedure, where the process intersects with the material to reach the desired outcome. Finally, the initial Framework was revised to the developed one.

In conclusion, the three qualitative phases are intersected based on the knowledge needed through framework development. In other words, in the third phase, new challenges appeared that required distinctive research based on previous knowledge from phase one and two which then tested through explicit knowledge.

3.4.3 Phase III (deductive)

The quantitative approach was used to refine the developed Framework by employing the Delphi method.

3.4.3.1 Sources of Relevant Knowledge

Knowledge was captured through procedural knowledge to refine the developed framework. According to Green (2021), Procedural Knowledge is the outcome of the owner's expertise and experience in design.

3.4.3.2 Delphi Method

(Skulmoski et al., 2007) Define the Delphi method as a flexible research strategy used when insufficient knowledge about a phenomenon exists. It is a distinctive approach used to methodically obtain knowledge about issues and establish agreement via the utilization of panels including carefully chosen experts (Koskey, May et al. 2023). It is very effective when developing predictions and expanding our understanding of issues, opportunities, or solutions (Skulmoski et al., 2007). This strategy is a process that consists of a series of consecutive or "rounds" unified with controlled feedback and aimed at achieving the most trustworthy consensus view of a group of experts (Linstone & Turoff, 1975). The Delphi method was chosen in this study for several reasons:

1.It assists the researchers in accomplishing the research objective through expert building consensus.

2.It facilitates the refinement of a framework based on an expert agreement approach.

In the Delphi procedure, qualitative and quantitative methodologies may be employed (Skulmoski et al., 2007). This research will follow a quantitative approach to gain consensus of expert feedback on the proposed Framework to show the feasibility of producing a beautiful waste-driven wall panel.

The decision to prioritize consensus over validation in this study was prompted by the knowledge-based nature of the proposed framework, which seeks to fill the existing knowledge gap associated with recycled biopolymer wall panels. Furthermore, due to the academic setting and time constraints during which the framework was developed, validation is not necessary because neither the performance nor the aesthetics of the proposed framework were evaluated. However, an empirical investigation into the aesthetics and performance aspects of the proposed framework is necessary, considering the panel's intended application. Consequently, my intention is to advance the investigation further and perform a thorough validation of the framework in future research.

3.4.3.3 Delphi Comments and Feedback

Analyzing expert feedback captured through procedural knowledge influences the revision of the framework toward the refined one..

3.4.4 Phase IV (complementarity)

In the final stage, the researcher conducts an exploratory follow-up, wherein the data is integrated and analyzed in complementarity. This stage established a connection between qualitative and quantitative data. This connection highlights the refined Framework and the qualities recycled biocomposite provides to final panels.

Initial Framework: Logical Argument Chapter 4

4.1 Introduction

Biocomposites are heterogeneous structural materials composed of two or more constituent materials with different characteristics (Aaliya et al., 2021). The composite performance, biocompatibility, and durability have all been the subject of many studies, but no definitive solution has yet been identified. In biopolymer composites, a reinforcement agent from a natural fiber is added to a polymer matrix to make the composite stiffer and stronger (Dicker et al., 2014). The performance of biopolymer composites, such as thermal performance, compact strength, crystallinity, and density, was studied extensively in various early research, including (Aaliya et al., 2021; Abdou et al., 1996; Augaitis et al., 2020; Dicker et al., 2014; Friedrich & Luible, 2016; Hassanin et al., 2018; Jawaid & Khalil, 2011; Mohamed et al., 2021; Nourbakhsh & Ashori, 2010) studies. Similarly, (Al-Kaabi et al., 2004; Binhussain & El-Tonsy, 2013; Ghori et al., 2018) illustrate the influence of reinforcing palm fibers and recycled thermoplastic on the produced composite's performance. Nonetheless, in manufacturing, the aesthetics of biopolymer composite products are as significant as their chemical, physical, and mechanical performance (Sauerwein et al., 2017). A lack of studies that capture the aesthetic aspects of biocomposites was conducted (Manu et al., 2022; Zuo et al., 2014). Consequently, the available knowledge to develop a beautiful wall panel is insufficient. Thus, an initial knowledge framework will be constructed based on the analyzed data captured from the literature review in this section.

4.2 Approach for establishing the Initial Framework

According to Al-Kaabi et al. (2004), the properties of biopolymer composites depend on the following:

1. The Fiber type and amount.
2. Processing methods and techniques.
3. The structure and design of the composite.
4. Additives and modification of the fiber's surface and adhesion between the fiber and the matrix.

Therefore, the previous literature on date palm fiber and thermoplastic composites waa studied to create an initially roadmap for developing the proposed panel. As illustrated below, I constructed a logical argument based on the results of three studies (Al-Kaabi et al., 2004; Binhussain & El-Tonsy, 2013; Dehghani et al., 2013). They all agreed on the influence of the matrix property, fiber quality, and the general interfacial adhesion strength between the fiber and the polymer composite matrix. These studies illustrated in **Table 4-1** assisted in determining the appropriate percentage of DPF content, chemical and physical pretreatment of the raw material, and the fabrication process of the proposed panel to address the knowledge framework.

TABLE 4-1 METHODS IN PREPARING POLYMER-FIBER COMPOSITE

	Study	(Al-Kaabi et al., 2004)	(Binhussain & El-Tonsy, 2013)	(Dehghani et al., 2013)
Polymer	Type	Polyester	Three Matrix 1. Polycarbonate 2.Poluvinyle chloride 3. Polystyrene	Polyethylene terephthalate
	source	QUALIPOLY CHEMICAL CORP	Randomly collected from domestic waste	Heterogeneous deposits of post-consumer bottles.
	Ratio	Not specified	1:1	Three patches with different percentages. 1. 95 WT.% 2. 90 WT.% 85 WT.%
	Pretreatment	The resin mixed with 1 wt.% methyl ethyl ketone peroxide.	Immersed in diluted Clorox (5%) for 60 m. ● Washed with a liquid detergent with two rinses in water. ● Dried in the open air Shredded into 1-4 mm particles.	Dried at 60C for 24h
Palm Fiber	Fiber Type	Palm mesh	Frond	Leaves
	Material Source	"Alain" date's factory	Randomly collected from agricultural farm	Randomly collected from agricultural farm
	Ratio	Not specified	1:1	
	Pretreatment	● Washed with Tap water ● Dry at room temperature. Dried in a vacuum at 60 C° for 24 h.	● Dried in sunlight Leaves Chopped and cut into pieces from 0.63to 4.0 mm in a Shredder machine	● Washed ● Leaves Chopped and cut into pieces to a particle size of 75 µm ● Treated using 5% Sodium hydroxide at 100C° for 1 h. ● washed with distilled water. dried in Vacuum oven at 60C° for 24 h
Additives	binding agents	Not used	coupling agent ● Three patches of mixed raw material were pretreated with different solutions as coupling agents. ● PC mix (Saturated solution of polycarbonate in methylene chloride) ● PVC mix (mixture of acetone + carbon disulfide + PVC polymer) PS mix (Saturated solution of polystyrene in chloroform)	(SEB-G-MA) coupling agent. Compatibilizer supplies by shell Co added during extrusion mixing.
	Coloring agent	Not used	used	Not used

TABLE 4-1 CONTINUED

	Study	(Al-Kaabi et al., 2004)	(Binhussain & El-Tonsy, 2013)	(Dehghani et al., 2013)
Composite	Mixing and fabrication process	The resin mixture was degassed in a vacuum desiccator and then poured on the randomly aligned fiber placed in the mold. Then, the mold was closed, pressed, and cured at room temperature for 24 hours. Then, the specimens were placed in an oven at 100 C° for 2 h post-curing.	• Patches mixed using a mixer. • Batches are allowed to air dry. • Remixing for 3-4 min. • The composite was extruded in different temperature profiles. The mixture was pressed with hydraulic compression under a hot molten condition using a hydraulic machine.	• PET and (SEB-G-MA) dried at 60C° for 24h. • PET (SEB-G-MA) and DPL were measured separately and mixed for 10 minutes using a mixer. • Simultaneously, the blend added into an extruder. • Pellets were dried in the dryer for 24 hours at 60 ° C. Specimens were made using injection molding and then conditioned at 25 C° in a laboratory atmosphere for three dyes.
	Molding	Aluminum mold	Extrusion and compression molding	
Discussion		• The date palm fiber's density is lower than that of other natural fibers. • The Izod impact test proved that DPF had increased the toughness of the composite. • Thermal degradation of DPF composite starts at 250C° • The microscopic examination shows an unsmooth fiber surface covering artificial impurities and residual lignin. The composite mechanical properties (flexural strength) are low.	• Less water absorption • It has a lower linear burning rate compared to natural wood and MDF. • It can be used for an outdoor structure. High density due to the fabrication process, which develops internal air voids	• The impact strength of the specimens increased from 7.9 kJ/m^2 with no compatibilizer to 18.4 kJ/m^2 • With the addition of a compatibilizer • The addition of 5% and 10% DPL increased the composite crystallinity. However, increasing the fiber addition to 15% negatively reduces the crystallinity and stiffness. • The TGA test illustrated a faster decomposition rate when the fiber content increased from 15%WT. • 10 WT.% of fiber content shows a slower decomposition rate than 5,15%. • The addition of DPL increases the energy dissipation when the material is under stress. Increasing the fiber load lowered the thermal stability of the composite.
Comments		No coupling agent or compatibilizer The mesh fiber contains a lot of dust and requires multiple cleaning processes.		

4.2.1 Material

4.2.1.1 COMPONENT

Based on the previous analysis in the literature review of the polymer market and waste in Saudi Arabia, PET Polymer and Date palm fiber (DPF) derived from palm stems were selected. I randomly collected the water bottle waste to obtain the PET polymer. As for the palm leaf, I brought it from Alhudaithi farm's agricultural waste.

4.2.1.2 PROPORTION

The studies in **TABLE 4-1** show that the percentage of DPL in the polymer matrix affects the biopolymer composites' mechanical, physical, and thermal properties. Understanding the influences of fiber proportion helped determine the appropriate percentage of DPL fiber for the proposed panel.
As illustrated in **Figure 4-1**, based on (Dehghani et al.,2013), the impact strength of polymer with no fiber addition was 7.9 kJ/m². Yet, the inclusion of DPL fiber increased the impact strength of the composite. Nonetheless, increasing the fiber by more than 15 WT.% significantly reduced the impact strength because of the rigid nature of DPL fiber (Dehghani et al., 2013). In addition, increasing the fiber content to 50 WT.% will cause the composite to fail in the brittle mode because there was no yield point before the fracture, as mentioned in the Binhussain et al., (2013) study.

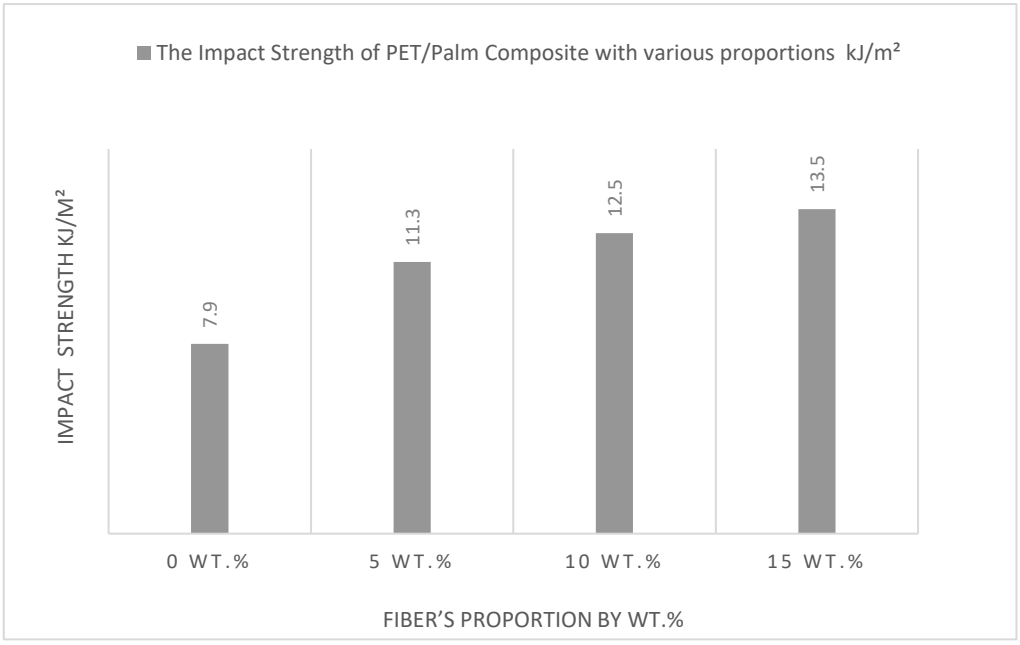


FIGURE 4-1 THE EFFECT OF FIBER ADDITION ON THE IMPACT OF STRENGTH KJ/M2, ACCORDING TO DEHGHANI ET AL., 2013 STUDY

Nonetheless, as illustrated in Error! Reference source not found. adding 5 or10% DPL to the composite influences the crystallinity of the polymer matrix. Yet, increasing the fiber to 15% negatively reduces crystallinity and stiffness (Dehghani et al., 2013). Consequently, the random accumulation of DPL causes the final products to have lower mechanical properties, as indicated in the study of K. Al-kaababi et al. (2004).

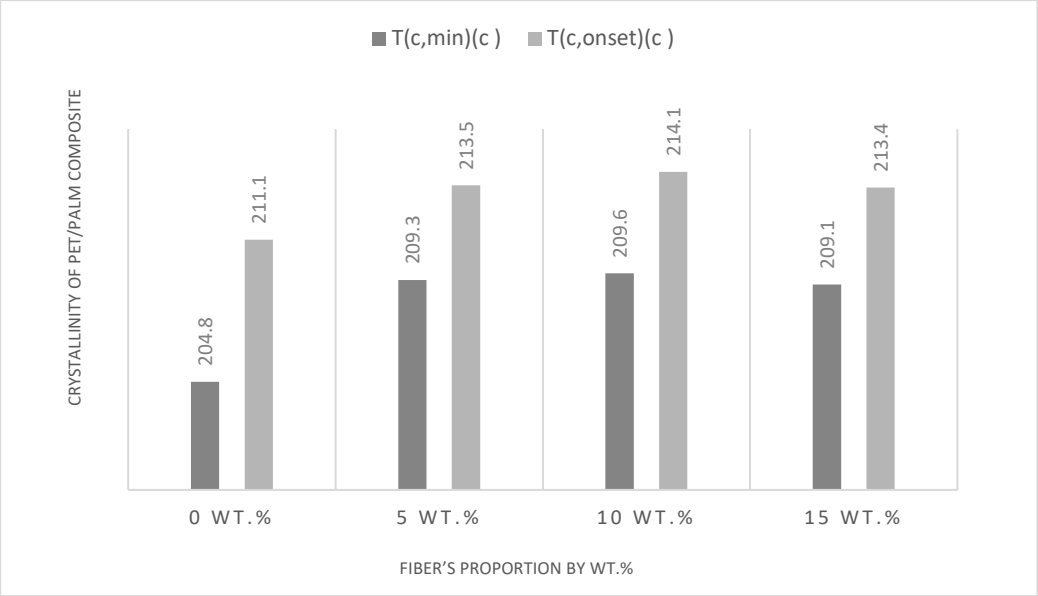


FIGURE 4-2 THE CRYSTALLINITY OF PET/PALM COMPOSITE WITH VARIOUS PROPORTIONS, ACCORDING TO (DEHGHANI ET AL., 2013)STUDY

The thermal property of materials also depends on the DPL content. Increasing the fiber load lowered the thermal stability of the composite and decreased the fiber compositions when exposed to heat (Dehghani et al., 2013). Thus, the addition of DPL increases the energy dissipation when the material is under stress starting at 45C°. However, 10 WT.% of fiber content shows slower decomposition rates than 5,15%.

Finally, based on the previous discussion, 5,10,15 WT.% of fibers could effectively produce a panel with suitable physical, thermal, and mechanical properties. Consequently, fiber content from 5% to 10% (WT.%) of DPL was considered for the proposed panel.

4.2.1.3 Additives and Raw Material Chemical and Physical Pretreatment

Chemical modification may enhance biopolymer composites based on processing types and methods (Ebnesajjad, 2012). Given that natural raw fibers are hydrophilic by nature and contain a high concentration of impurities on their surface, it is anticipated that this would result in inadequate bonding between untreated natural fibers and the polymeric matrix (Al-Kaabi et al., 2004; Karimah et al., 2021). The interfacial adhesion must be firm and practical for stress to be transmitted from the matrix to the fibers. Inadequate interfacial adhesion limits stress transfer, decreasing the composite's mechanical properties (Al-Kaabi et al.,2004). Numerous studies suggest that chemical treatment may enhance the performance of date palm fibers (Ghori et al., 2018).

The following paragraph illustrates the significance of fiber pretreatments based on the studies' results shown in **Table 4-1**. Al-Kaabi et al. (2004) revealed in their research that the final products had poor mechanical properties as a consequence of poor adhesion between the fiber and polymer matrix. According to (Alkabbi et al.,2004), the scanning electron microscopy test shows an unsmooth fiber surface covered with dust. The study by Binhussain et al. (2013) also resulted in a low mechanical property on the final product due to untreated fiber. Thus, treating the DPL improves their compatibility with the polymer in the composites, as shown in (Dehghani et al., 2013) study where the pretreatment of DPL with 5%NaOH produces a clean and smooth fiber surface and enhances the final product property.

Furthermore, treating the polymer is also required by using a coupling agent and compatibilizer to improve the interfacial adhesion between the fiber and the polymer in the polymer matrix (Dehghani et al., 2013). The interfacial adhesion must be solid and practical to transfer stress from the matrix to the fibers. Inadequate interfacial adhesion decreases stress transmission, lowering the composite's mechanical

characteristics (Alkabbi et al.,2004). In the study by Binhussain et al. (2013), a coupling agent was used as a pretreatment for the polymer. Yet, mechanical strength and the fiber's surface topography were ineffective as the compatibilizer was used during pretreatment. In the Dehghani et al. (2013) study, the compatibilizer was added during the mixing and fabrication process. This result goes back to the treatment process. According to Ghori et al. (2018), the internal pretreatment coupling method is more effective than the pretreatment method in the Binhussain et al. (2013) study. The coupling agent was applied as a pretreatment method for the polymer, slightly enhancing the final product's mechanical properties. In contrast, the study by Dehghani et al. (2013) used internal pretreatment where the compatibilizers were added during the blend mixing, which improved the interfacial adhesion and enhanced the composite's mechanical properties. Finally, surface treatment procedures, coupling agents, and compatibilizers affect the compatibility of natural fibers with thermoplastic matrices (Dehghani et al., 2013).

Based on the previous discussion, the palm fiber will be pretreated according to the (Dehghani et al., 2013) study. Then, the polymer should be treated using the internal pretreatment method according to the (Dehghani et al., 2013) study by adding 5WT.% (SEB-G-MA). Moreover, since the PET polymer will be randomly collected from the personal recycling bin, the (Binhussain et al., 2013) process for collecting and preparing the raw plastic material will be adopted. The following paragraphs explain the detailed steps of preparing the DP fiber and PET.

First, adapting Binhussain et al. (2013), the collected polymer will be placed in a dilute Clorox disinfectant solution (5 percent) for 60 minutes before the material is washed twice with a liquid detergent solution and rinsed twice with water. After that, the waste polymer will be allowed to air dry completely. Then, the materials will be compacted, shredded into particles, and stored in containers. Then, the

polymer will be dried at 60 °c for 24 hours (Dehghani et al., 2013). Secondly, by adopting Dehghani et al., (2013) method, the (DPL) will be prepared in three steps. First, the palm fiber surface will be treated using 5% sodium hydroxide at 100°c for one hour. Then, the fibers will be rinsed with distilled water and dried in a vacuum oven at 60°c for 24 hours. After that, the (DPL) will be grounded to different sizes. Thirdly, the compatibilizer material will be prepared by drying at 60 °c for 24 hours (Dehghani et al., 2013).

4.2.1.4Panel Size

The Saudi building code has no size or thickness restrictions on fiber-reinforced bioplastic materials used as wall panels; nonetheless, these materials must adhere to certain safety requirements and pass the thermal performance standard test (SBC, 2018). Therefore, since wood-plastic composite wall panels offer properties comparable to the suggested material, the WPC dimensions will be implemented. The (WPC) product sizes and thicknesses vary by application and manufacturer. WPC wall panels are available in 19 to 30mm thicknesses, 2 -6 m lengths, and 100-300 mm widths. Furthermore, the flexibility of the consumer to personalize the panel design to create an aesthetically pleasing product allows them to choose between these dimensions. Thus, allowing for customization while scaling up the project needs a procedure plan and innovative techniques to ensure a low-cost manufacturing process.

4.2.2 Composites fabrication (process)

Depending on their intended use, various processing methods have been suggested and used for biopolymer composites (Aaliya et al., 2021). Compression molding, injection molding, and extrusion are the primary processing techniques used most often for creating biopolymer composites (Ebnesajjad, 2012). The product's size, shape, reinforcing fiber type, polymer matrix type, and production cost

determine the appropriate production technique for biocomposites (Aaliya et al., 2021). The previous studies illustrated in **TABLE 4-1** highlight diverse processing techniques yet had different performance outcomes. Al-Kaabi et al., (2004) His study used a heat compress method, yet the mechanical strength of the final composite was low compared to (Binhussain & El-Tonsy, 2013; Dehghani et al., 2013). This refers to the good mixing of the composite by using the extruder. Extruders are usually utilized to compound polymer matrix and fiber to produce pellets, typically fabricated using injection molding (Ebnesajjad, 2012).

Constraints of Fabrication instruments for this research necessitated using a basic method in the lab for the study. The extrusion method adopted by (Dehghani et al., 2013) will be utilized to produce the composite pellets. Then the pellets will be added to the mold and compacted using the heat press machine according to (Al-Kaabi et al., 2004; and Raza et al., 2022) study to develop various panel appearances based on the desired outcome.

4.2.2.1 THE FABRICATION PROCESS WILL BE AS FOLLOWS:

A stainless-steel pre-press box will be utilized to cast the biopolymer composite. However, as both did, the plastic and fiber will not be randomly positioned. Extrusion will be used to form small composite pellets before construction to guarantee high mechanical strength and bonding between the polymer matrix and fiber. The pre-press cast will include the composite pellets. Once the samples are complete, the boxes will be put in a hot press machine for three hours at 70 °C with a weight of three tons. The compressed sample will be then placed in an oven for 48 hours at 100 °C to cure the mold. Finally, the size of the panels proposed on the framework will not be manufactured due to limitations.

However, to suit the available mold box, the patches will be 1.57"x 0.27"3.34" in size. The box measures 3.8"x 2.1"x 3.34" externally and 1.57"x 0.27"1.8" internally.

4.2.2.2 Textures

The product will be given the necessary finishing by inexpensive techniques such as brushing, embossing, and sanding, allowing for various textures based on the desired outcome.

4.2.3 Aesthetics (outcome)

The study adopted an aesthetics theory called "Unity-in-variety." (Sauerwein et al., 2017). This theory is based on the fact that pleasure may be derived by exploring the differences in how a material looks and feels by altering its physical and sensory characteristics. In other words, combining visual aesthetics with tactile contrast AB, as illustrated in **Figure 4-3** will lead to a visually appealing product. The fibers' proportions, size, and finish techniques will be selected above and tested based on the appearance variables.

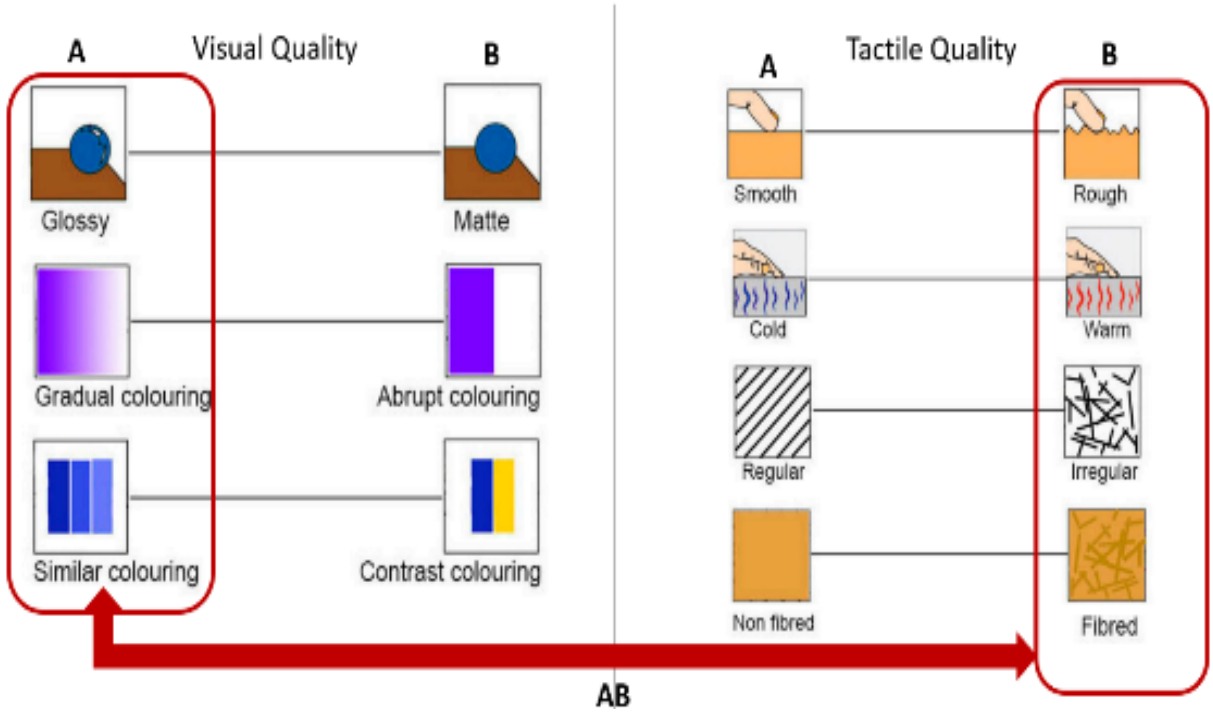


FIGURE 4-3 VISUAL TRANSLATION OF TACTILE PROPERTIES

ADAPTED FROM (SAUERWEIN ET AL., 2017) STUDY

4.3 Conclusion and Integration

In conclusion, the data analysis was completed by applying the logical argument presented in **Table 4-2**, which was derived from priori knowledge acquired through qualitative methods. This allowed for the construction of the initial knowledge framework, as shown in **Figure 4-4.** The second phase involves using quantitative methods to assess the initial framework in order to achieve a more refined outcome.

TABLE 4-2 LOGICAL ARGUMENTS TO CONSTRUCT THE INITIAL FRAMEWORK

Framework section	framework category		Notes & Recommendation
Material	Primary components	Palm fiber(stem) and Recycled PET polymer	
		Employing (FG1901) (SEBS), adopted by (Dhegihan et al.,2013) for enhanced bonding and thermal stability	
	palm physical and chemical pretreatment	Physically treating the palm by grinding it to small particles before the chemical treatment.	
		Alkali treatment by adding 5% NaOH enhanced thermal stability	Positively enhance the palm's thermal stability.
	PET physical and chemical pretreatment	Reducing PET size using a shredding machine into 1-4 mm particles.	
		●Immersed in diluted Clorox (5%) for 60 m. ●Washed with a liquid detergent with two rinses in water.	
	proportion	5,10,15 WT.% fibers might generate a panel with appropriate physical, thermal, and mechanical properties	
		(SEBS) will be 5WT.%	
	Particle size	● Fiber Sizes range between 6,2,0.75,0.5,0.25,0.18 based on the Aesthetics goal. ● (PET) size - 0.75 particles	
	Drying	Compatibilizer, plastic, and wood particles were dried at 60 C for 24 h.	
	Panel dimensions	●Thickness 19mm to 30mm ●Length 2-6 m ● Widths 100-300mm	
Process	Material Configuration	Select from material the colors, texture, fiber size, proportions, and panel dimensions based on the desired outcome	
	Fabrication method	Extruder followed by compaction will be employed for faster production and high mechanical strength.	
Outcome	Desired Aesthetic	adopting the "Unity-in-variety." by creating a contrast between tactile and visual property	

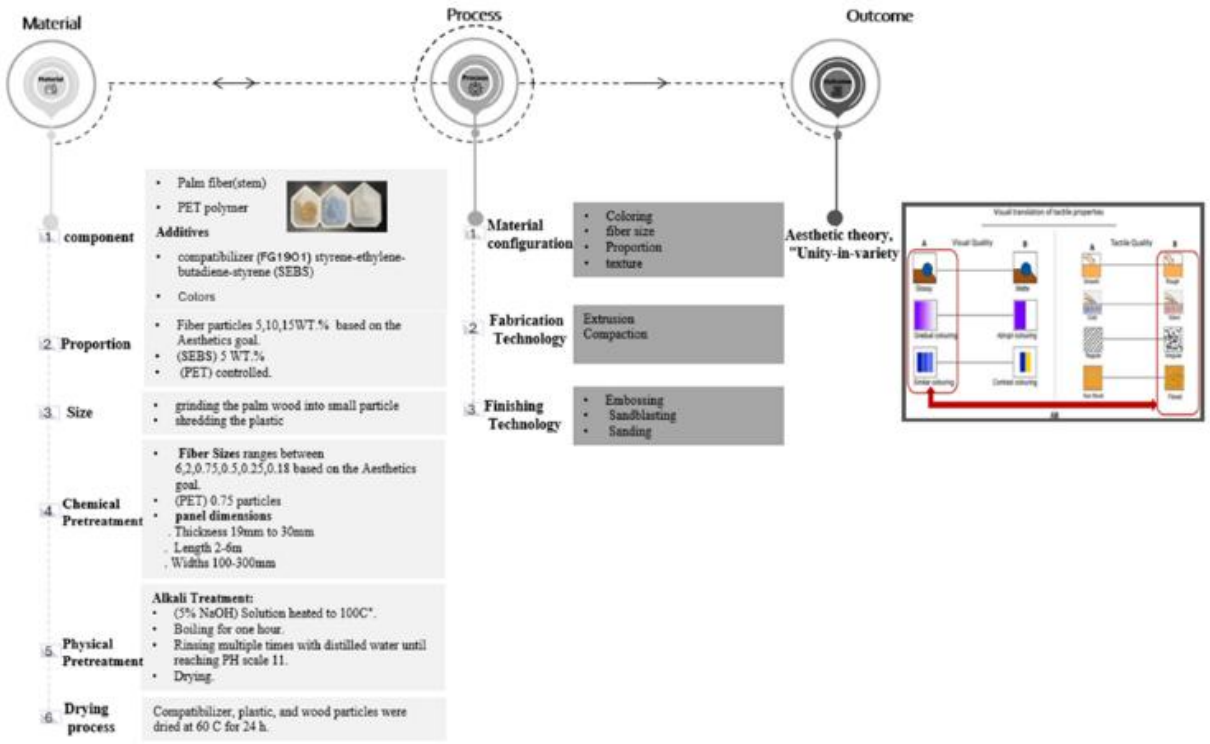


FIGURE 4-4 THE INITIAL FRAMEWORK

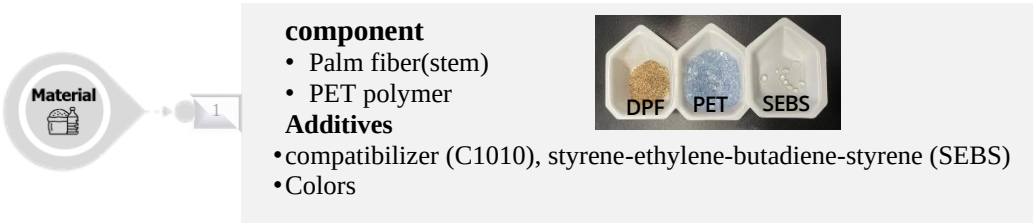
Developed Framework: Immersive case study Chapter 5

5.1 Introduction

The tacit knowledge required to construct the Framework was obtained through a qualitative approach. In this research, the proposed knowledge Framework was examined in the lab through an immersive case study at the laboratory level at King Abdulaziz City of Science (KACST). KACST significantly facilitated the execution of the immersive case study. The documentation process during the immersive case study was done through a journal and camera, as shown in **Figure 5-1.** Doing an immersive case study allowed me to gather insights that developed as a result of my direct interaction in the design process. The developed framework was shared with experts for consensus using the Delphi approach to refine the Framework based on their feedback.

FIGURE 5-1 DATA COLLECTION METHOD

The first stage of this method was to evaluate the material section of the framework, which is as follows:



5.2 Material

5.2.1 Compatibilizer

Kraton Corporation supported the research endeavor and supplied the necessary compatibilizer substance for the project's successful completion. Kraton offered two distinct varieties of compatibilizers.

1. The first copolymer is CirKular+ C1010 (50% recycled). It is based on polystyrene and polyethylene/butylene rubber (styrene-ethylene-butadiene-styrene (SEBS)).
2. The second copolymer is FG1901. It is based on a 30% content of polystyrene and polyethylene/butylene (styrene-ethylene-butadiene-styrene (SEBS)).

An evaluation was performed on the morphological and thermal properties of two samples of biopolymer composites that were extruded through a double-screw extruder. The investigation aims to explore the efficacy of two types of compatibilizers concerning the fabrication of the suggested wall panel to identify the most optimal alternative. Both samples comprised of 5 wt.% 6mm-fiber, 90 wt.% PET, and 5 wt.% of SEBS. It is worth mentioning that the SEBS utilized in sample one is FG1901, whereas in sample two it is C1010.

I examined the two samples' morphological features by capturing their surface using a Scanning Electron Microscope (SEM) machine, as illustrated in**, Figure 5-2** images 1 and 2. The SEM analysis revealed clumping in both samples, attributed to a high affinity for hydrogen bonding or inadequate mixing. It was apparent that sample 2 had a significantly more favorable surface morphology than sample 1. Additionally, sample 2 had a relatively smooth surface texture, suggesting greater compatibility among its components. On the contrary, sample 2 exhibited irregular porosity throughout its surface. Thus, utilizing the recycled compatibilizer C1010 improved the properties of the composite, as indicated by the test results.

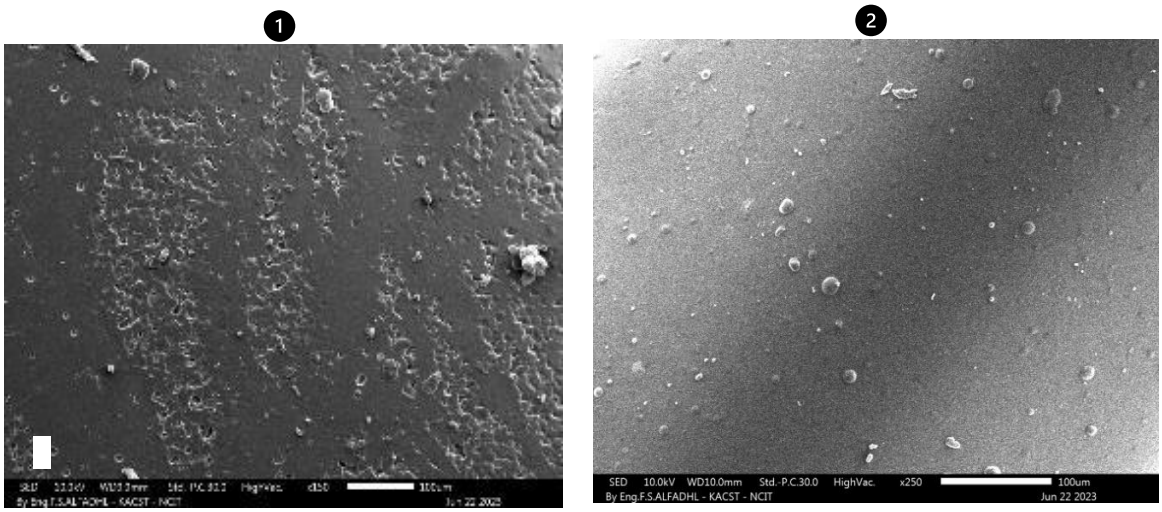


FIGURE 5-2 (SEM) MORPHOLOGICAL ANALYSIS

Figure 5-2 illustrate the SEM result of two samples of biopolymer composite at 100 nμ. **Image 1**, contain pure SEBS, FG1901. **Image 2**, contain a recycled SEBS substance, C1010.

The thermal stability of the biopolymer composites was analyzed using thermogravimetric analysis (TGA) utilizing equipment from Perkin Elmer, model TGA1. The samples were heated from 25 °C to 800 °C at a heating rate of 10 °C/min under nitrogen. **Figure 5-3** illustrates that Specimen #2 has better thermal stability than Specimen #1. The test results suggest that compatibilizer (C1010) enhances the biopolymer composite property more effectively than compatibilizer (FG1901). Improving the mechanical properties of recycled plastics, including their strength, durability, and flexibility, making them adaptable to various applications (Hopewell, 2009). This quality enhancement enables substituting virgin materials with recycled plastics in a broader range of applications, reducing landfill waste and resource consumption (Hopewell, 2009).

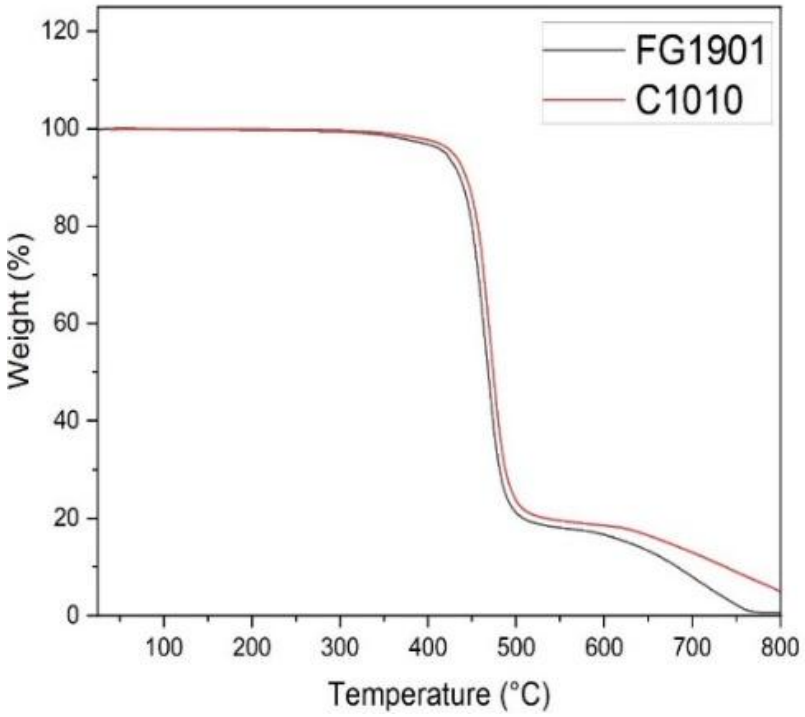
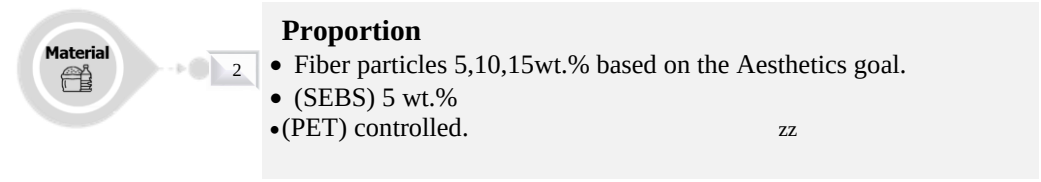
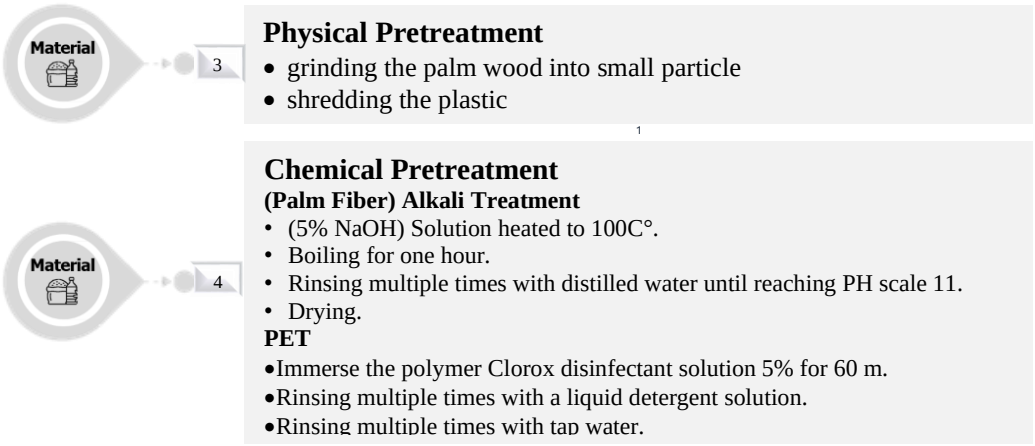


FIGURE 5-3 TGA OF COMPOSITES WITH TWO DIFFERENT COMPATIBILIZER



5.2.2 Proportion

Based on the prior logical argumentation, 5,10,15 wt.% of fibers might generate a panel with appropriate physical, thermal, and mechanical properties. Thus, based on the desired outcome, the fiber proportion will range between 5-15 wt.%, SEB 5 wt.%, and PET proportion is controlled.



The following paragraphs illustrate the physical and chemical pretreatment of the palm fiber and then the PET polymer.

5.2.3 Palm Fiber Physical and Chemical Pretreatment

Two physical treatments were performed on the palm fiber. The first method utilized a Wiley mill machin as shown in,**Figure 5-4** to generate particle sizes of 0.5, 1, 2, and 6 mm. The second method used a flaker to produce thin slices of palm. This equipment operates more efficiently than the mill.

The use of the Wiley mill was as follows:

1. Palmwood was cut into slices, as shown in **image 1**.
2. A screen of the right size was inserted into the machine, as **image 2** shows.
3. The wood was added to the feed section, as shown in **image 3**.
4. The machines operated , and the ground particles were collected in a sealed plastic bag, see **image 4**.
5. The process was repeated to generate different particle-size as shown in **image 5**.

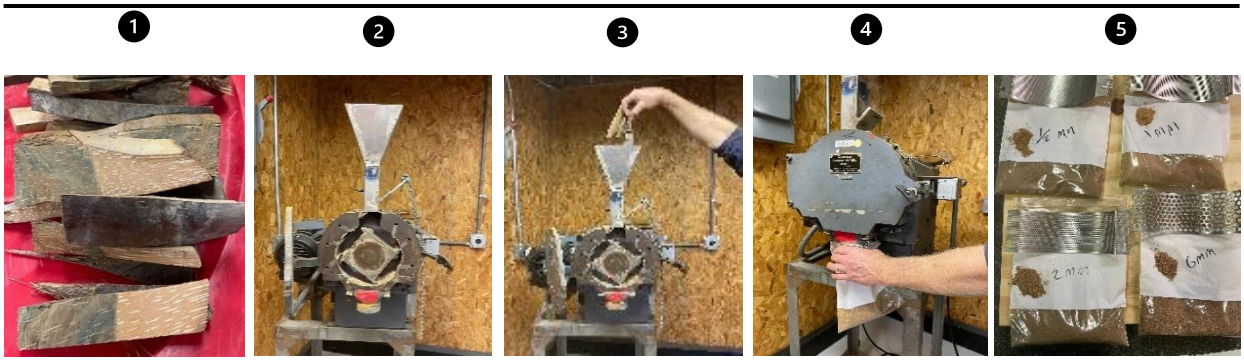


FIGURE 5-4 WILLY MILL MACHINE PROCEDURE

The procedure for using the flacker machine is illustrated in **Figure 5-5** It was done by loading a bulk of palm wood as shown in **image 1** into the machine's feed section, as illustrated in **image 2**. Then, the machine was operated and produced wood slices, as seen in **image 3.**

FIGURE 5-5 FLAKER MACHINE PROCEDURE

5.2.3.1 CHEMICAL PRETREATMENT (ALKALI)

Processing DPF with Alkali Treatment, according to Dehghani et al. (2013), cleans and smoothes the fiber surface and improves its mechanical properties. The treatment includes three steps:

1. Mercerization with 5% sodium hydroxide NaOH, as shown in **Figure 5-7**.
2. Rinsing with distilled water, as illustrated in **Figure 5-9**.
3. Drying the palm particles in a vacuumed oven at 60C° for 24 hours, as **Figure 5-10** shows

The subsequent sections outline the sequence of treatment that proceeded throughout the immersive case study. Various studies employed alkali treatment to cleanse the fibers; however, there is no standardized approach since it varies across investigations. Consequently, four different types of procedures, as shown in **Figure 5-6** were tested then the thermal stability was evaluated using a (TGA) test to select the one that performed most effectively.

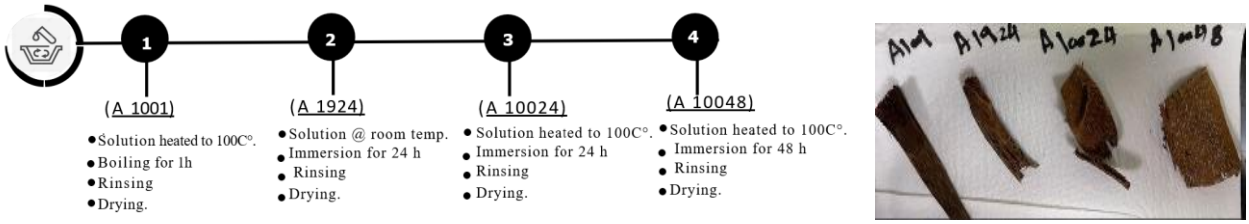


FIGURE 5-6 VARIOUS ALKALI PROCEDURES' SAMPLES

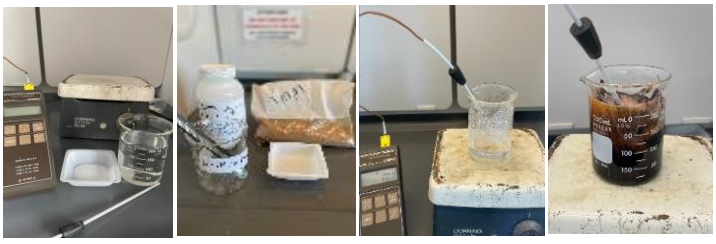


FIGURE 5-7 MERCERIZATION PROCEDURE

The thermogravimetric study **Figure 5-8** shows that sample A1001's treatment procedure exhibits the maximum thermal stability property, which is addressed in the knowledge framework.

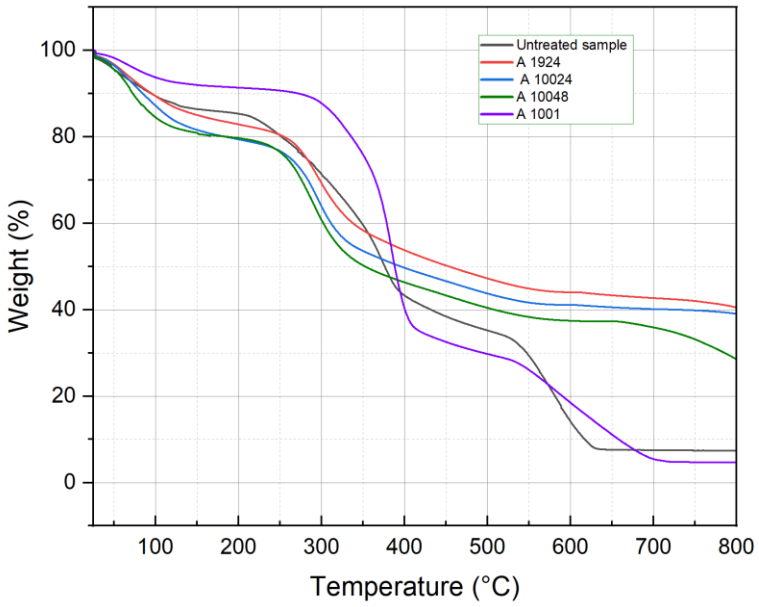


FIGURE 5-8 THERMOGRAVIMETRIC ANALYSIS OF VARIOUS ALKALI TREATMENTS

Samples of different particle sizes 0.5-6mm and sliced palm wood were treated following the mercerization method of A1001. Then, different filtration procedures to rinse and filter palm particles were tested, as shown in **Figure 5-9 .** The result indicates that the Buchner funnel, characterized by larger perforations, exhibited the highest level of effectiveness compared to the other two filtration systems that were assessed, which improved the efficiency of the filtration process.

FIGURE 5-9 RINSING PROCEDURE

After filtering, the samples were dried for 24 hours in a vacuum oven at 60°C. **Figure 5-10** shows dried samples of different forms. **Image 1** shows clumps in the particles of sizes between 0.5- and 6-mm, requiring further physical treatment. Additional physical treatment is expensive and time-consuming, elevating the issues caused by the prolonged filtering process. As for the sliced wood samples illustrated in, **image 2**, showed a transformation in their shape, with just the fiber component remaining unaffected. This change does not align with the intended aesthetic result, requiring more physical involvement. To address these problems, the dimensions of the treated wood were reassessed, as shown in **Figure 5-11** by cutting specimens into about 1-inch pieces, see **image 1**. The procedure stages proceeded well, however, a sample portion revealed inadequate treatment in the center, as shown in **image 2**. Following this, a reduced sample size of around 1/4-inch, as **image 3** illustrated, was used, resulting in successfully completing the treatment process.

FIGURE 5-11 DRYING PROCEDURE

FIGURE 5-11 RESIZING THE PALM SAMPLES FOR AN EFFICIENT TREATMENT

5.2.3.2 BLEACHING

An additional challenge addressed during the case study is that palm fiber discolors to a dark brown under alkaline treatment, as shown in **Figure 5-12**, which is undesirable if a lighter coloration is preferred.

FIGURE 5-12 PALM DISCOLORATION UNDER ALKALINE TREATMENT

Thus, previous literature was studied to identify an alkali-compatible bleaching method. The samples were treated with hydrogen hydroxide H2O2, resulting in the formation of a beige shade. Nevertheless, the literature did not specify any concentration of H2O2, so different concentrations of 5% and 10% were examined, as shown in **Figure 5-13**. A thermogravimetric analysis was conducted to evaluate the thermal stability of bleached samples with varying concentrations compared to alkali-treated and untreated samples. Significantly, the lower concentrate of 5% shows improved pigmentation and better thermal stability than all samples, as demonstrated in the following graph, **Figure 5-14**, where it can withstand temperatures exceeding 316 degrees Celsius.

FIGURE 5-13 BLEACHED PALM SAMPLES

Finally, the documentation of the appropriate procedure resulting from the pretreatment

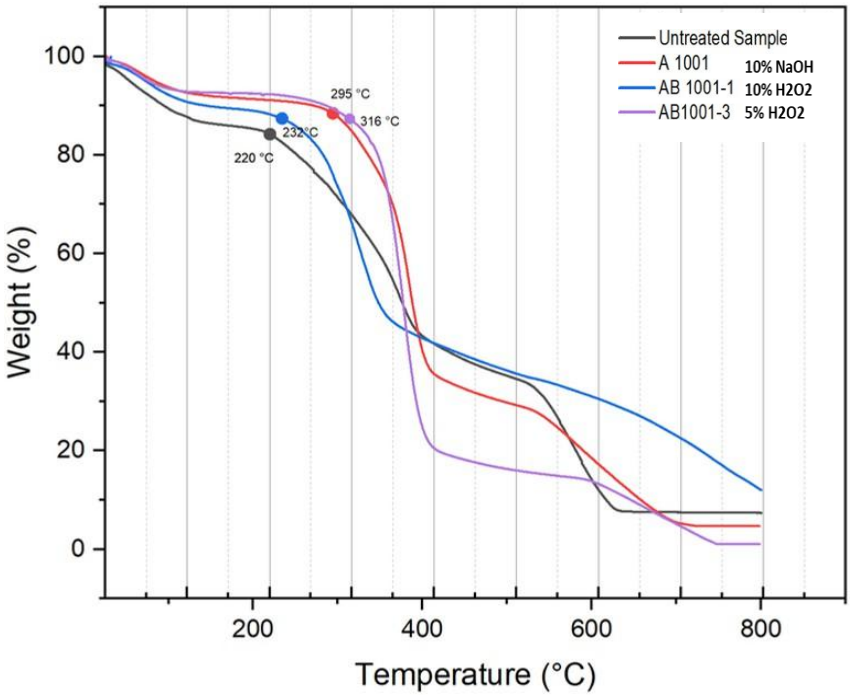


FIGURE 5-14 THERMOGRAVIMETRIC ANALYSIS OF VARIOUS BLEACHING CONCENTRATES

experiment contributes significantly to the knowledge concerning the chemical treatment process for treating palm particles.

5.2.3.3 PHYSICAL PRETREATMENT

Figure 5-15 illustrates the physical pretreatment of the palm wood. The procedure started by chemically processing a large quantity of palm, as shown in **image 1**. Then, the samples were mechanically chopped using a chopping machine from FRITSCH GMBH, see **image 2**, using different screen sizes, see **image 3**. The machine has a vacuum absorber and collector combined with the sieve system, see **image 4**. The machine produces chopped sizes of 6, 2, 0.75, and 0.5. Thus, a shaker by FRITSCH, see **image 5**, was used to produce smaller sizes of 0.25 and 0.18. The particles of size 0.5 were

put on a screen with a size of 0.25, shown in **image 7** on top of another screen with a size of 0.18mm, see **image 6**, which was placed on a collection plate.

5.2.4 PET Physical and Chemical Pretreatment

FIGURE 5-15 PHYSICAL PRETREATMENT OF THE PALM USING CHOPPING MACHINE

The PET polymer was subjected to physical and chemical treatment as follows. **Figure 5-16** illustrates that the water bottle plastics were shredded twice and then placed in plastic bags for storage. The gathered polymer was immersed in a 5 percent dilute Clorox disinfection solution for 60 minutes. Then, the plastic particles were washed twice with a liquid detergent solution and rinsed twice with water. The particles were then let to air dry thoroughly. Following that, the PET particles were dried at 60Co for 24h in a vacuum oven before processing the composite, as shown in **Figure 5-17.**

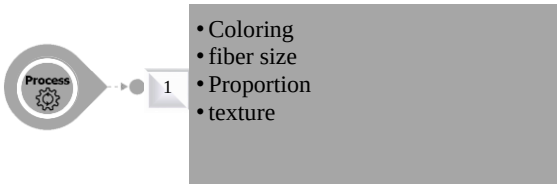
FIGURE 5-16 PET PHYSICAL PRETREATMENT

FIGURE 5-17 PET CHEMICAL PRETREATMENT

The following table summarizes the issues faced during the evaluation of the material section and their corresponding solutions for updating the initial framework as a second version.

TABLE 5-1 CHALLENGES FACED DURING MATERIAL SECTION ASSESSMENT AND POSSIBLE SOLUTIONS

Framework section	Challenges		Solutions	Update to framework	Notes & Recommendation
Material	Bonding issue	(FG1901) (SEBS) adopted by (Dhegihan et al.,2013) illustrates inadequate adhesion.	Employing the recycled (C1010) (SEBS) for enhanced bonding and thermal stability	Using the recycled (C1010) (SEBS)	
	palm physical and chemical pretreatment	Initiating the physical pretreatment of small particles before the chemical treatment results in an increase in both the duration and resource expenses of the process.	preceding the chemical treatment by slicing the palm into 1/4-inch-thick sections, followed by a physical pretreatment of the small particles.	initiate the pretreatment chemically of palm-sized 1/4" thick, followed by particles physical treatment	
		Alkali treatment caused black discoloration	Bleaching with hydrogen hydroxide	Adding the bleaching method to the chemical treatment of the palm	positively enhance the palm's thermal stability
	PET physical and chemical pretreatment	Reducing PET size using only a shredding machine is costly and ineffective.	Designing a sieve panel solves the issue temporarily.	Employing a sieve panel and reducing PET size	Using a ball milling machine



5.3 Processes

5.3.1 Fabrication techniques

The subsequent stage of this immersive case study included assessing the process part of the Framework to accomplish the intended result. The Process aspect encompasses material configuration, fabrication technology, and finishing technology, which are detailed in the next section. The material configuration includes coloring, fiber size, proportion, and texture, which will be chosen based on the aesthetic goal.

5.3.1.1 EXTRUSION METHOD

As the project scales up, the extruder becomes the most efficient method for fabricating the wall panels; consequently, this method is chosen as the primary fabrication technique, with compaction being employed to heat-press the extruded pellets to produce the wall panel prototypes. However, several obstacles were encountered throughout the extrusion process, resulting in a modification of the fabrication strategy, as exemplified in the subsequent paragraph.

Figure 5-18 represents the extruding procedure that starts by choosing the material configuration according to the intended result and measuring the components, see **image 1,2**. Then, as seen in **image 3**, a micro twin-screw extruder from Xplore was used, presenting the first obstacle because of the extruder's nature and the laboratory setting. The micro extruder cannot manage temperature evenly throughout all barrel zones, setting it apart from other extruders. While creating the first sample, the temperature

difference between the cold lab setting and the extruder caused the material to freeze within the extruder's die head. This issue required forcible removal or raising the temperature, resulting in quick melting and sample deterioration, see **image 4**. A series of experiments were performed to solve the issue, which led to identifying certain techniques that helped reduce the problem. Those techniques start with preheating the extruder for 30 minutes, raising the lab temperature, and maintaining a regulated temperature profile throughout the extrusion process to help address the freezing issue. Then, it was found that the barrel temperature should start at 240°C and a speed of 100 rpm for two minutes after introducing the component. Then, the temperature should be increased to 250°C, while the speed should be decreased to 55 rpm for two more minutes. Finally, the speed must be raised to 100 rpm, and the die head shall be opened to allow the patch to extrude. Frequent machine cleaning is essential to maintaining optimal operation.

The second obstacle was gray discoloration, as shown in **image 5**, which was encountered during the extrusion procedure. The previous literature illustrates that the grey discoloration may be attributed to metallic antimony used as a catalyst during polymer production, which becomes evident under high temperatures and shear stress due to the use of a double screw extruder (Berg, 2018).

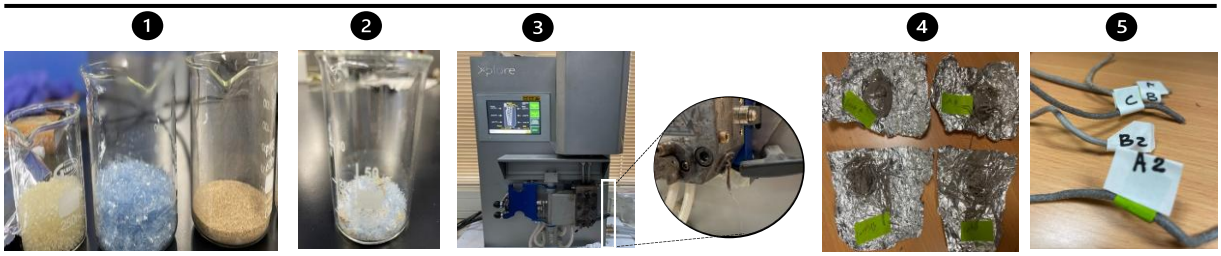


FIGURE 5-18 EXTRUDING PROCEDURE

Different procedures were tested in the lab to solve the issue. First, the iced bath technique was used for the extruded patches to enhance their translucency through a controlled quenching process, as shown in **Figure 5-19**. Quenching can impact the material's crystalline structure and, consequently, its optical properties by forming smaller crystalline structures within the PET matrix. Moreover, rapid cooling can influence the molecular alignment of the polymer chains, contributing to improved transparency. Unfortunately, this technique did not solve the problem.

FIGURE 5-19 QUENCHING METHODS

The second technique, shown in **Figure 5-20,** involved applying bleach to the blend with 0.1-0.4 wt.% of zinc peroxide (ZnO2) under nitrogen to enhance the composite's translucency. The process caused the patches to deteriorate, see **image 1**. Nevertheless, when applying the technique without the nitrogen, as shown in **image 2**, bleached the extruded pellets, allowing the coloring to attain the desired finish.

The third obstacle encountered during the extrusion process was the tearing of the large fiber size created by the double screw shear force associated with the extruder. The issue resulted in an undesirable appearance for the sample. Thus, the compaction method was employed instead of the extruder to create samples with fiber-looking appearances.

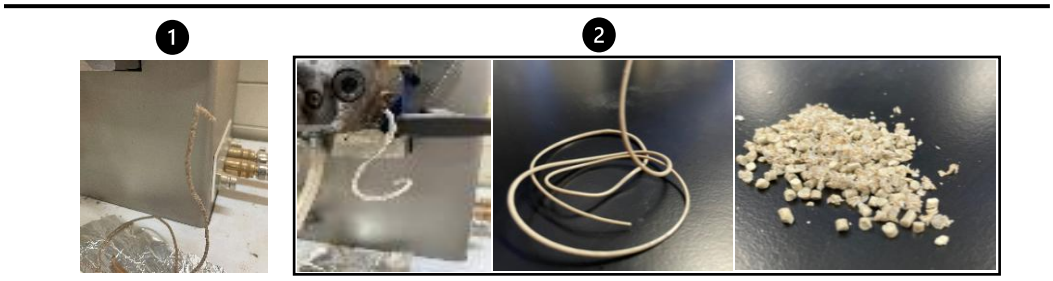


FIGURE 5-20 BLEACHING WITH ZNO2

In conclusion, the large PET particles presented numerous challenges throughout fabrication. **Figure 5-21**, illustrates some of the issues related to the size restriction. The most notable impeding of the sample's blend is due to their disproportionately large size compared to the fiber, compatibilizer, and small syringe opening size, **see image 1**. Consequently, after three failed attempts at shredding the particles to a small size, PET particles were frozen in liquid nitrogen, see **image 2** to grind the polymer using a chopping machine, see **image 3**. This method also proved ineffective. Subsequently, the Sieve panel shown in **image 4** was designed, which enabled the small particles' sieve.

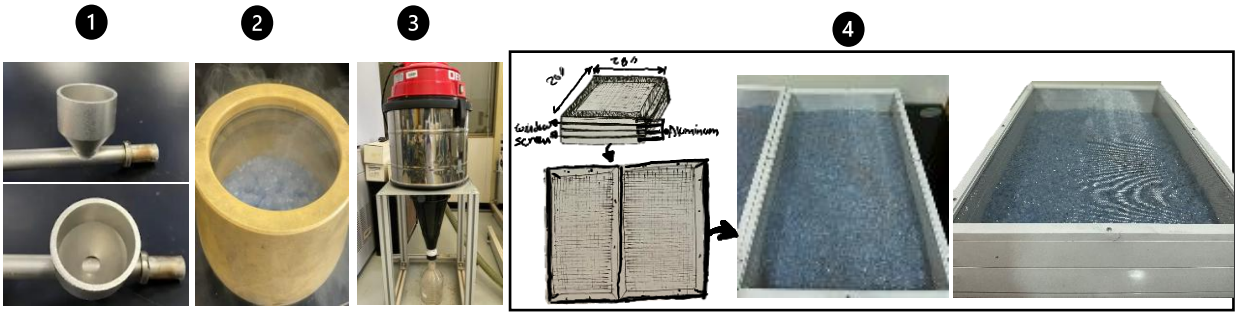


FIGURE 5-21 PET SIZE LIMITATION

As previously mentioned, the fabrication process for the initial framework involved the extrusion of composite pellets, which were subsequently compacted using a compaction method to achieve the desired aesthetic outcome for the wall panel. However, the previously mentioned obstacles necessitated compaction as another primary technique. As an illustration, the color shift that was evident during the extrusion process might be minimized by applying compaction due to the lack of shear stresses. Furthermore, this method successfully produces colors reflective of ultraviolet light, translucent, or glossy.

5.3.1.2 COMPACTION METHOD

Figure 5-22, illustrates the laboratory exploration of the compaction method.

In this procedure, heat press equipment supplied by Collin was utilized, as shown in **image 1**. A 260°C-resistant polymer tape was applied for coating in this procedure. The initial framework suggested the fabrication of a wall prototype utilizing two mold dimensions of 2x4 inches and 2x2 inches, see **image 2**. Several attempts were made to fabricate the composite using the mold; however, they were all

unsuccessful due to the mold's high-temperature requirement of approximately 260 degrees Celsius for five minutes with rapid cooling. However, the samples were burned due to the lack of a cooler mounted to the machine, see **image 3**. Alternatively, the component was pressed between two sheets, see **image 4**. However, the attempt was also unsuccessful due to the absence of mold boundaries. Then, a sheet, shown in **image 5**, was designed comprising 1x1" squares with a thickness of 1 mm, which proved extremely useful. By engraving a sign onto the sheet to create the mold, I numbered the squares using pieces of paper, **image 6**. The aesthetic objective of each number was determined by the design theory adapted to this research, which considered both the visual and tactile qualities.

Nonetheless, several obstacles were faced while utilizing this mold. Initially, the samples continued to break, as seen in **image 7**; therefore, the issue was resolved by increasing the compatibilizer to 10 wt.%, as seen in **image 8**. Although the compatibilizer is required to prevent the breaks, improper component elevation within the mold during fabrication also contributes to the breaks. On the other hand, the pressing method employed involved a single mold press at 260Co. This resulted in an uneven surface with portions that were not melted, see **image 9**. As a result, various approaches were tested before determining the optimum solution to alter the compression during fabrication. Thus, the best method was to press the mold with a pressure of 30-60-90-100-60 pound-force per square inch while maintaining the temperature at 250 degrees Celsius. Furthermore, in the absence of a cooler integrated into the machine, the sheet was manually transported to the table, which caused samples to break, as seen in **image 10**. However, the issue was solved by placing a heavy block over the sheet on the table after fabrication and

allowing it to cool for an additional two minutes before opening it, see **image 11**. This effectively mitigates the cooling issue.

FIGURE 5-22 COMPACTION PROCEDURE

In conclusion, a recurring challenge that emerged during the extrusion and compaction phases of the composite preparation process was the requirement to thoroughly mix the components, as shown in **Figure 5-23**. The limitation from the micro extruder prevented simultaneous merging and addition due to the syringe's small opening. So, the components were manually mixed, as illustrated in **Image 1**. Nevertheless, this methodology resulted in undesirable outcomes. A similar challenge was faced throughout the compaction procedure, which required pre-mixing before fabrication, see **Image 2**.

Several attempts were made to address the mixing issue. One method was by generating the composite on the extruder at 240°C for 1 minute; subsequently, the composite was cut into small pellets, see **Image 3**, and then the extrusion process was repeated. However, this method degrades the samples, see **Image 4**. Thus, integrating specialized heat-combining equipment or a ball-milling machine could overcome this challenge in the future, as shown in **image5**. The heat machine involves extended blending at decreased temperatures, producing dough for compaction. This approach is used in large-scale projects in manufacturing settings. As for the ball milling machine illustrated in **image 6**, it utilizes aluminum balls that allow mixing and grinding of the components. This could solve both the sizing and mixing issues. The proposed solutions were promising for enhancing the uniformity and quality of the composite material for future industrial endeavors.

The **Table 5-2** below outlines the challenges encountered when assessing the process section and alternative solutions for updating the initial framework.

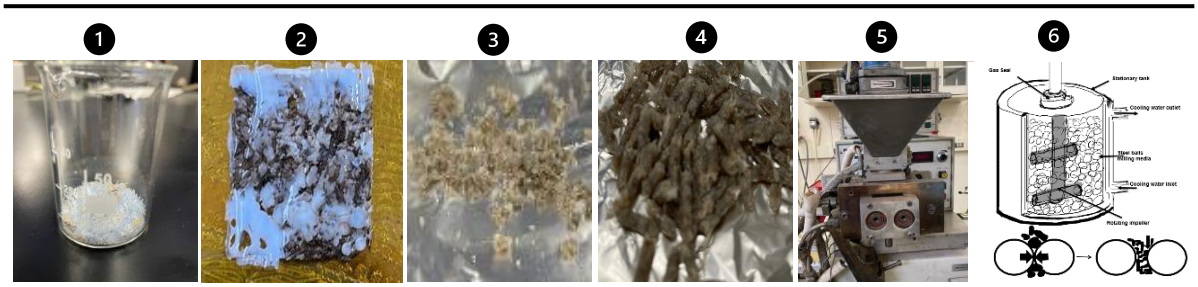
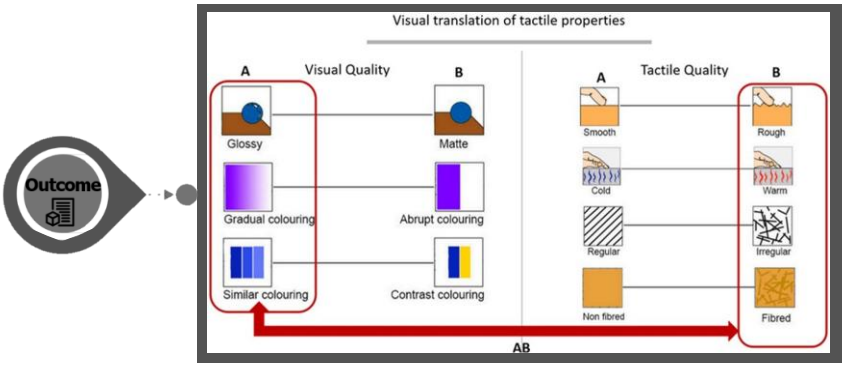


FIGURE 5-23 MIXING ISSUE

TABLE 5-2 OUTLINE OF THE CHALLENGES ENCOUNTERED DURING PROCESS SECTION EVALUATION

Framework section		Challenges	Solutions	Update to framework	Notes & Recommendation
Process	Extruder type	Increased shear stress due to the use of a double-screw type causes a tear to large-size fiber, which causes an aesthetics issue.	The compaction method will be applied if the desired outcome is fibered-looking material.	Fabrication methods are extruding with compaction or only compaction	Using single-screw type might perhaps prevent this issue
		Production difficulty was caused by temperature variations owing to micro-vertical extrusion.	1. If this type will be used, the following steps are recommended 2. preheat the machine to 240C for 30 minutes 3. Start the operation with 240C at 100 rpm for two minutes. 4. Increase the temperature to 25C by reducing the speed to 55rpm for two minutes 5. Increase the speed to 100 rpm and open the die head for the composite to come out 6. cleaning the machine frequently	adding notes of the procedure to avoid the temperature issue	Micro-vertical extrusion is not recommended because of the limitation of controlling the temperature on various barrel zones compared to the horizontal type
	Sample disintegration	Samples generated by compaction, without being processed through the extruder, exhibit fragmentation problems.	Increasing the (SEBS) to 10. WT%	the (SEBS) is range between 5-10. WT% based on the method selected to fabricate the wall panel	
	Inadequate topography	Even if the component is evenly distributed in the mold, the result shows many issues, such as breaks or uneven surfaces	Modify the heat press technique by increasing the temperature to 250 degrees Celsius for four minutes, adjusting the pressure accordingly throughout this period. 30, 60, 90, 100, and 60 pounds per square inch, respectively	adding notes of the steps required through this procedure	
	Cooler issue	The absence of a cooler integrated into the heat press machine limits the production of a large-size panel.	Small mold sheets designed to produce the prototype samples.	Integrating a cooler machine into the heat press is required for scaling up the panel project.	



5.4 Outcome

Ultimately, addressing the issues related to material selection and fabrication procedures indicated in the initial framework allows for the intersection of these components, permitting the manufacture of prototype samples displaying various visual qualities according to the outcome I intended to test through the knowledge framework, as illustrated in **Figure 5-24**.

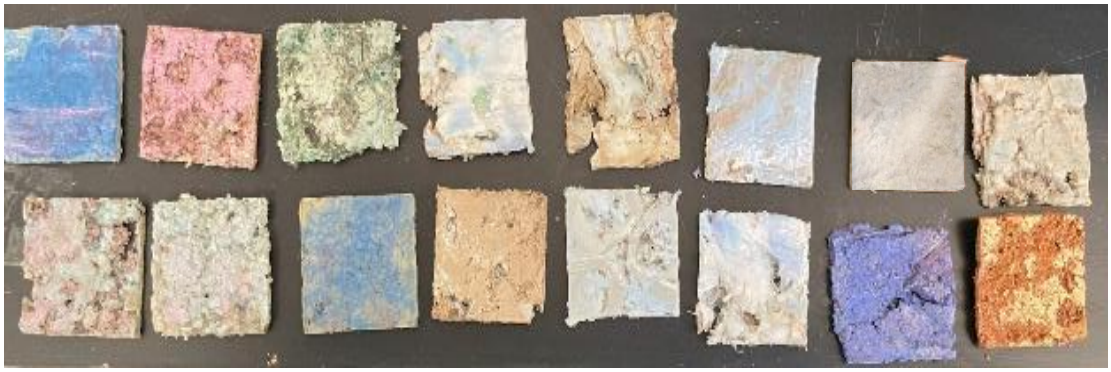


FIGURE 5-24 PROTOTYPE OF THE MANUFACTURED AESTHETICALLY PLEASING WALL PANEL

In conclusion, the takeaways gained from the Immersive Case Study that were incorporated into the knowledge framework demonstrated in **Figure 5-25** The developed framework are detailed in the table following **Table 5-3**.

TABLE 5-3 OUTLINE OF THE MODIFICATION OF THE KNOWLEDGE FRAMEWORK BASED ON THE IMMERSIVE CASE STUDY RESULTS

Framework section	framework category		Notes & Recommendation
Material	Primary components	Palm fiber(stem) and Recycled PET polymer	
		Employing (FG1901) (SEBS), adopted by (Dhegihan et al.,2013) for enhanced bonding and thermal stability	
	palm physical and chemical pretreatment	Physically treating the palm by grinding it to small particles before the chemical treatment.	
		Alkali treatment by adding 5% NaOH enhanced thermal stability	Positively enhance the palm's thermal stability.
	PET physical and chemical pretreatment	Reducing PET size using a shredding machine into 1-4 mm particles.	
		Immersed in diluted Clorox (5%) for 60 m. Washed with a liquid detergent with two rinses in water.	
	proportion	5,10,15 WT.% fibers might generate a panel with appropriate physical, thermal, and mechanical properties	
		(SEBS) will be 5WT.%	
	Particle size	Fiber Sizes range between 6,2,0.75,0.5,0.25,0.18 based on the Aesthetics goal. (PET) size - 0.75 particles	
	Drying	Compatibilizer, plastic, and wood particles were dried at 60 C for 24 h.	
	Panel dimensions	. Thickness 19mm to 30mm . Length 2-6 m . Widths 100-300mm	

TABLE 5-4 CONTINUED

Framework section	framework category		Notes & Recommendation
Process	Material Configuration	Select from material the colors, texture, fiber size, proportions, and panel dimensions based on the desired outcome	
	Fabrication method	Extruder followed by compaction will be employed for faster production and high mechanical strength.	
Outcome	Desired Aesthetic	adopting the "Unity-in-variety." by creating a contrast between tactile and visual property	

The graph below illustrates the revision of the initial framework based on the findings of the immersive case study.

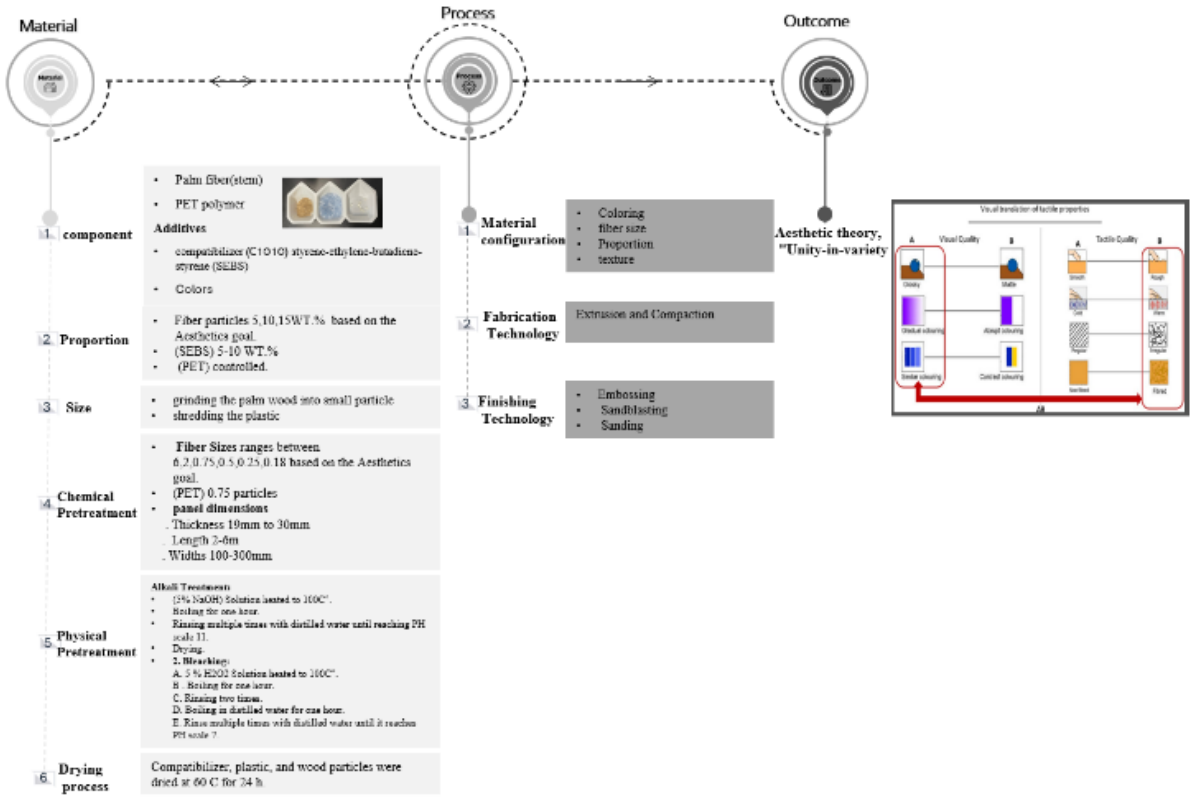


FIGURE 5-25 THE DEVELOPED FRAMEWORK

Framework Implementation Chapter 6

6.1 Introduction

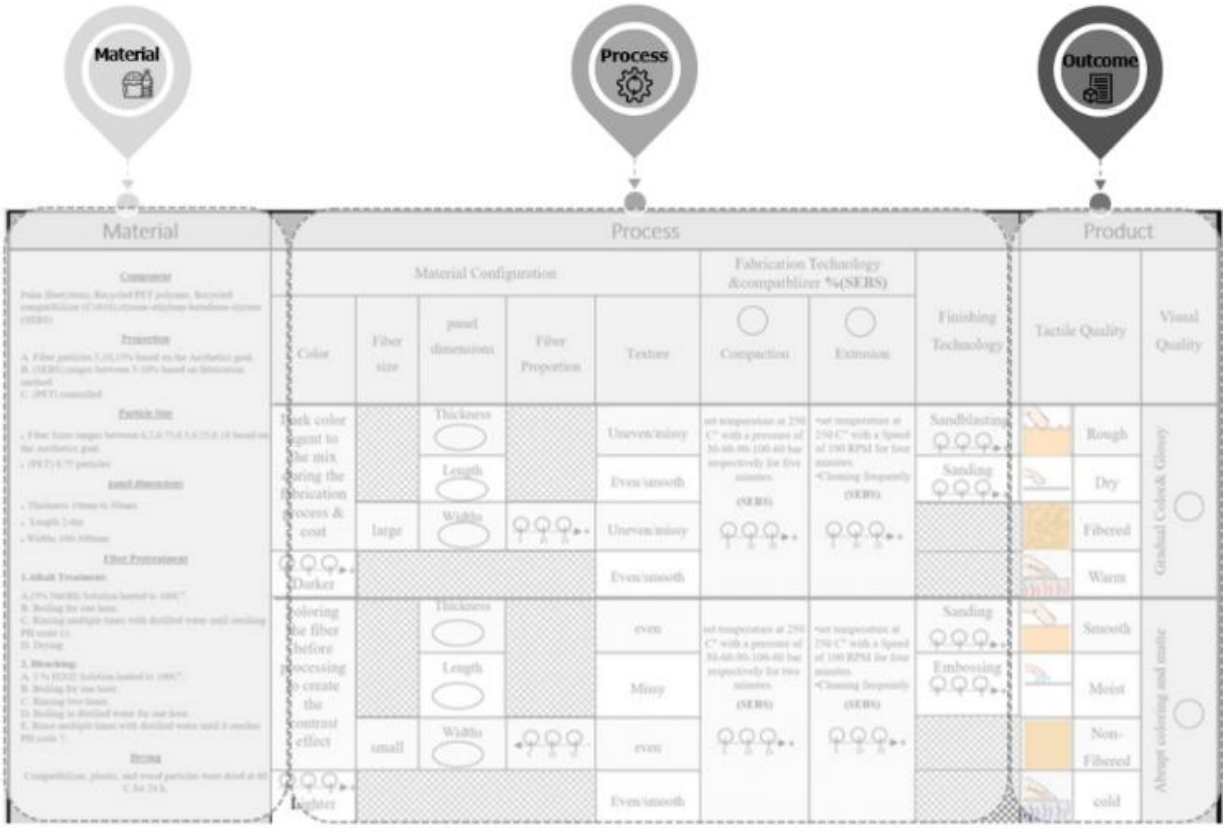
The knowledge framework was applied to the development of a design matrix and a design selection tool to demonstrate its implementation.

6.2 Design Matrix

The formulation of a design matrix was done to facilitate the practical application of the developed knowledge framework for producing aesthetically pleasing wall panels, as shown in **Figure 6-1**. This matrix serves as a tool for manufacturers to navigate the complex interaction between material selection, manufacturing processes and desired aesthetic outcomes. Through the matrix, users can select from a variety of aesthetic preferences, which in turn guides the determination of material compositions and process modifications that are necessary to achieve the desired appearance. It outlines the potential combinations of material compositions, fiber size, proportionality considerations, pretreatment approaches, texture, color, and innovative manufacturing techniques that identify composite structures according to the desired output.

Consequently, manufacturers can manage the complicated intersection between aesthetic goals and production methods based on material science with the help of the design matrix, which acts as a strategic tool for manufacturers. Its application makes it easier to make well-informed decisions and encourages the creation of individualized solutions designed to satisfy the varied aesthetic preferences of the end user.

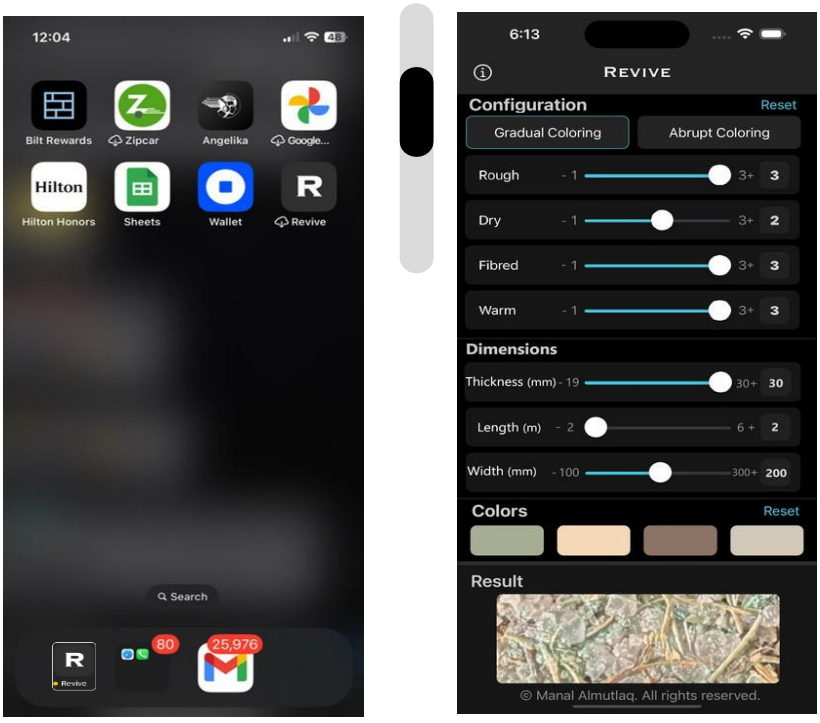
FIGURE 6-1 DESIGN MATRIX



6.3 Design selecting tool

From the framework and the design matrix, a design decision tool, as shown in **Figure 5.34**, was developed. The tool allows users to evaluate the aesthetics of the proposed wall panel design. It is envisioned that the design tool would enable the manufacturer to utilize the matrix to determine the combination of materials and processes that yield the desired appearance of the wall panel. The tool was created based on the aesthetic theory adopted within the framework by linking contrasting visual and tactile characteristics. For example, consider a user who selects contrasting color and translucency qualities. In addition, they may choose between different tactile characteristics, such as rough, dry, fibered, or warm. Since the proportion of the fiber ranges between 5-15 wt. % based on the desired outcome, each tactile figure will have a 1–3 scale options. The selector shows the fiber percentage or

FIGURE 6-2 DESIGN SELECTING TOOL



finish. Users may customize their wall panels by choosing pigments in the design selection tool, increasing individuality, flexibility, creativity, and market appeal. Finally, the user can visualize the proposed panel before production.

6.4 Utilization examples of design matrix and tools

In the following examples, three steps were implemented:

1. The user will use the design tool to determine the Aesthetic goal.
2. Based on the tool selection, the matrix will be used to determine the (Material aspects)
3. Proportion of components, color, and molding process.
4. The manufacturer will use the design matrix as a guideline to produce the wall panel (outcome).

6.4.1 Example 1

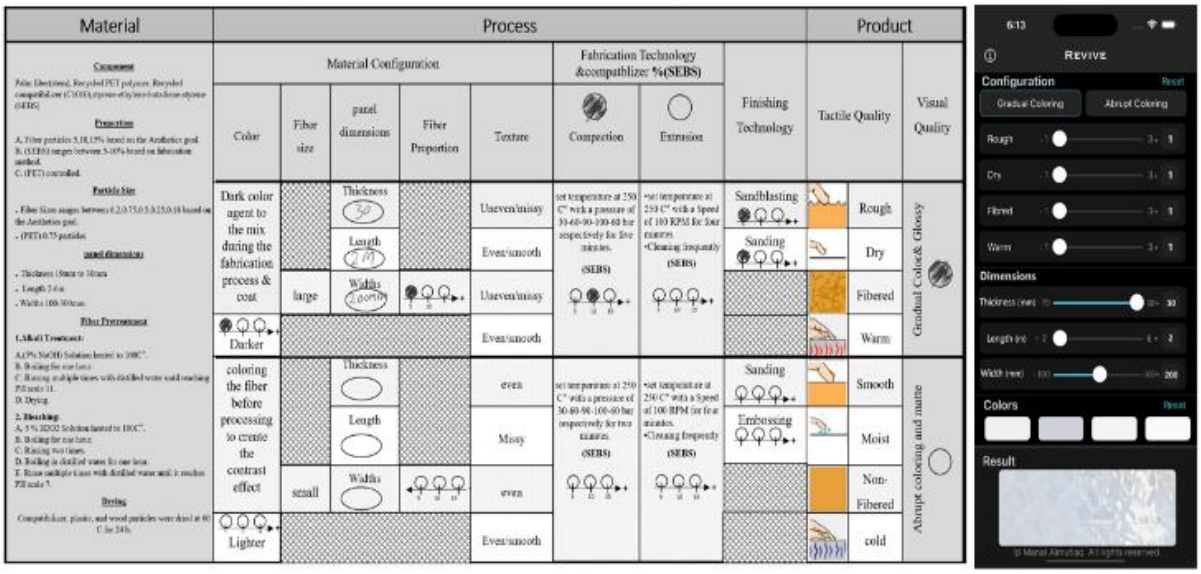
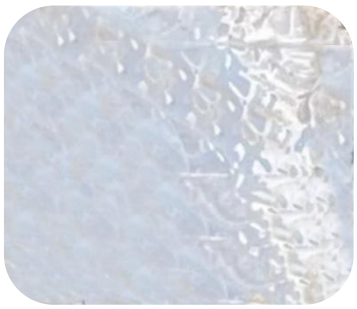


FIGURE 6-3 EXAMPLE 1 DESIGN TOOL & MATRIX USAGE

1. The design tool was used to define the aesthetic goal as follow:
    - **Gradual coloring** (roughness (1), Dryness (1), Fibred (1), warmness (1))
    - The panel size (thickness 30mm, length 2m, width 200mm)
2. The matrix was used to ascertain the manufacturing process, considering the tool selection as follow.
    - **Color-** The treated fiber was colored with a light brown pigment.



    - **Fiber size-** A fiber size of 0.75 mm was selected to provide the desired appearance of fibers.
    - **The fiber proportion** of 5% was selected based on the criteria of the design tool (1).
    - **Compatibilizer-** 10. wt.%
    - **Fabrication process -** The compaction processing technique was used to produce a material.

    resembling less fibered looking.

    - **Finish texture -** The desired level of roughness is (1); to achieve this, I should use the sandblasting gun to generate the desired rough surface. However, due to my inability to use it, I used an embossing technique.
3. **Outcome**

6.4.2 Example 2

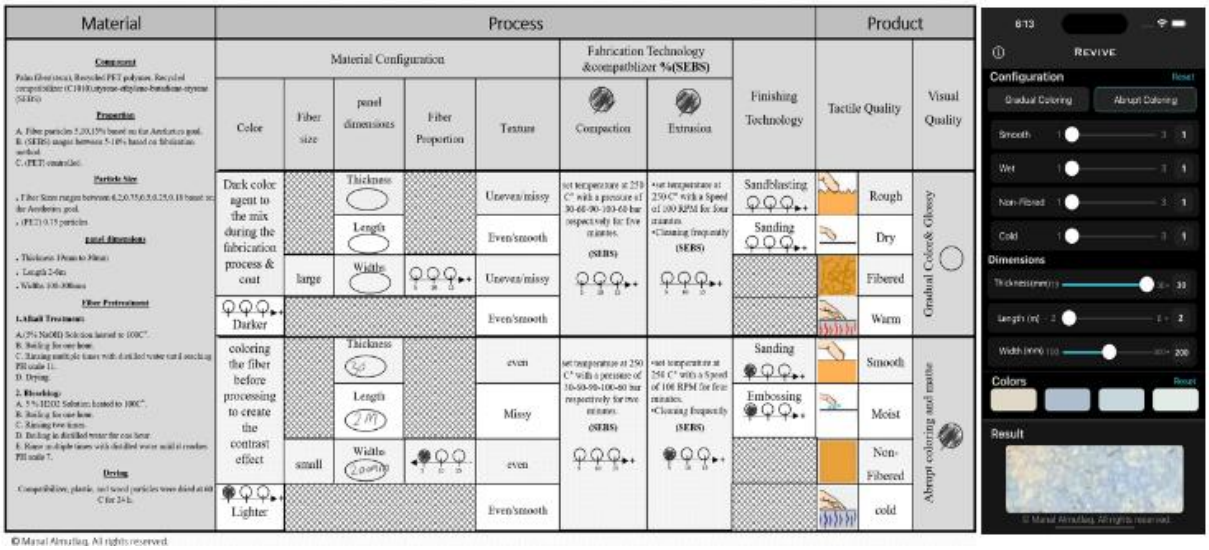


FIGURE 6-4 EXAMPLE 2 DESIGN TOOL & MATRIX USAGE

1. The design tool was used to define the aesthetic goal as follow:

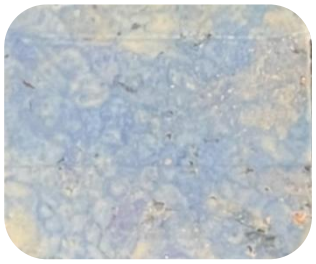
- **Abrupt coloring** (smoothness (1), wetness (1), non-Fibred (1), coldness (2))
- The panel size (thickness 30mm, length 2m, width 200mm)

2. The matrix was used to ascertain the manufacturing process, considering the tool selection as follow.

- **Color-** The PET particles were colored with a dark blue pigment.
- **Fiber size-** A fiber size of 0.18 mm was selected to create a non-fiber appearance.
- **The fiber proportion** of 5% was selected based on the criteria of the design tool (1).
- **Compatibilizer-** 5. wt.%
- **Fabrication process -** First, the extruder was used to create the white composite, then small pellets of the composite were mixed with particles of PET and 5% compatibilizer. Finally, the compaction processing technique was used to produce a less wet-looking appearance.

- **Finish texture -** The desired level of smoothness is (1); to achieve this, I use the sanding technique to generate the desired smooth surface.

3. Outcome



6.4.3 Example 3

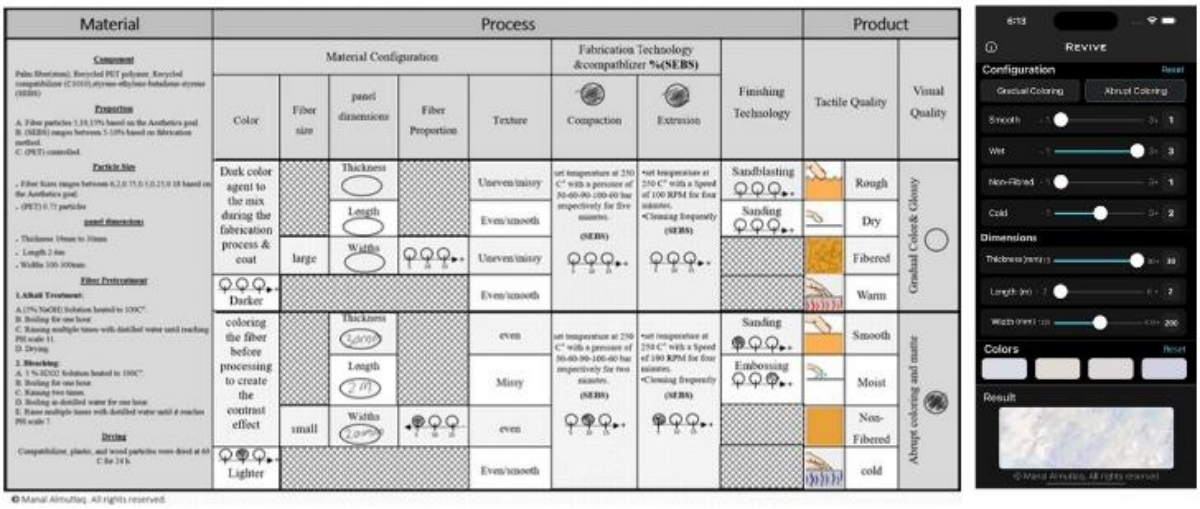


FIGURE 6-5 EXAMPLE 3 DESIGN TOOL & MATRIX USAGE

1. The design tool was used to define the aesthetic goal as follow:
   - **Abrupt coloring** (smoothness (1), wetness (3), non-Fibred (1), coldness (2))
   - The panel size (thickness 30mm, length 2m, width 200mm)
2. The matrix was used to ascertain the manufacturing process, considering the tool selection as follow.

- **Color-** The PET particles were colored with a light blue pigment.
- **Fiber size-** A fiber size of 0.18 mm was selected to create a non-fiber appearance.
- **The fiber proportion** of %5 was selected based on the criteria of the design tool.(1)
- **Compatibilizer-** 5. wt.%
- **Fabrication process –** Firs ,the extruder was used to create the white composite ,then small pellets of the composite were mixed with particles of PET and %5 compatibilizer .Finally ,the compaction processing technique was used to produce a wet-looking appearance.
- **Finish texture -** The desired level of smoothness is (1) to achieve this ,I use the sanding technique to generate the desired smooth surface.

3.Outcome

6.4.4 Example 4

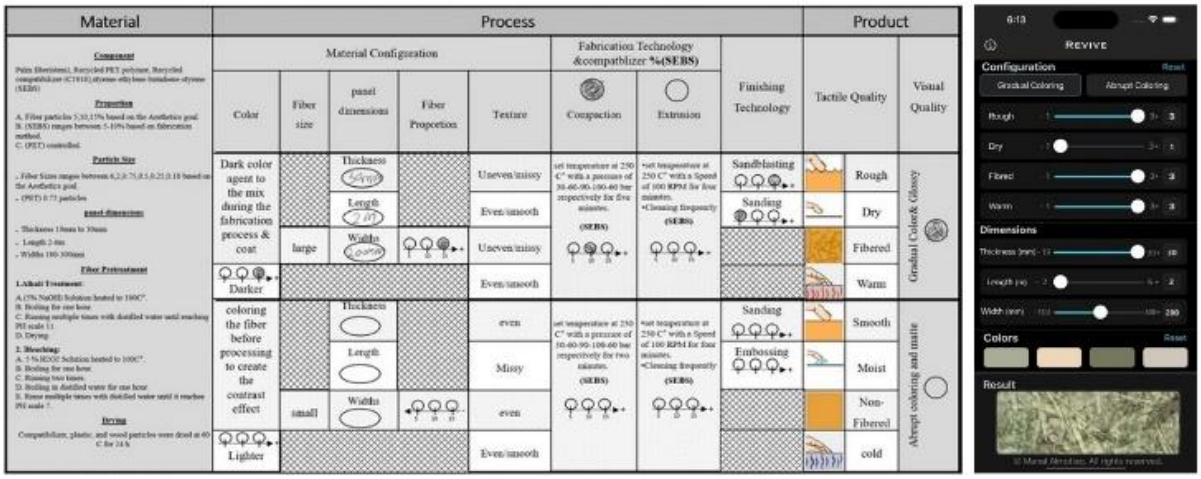


FIGURE 6-6 EXAMPLE 4 DESIGN TOOL & MATRIX USAGE

1. The design tool was used to define the aesthetic goal as follow:

- **Gradual coloring** (roughness (3), Dryness (1), Fibred (3), warmness (3))
- The panel size (thickness 30mm, length 2m, width 200mm)

2. The matrix was used to ascertain the manufacturing process, considering the tool selection as follow.

- **Color-** The treated fiber was colored with a dark green pigment.
- **Fiber size-** A fiber size of 6 mm was selected to provide the desired appearance of fibers.
- **The fiber proportion** of %15 was selected based on the criteria of the design tool.(3)
- **Compatibilizer-** 10. wt.%
- **Fabrication process - -**The compaction processing technique was used to produce a material resembling fibered looking, during which the extruder inadvertently created a tear in the fiber.
- **Finish texture -** The desired level of roughness is (3); to achieve this, I should use the sandblasting gun to generate the desired rough surface. However, due to my inability to use it, I

included particles of recycled PET after the compression procedure. Subsequently, I sent the material to a heat press machine for a further cycle forming distinct surface levels of roughness.

3. **Outcome**

A different example of adapting the framework and the design tool is the proposed "Glowing Wall Panel." The film "Castle in the Sky" by Hayao Miyazaki has been a source of inspiration for me. It depicts an island named Laputa, which floats in the sky by a glowing crystal stone.

1. I modified the coloring technique to achieve the illumination objective while maintaining the same configuration as the previous slides.
2. As previously stated, a dark green pigment was applied to the fiber 1-1.
3. I applied colors reflecting UV light to the PET particles: green in the first patch and blue in the second patch.
4. UV light was applied to the samples 1-3.
5. Both samples appear green in a natural light environment 1-2. However, one emits a luminous blue light 1-4, while the other emits a green glow 1-5 in the dark ,which turns into beautiful outcomes.

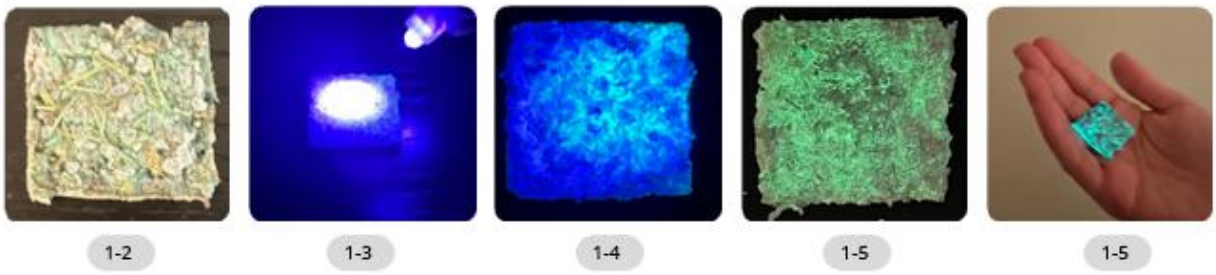


FIGURE 6-7 AN INSTANCE OF AESTHETIC MANIPULATION TO CREAT A LUMINOUS APPEARANCE

6.5 Graphical Representation

The addition of a visual representation of the material to the intended wall application as an architectural rendering increased the functionality of the tool. The graphical representation is an essential feature of the tool that enables clients to make well-informed decisions before selecting the wall panel and, subsequently, the manufacturer to determine the appropriate combination of material properties and processing to make the panel. The subsequent instances, **Figure 6-8, Figure 6-9, Figure 6-10** illustrate the implementation of the material prototype I created across various building types in Saudi Arabia during the morning, afternoon, and night throughout the summer seasons.

FIGURE 6-10 INTERIOR APPLICATION OF THE RECYCLED WALL PANEL

FIGURE 6-8 RESIDENTIAL APPLICATION OF THE RECYCLED WALL PANEL

FIGURE 6-9 COMMERCIAL APPLICATION OF THE RECYCLED WALL PANEL

6.6 Conclusion

An attractive wall panel is the intended outcome of this research, which seeks to build a body of knowledge in this area. The project's overarching objective is to bridge the aesthetics knowledge gap in waste-driven wall panel production, potentially attracting more users and making this material more competitive. Nonetheless, the knowledge framework was applied to a developed design matrix and selection tool to facilitate both the manufacturer and the end user's comprehension of the knowledge framework and the intersection between the material and processes that influence the outcome.

This chapter demonstrates how to apply the framework using the design selection tool and the design matrix to predict its future implementation. The tool was used to select an aesthetic configuration. Then, the architect allows the user to see how the material will look in the early design stage by visually representing the material application in the space before production. Subsequently, the manufacturer creates a prototype of the wall panel using the design matrix before manufacturing the actual panel.

Using the design matrix and tool to implement the knowledge framework may anticipate how the innovative framework will contribute to the success of waste-driven recycled materials in the future, giving them an edge over their competitors. In addition, the demand for materials will rise due to the unique customization feature. This feature distinguishes the sensory, perceptual, and experiential properties of waste-driven wall panels, which helps move the country's waste management away from a linear approach and toward a circular one.

Refined Framework: Delphi Approach Chapter 7

7.1 Introduction

In accordance with the methodology outlined in chapter three, the Delphi approach was employed to gain consensus from a group of knowledgeable stakeholders for the usefulness of the proposed framework. The Delphi involved the participation of an eight-member panel of stakeholders. The following presents the detailed process of this method.

7.2 Delphi Method Process

The Delphi method is a procedural structure consisting of a series of sequential "rounds" developed through specified feedback. The primary aim of this process is to achieve the most reliable consensus perspectives feasible from a group of experts (Linstone & Turoff, 1975). Analysis is conducted subsequent to each iteration of data collection in order to ascertain the point at which consensus is achieved (Koskey et al., 2023). According to Linstone and Turoff (1975), although three-round Delphis are typical, single-round and double-round Delphis have also been utilized to reach a consensus on a new developing procedure (Skulmoski et al., 2007). Hence, a single round might be sufficient in cases where the expert sample is small (Giannarou & Zervas, 2014). In this study, the Delphi technique was chosen as the research approach to obtain expert consensus regarding the proposed framework by analyzing their responses. In pursuit of this objective, I invited panelists by sending them an email letter that explained the research goal, the Delphi technique, and the value that their participation would bring to the research, **Appendix** 1. Then, I delivered a presentation to the focus group incorporating a detailed explanation of the constructed framework and a brief introduction to the study. The knowledge framework was presented for around 30 minutes via Zoom meeting, **see Appendix 3**. Then, a summary of the constructed

framework, including the aesthetic design tool and matrix and the Delphi questionnaire, was sent to the stakeholders by email, see **Appendix** 2. Participants then were asked to respond to the questions about the proposed framework. Finally, after considering their responses, a second round was planned to reach an agreement.

7.3 Delphi panel participants

In the Delphi study, expert panels may exhibit homogeneous characteristics or exhibit diversity, depending upon the specific context and objectives of the study. Thus, to establish agreement on the items that represent a construct for a recently developed instrument or knowledge, it is advisable to seek the participation of researchers and practitioners who possess specialized knowledge in the relevant field, as well as individuals from the target population (Koskey et al., 2023). The study utilizes a transdisciplinary approach to develop the knowledge framework for an appealing wall panel. This method integrates theoretical knowledge with practical application by merging perspectives from several disciplines to tackle practical issues (McGregor, 2004). Obtaining expert agreement is essential for improving the framework by integrating stakeholders' knowledge besides the scientific and architectural domains. According to Okoli and Pawlowski (2004), the size of a Delphi group needed to reach an agreement among experts is determined by group dynamics rather than statistical power. An integrative approach was used to address the many concerns raised by stakeholders, which considerably influenced the selection of materials. Scientists focus on manufacturing feasibility, whereas consumers value aesthetics, feelings, and other perceptual and sensory aspects. Thus, eight participants were engaged in the selection process: two clients, two material scientists, two architects, and two interior designers.

7.4 Delphi questionnaire

The Delphi questionnaire starts with biographical inquiries about the participant's area and expertise. Subsequently, a set of questions was asked under the primary research question, which focuses on determining whether the knowledge framework contributes to creating an aesthetically pleasing wall panel that competes with traditional applications in the Saudi market. These questions are:

1. Can you identify the strengths and weaknesses of the proposed framework?
2. Does the developed framework contribute successfully to creating a panelized wall system from biopolymer waste?
3. Is creating an aesthetically pleasing wall panel using waste materials as the primary component feasible?
4. Does the proposed framework effectively present the knowledge that connects material, process, and outcome for plastic waste recycling for architectural wall panels?
   sed framework?

Finally, the questionnaire incorporated a section where experts could provide additional comments or feedback if they wish to do so.

7.5 Pilot study

A pilot study can be conducted to test and adjust the Delphi questionnaire, increasing understanding and resolving any procedural issues (Linstone & Turoff, 1975). Therefore, I run a pilot study test before proceeding with the Delphi process. In this test, I briefly introduced the study to four colleagues, providing them with a thorough description of the framework, including the aesthetic design tool, matrix, and the Delphi questionnaire. The presentation lasts around 30 minutes via a Zoom conference. Finally, the Delphi procedure was revised based on their feedback.

7.6 Summary of Delphi Comments and Feedback

The transdisciplinary knowledge framework was created by gathering diverse information using qualitative and quantitative methodologies. In this step, the experts' responses are analyzed to help finalize the developed framework if they reach an agreement. Below is the analysis of the Delphi questions and feedback.

Responses for the Delphi were received by email in text format. However, the consensus threshold agreement must be selected to analyze the results. As stated by Hasson et al. (2000), the percentage of agreement when conducting a Delphi depends on several factors, such as the study's objective and the sample size. McKenna (1994) highlights that a consensus can be reached if 51% of respondents agree, while Sumsion (1998) recommends a threshold of 70%. Nevertheless, as an ideal threshold of 69.7%, consensus was established for this study. The following are summary of the Delphi feedback and analysis.

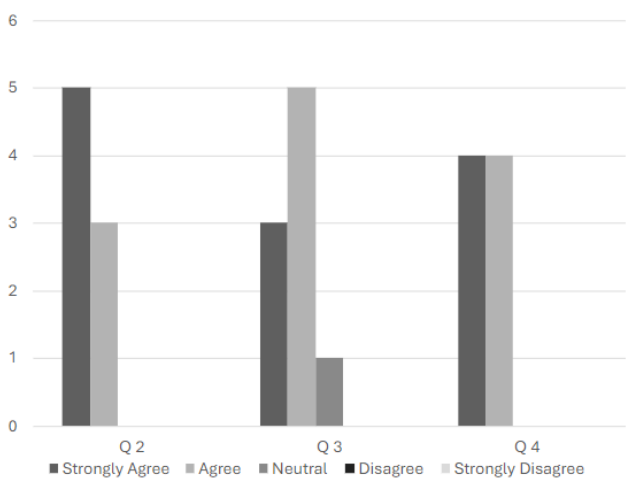
TABLE 7-1 DELPHI PANELISTS' DEMOGRAPHIC

Participant	Profession	Expertise
1	material scientist	Polymer and nanocomposite, surface modification of polymers using ionizing radiation, plastic recycling and application, synthesis, and modification catalysis of olefine polymerization, improving the UV radiation resistance of polyethylene using synergistic combination of stabilizer and ionizing radiation, development of new materials for ultra-high temperature application
2	material scientist	18Y of experience in the field of advanced materials, matrix composites reinforced with both natural and/or synthetic fiber, nano material development, leading scientific research institutions in Saudi and British universities, renewable energy applications, recycling agricultural and plastic waste.
3	Architects	GM of architecture firm, sustainability projects leader
4	Architects	Executive director of Architecture firm, participating in governmental projects and initiatives such as Riyadh metro
5	Interior Designer	Interior designers and journalist, Executive of architecture firm since 1997, furniture design, specialized in hospitality projects
6	Interior Designer	Interior designers, graphics, and branding designer, interested in sustainability projects and designs
7	Clients	Working in business and hospitality fields, interested in material and design.
8	Clients	Sales manager, marketing, specialized in biomaterial and biomedical instruments

Q1. Can you identify the strengths and weaknesses of the proposed framework?

strengths	weaknesses
The idea of the research (idea) is easy to understand for people who doesn't have an architecture background. The project can attract people and encourage them more into recycling. The research includes before and after images for the materials in difference. The idea of creating an app was even more attractive this way the customers can choose the material in early design stage. Recycling materials for construction reduces the demand for new resources, helping to conserve natural resources and reduce waste. Recycled materials can be transformed into unique, visually appealing finishes, adding character and charm to buildings. The proposed framework has a clearly defined and focused research question that addresses a gap in the existing literature. The proposal has well-designed and appropriate research methodology to address the research question, including selecting appropriate materials, analysis techniques, and sampling procedures. The proposal presents a novel approach methodology, as it contributes to the advancement of knowledge and design of aesthetically pleasing waste-driven wall panel. Verity of color Sustainability Flexibility Unique design and High thermal stability	Limited market PET size control High cost of manufacturing equipment (equipment price, maintenance, and operation) Availability Client Knowledge The proposal framework outcomes need to improve material properties such as flame retardancy properties. High cost of manufacturing equipment (equipment price, maintenance, and operation) Other applications such as floors ceilings and the thermal insulation might improve the market demand

Q.2 Does the developed framework contribute successfully to creating a panelized wall system from biopolymer waste?				
Strongly Agree	Agree	Neutral	Disagree	Strongly Disagree
5	3	0	0	0
Q.3 Is creating an aesthetically pleasing wall panel using waste materials as the primary component feasible?				
Strongly Agree	Agree	Neutral	Disagree	Strongly Disagree
3	5	1	0	0
Q.4 Does the proposed framework effectively present the knowledge that connects material, process, and outcome for plastic waste recycling for architectural wall panels				
Strongly Agree	Agree	Neutral	Disagree	Strongly Disagree
4	4	0	0	0



The analytical methods by which consensus is ascertained vary, but the most frequently employed are median agreement ratings and percent agreements (Koskey et al., 2023). In the study, I determined the overall percentage of agreement by combining and summarizing the agreement criteria (Strongly agree + agree) and disagreement (Strongly disagree + disagree). Then, the overall percentage of agreement was calculated as follows.

$$\text{The overall percentage of agreement} = \left(\frac{\text{sum of strongly Agreeand disagree" responses}}{\text{Total responces}} \right) \text{X } 100$$

Sum of agreement for Q2=8, Q3=8, Q3=8, The total sum of agreement is 24

$$\text{overall percentage of agreement} = \left(\frac{24}{24} \right) \text{X } 100 = 100\%$$ Thus, based on this result, the consensus threshold is 100%. Therefore, the Delphi study ended as the consensus threshold had been achieved during this round.

7.7 Refined Framework

Consensus feedback from the Delphi group indicates a general agreement of 100% regarding the proposed framework, which is accepted as an enhancement of the developed knowledge framework, as presented in **Figure 7-1**

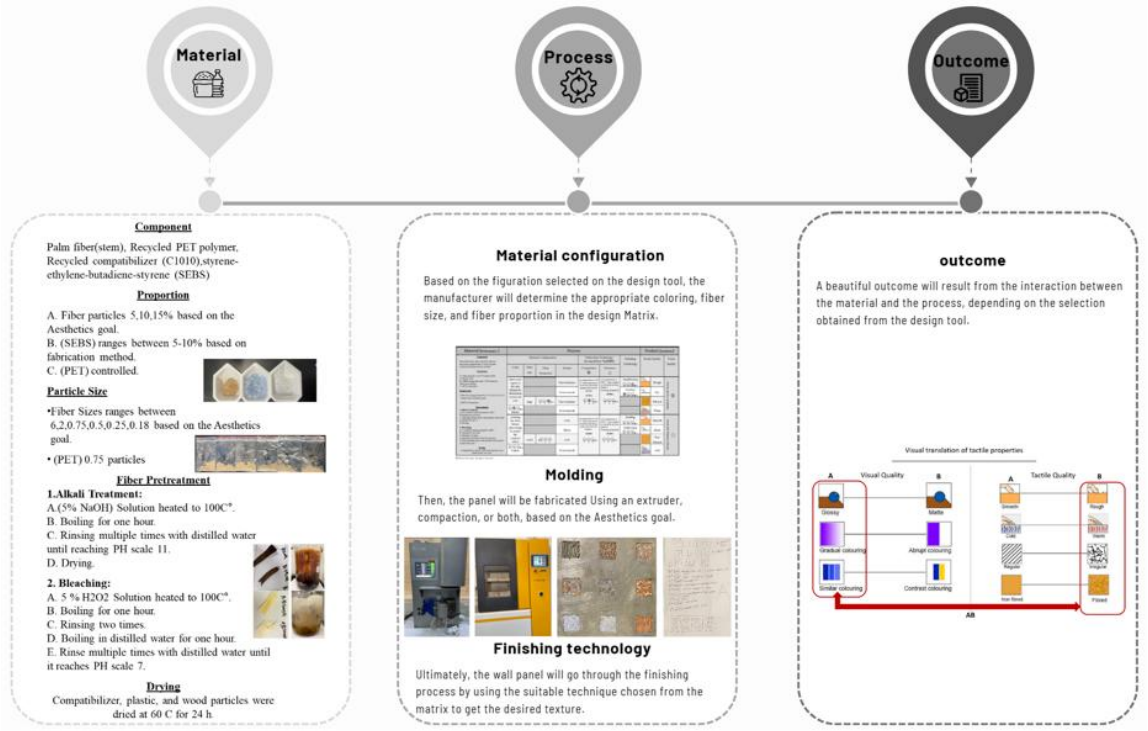


FIGURE 7-1 REFINED FRAMEWORK

7.8 Conclusion and Integration

This section illustrates the procedure for developing the knowledge framework, including the immersive case study as an evaluation method and the Delphi approach to generate stakeholder consensus regarding the developed framework. Finally, expert feedback influences the revision of the framework toward the refined one.

Key findings and future direction Chapter 8

8.1 Research Summary and Findings

This research project aims to provide a descriptive framework that explores the intersection between material process and outcome in developing aesthetically pleasing exterior wall panels. It is divided into three phases to answer the research questions as illustrated in **Figure 3-2** The first phase espouses the inductive approach. This phase primarily employs an analytical literature review and logical argumentation to develop the initial Framework. The Framework developed consists of configurations and procedures under three sections: material, process, and outcome. After that, a deductive approach was conducted in the second phase to develop the Framework toward a refined one. This approach starts with an immersive case study. I immersed myself in producing wall panel samples following the aesthetics theory and procedure of the initial Framework. Following that, I used the key takeaways to refine the Framework. Subsequently, I used the Delphi approach to facilitate a consensus among experts over the proposed Framework, whereby their input contributed to developing the refined framework. Finally, in the third phase, the researcher conducts an exploratory follow-up where data is analyzed, merged, and interpreted through complementarity. Complementarity refers to establishing a relationship between qualitative and quantitative data findings to emphasize the refined Framework.

This study's results show that utilizing recycled materials to create an aesthetically pleasing wall panel can contribute to the principles of the circular economy in Saudi Arabia. The anticipated findings and insights from this study will contribute to the existing body of knowledge, providing practical guidance for designers and architects while promoting a more sustainable and environmentally conscious approach to construction.

8.2 Contributions to the Body of Knowledge

Who cares?

This research aims to develop a knowledge framework that explores the intersection of material process and outcome in creating aesthetically pleasing exterior wall panels. The study contributes to the body of knowledge by demonstrating how the utilization of recycled materials in panel production can promote sustainable building practices and foster the principles of the circular economy in Saudi Arabia. This research will provide valuable insights into the design and construction industry's potential for reducing waste, minimizing environmental impact, and promoting economic growth.

As for the economic growth of the construction industry, it is affected by the high demand for such materials by clients and stakeholders. The clients are interested in the aesthetics of the product and its cost. The cost of a waste-driven wall application will be less than the conventional materials offered in the market. As for the aesthetics part, Louis Kahn said that "*it is critical for the architect to listen to the whispers of the material*." Developing a framework that focuses on producing a high-quality, aesthetically pleasing application will distinguish the waste-driven wall panel from the cladding application in the Saudi market. In return, building users who walk around the building can feel and engage with such unique material instead of avoiding it. Concerning the stakeholders, they will not support any project with no benefit. Thus, the increasing demand for the proposed product promises to build a successful business by selling high-quality material at a low cost. Ultimately, the product will contribute to renewable energy generation in Saudi Arabia and reduce the costs involved with landfilling and the accompanying environmental implications. In addition, it may change the municipal waste system from linear to circular. Thus, this work will significantly benefit sustainable waste management methods and renewable energy generation in the Kingdom of Saudi Arabia.

8.3 Future Research

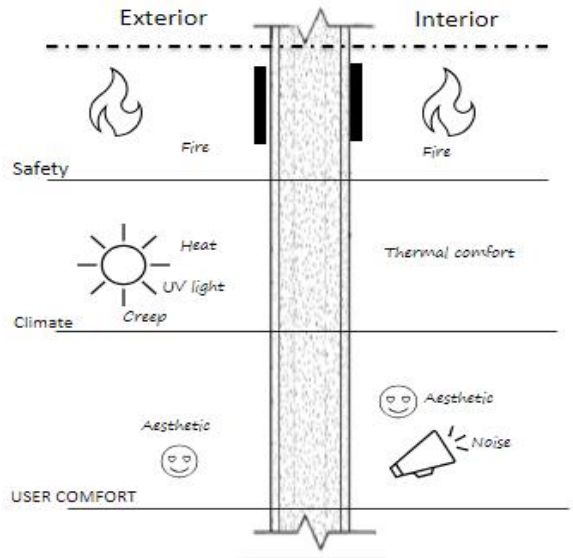


FIGURE 8-1 PERFORMANCE CRITERIA OF WALL PANEL

This research addresses the aesthetics knowledge gap by establishing a knowledge framework for an aesthetically appealing wall panel. However, neither the aesthetics nor the mechanical, thermal, or chemical efficacy were evaluated in this study. The knowledge framework serves as an initial foundation for subsequent advancements in research, depending upon its intended application, as illustrated in **Figure 8-1** For instance, interior acoustic characteristics and thermal comfort must be considered when installing the wall panel indoors. Nevertheless, if the application is for an outdoor environment, adequate measurements must be considered due to weather conditions. Therefore, an extended knowledge framework will be developed and validated for each intended use.

Consequently, I will proceed with this research in the near future in collaboration with the King Abdulaziz City of Science. Together, we shall initiate the construction of the framework for exterior wall panels and assess their resistance to harsh weather environments, as it is a promising application based on the previous literature discussed in this research and the pilot thermal test, I did on one of the produced prototypes that include 5. wt.% palm and the result shows heat resistance beyond 470 C^{o}, as illustrated in **Figure 8-2**.

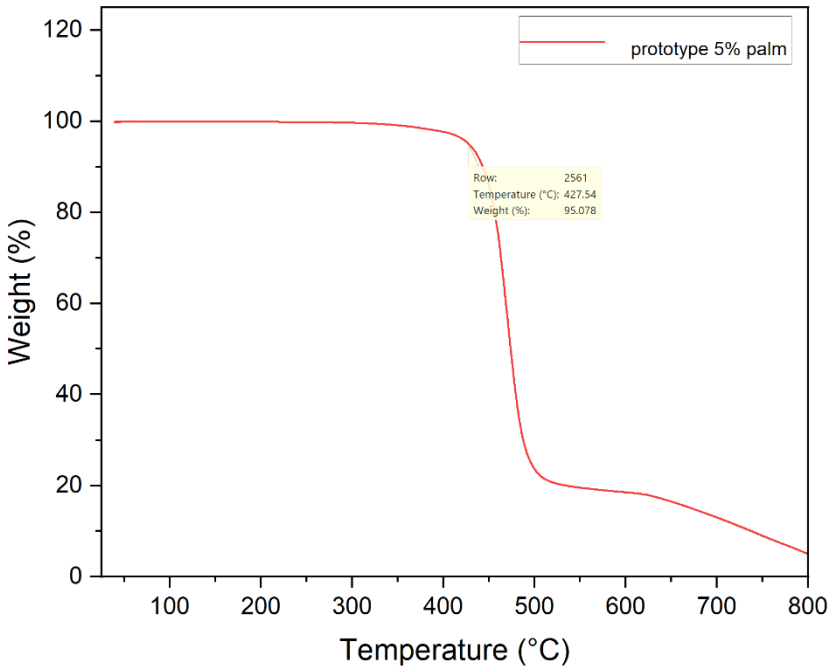


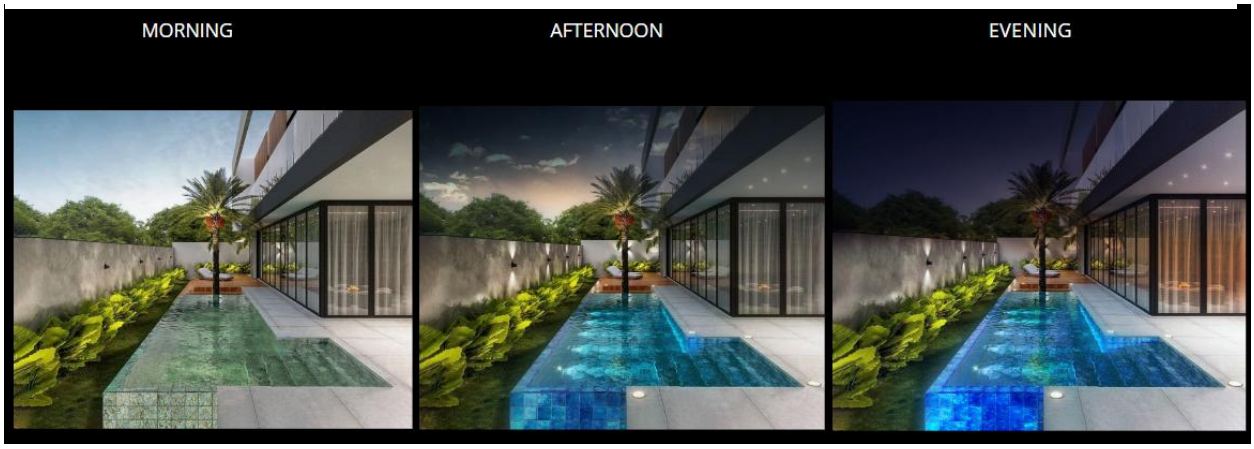
FIGURE 8-2 TGA OF RECYCLED PALM/PET BIOPOLYMER COMPOSITE

The performance test will be done using the instrument illustrated below in **Figure 8-3**, and the aesthetics test will be done using the aesthetics theory applied to this study.

FIGURE 8-3 INSTRUMENTS FOE WEATHERING TESTING AT KACST

Developing a method for producing aesthetically appealing applications will make further investigation into alternative building material categories, such as swimming pools, possible. Subsequent representation is suggested utilizing the prototype material created as part of this investigation. Thus, this application will require a sequence of examinations to meet the aesthetics and functions of such a product.

FIGURE 8-4 SWIMMING POOL APPLICATION OF THE RECYCLED BIOPOLYMER COMPOSITE



8.4 Conclusion

"I touch the wall with my eyes." Juhani Pallasmaa

Recycling biopolymer waste with consideration of its functions and aesthetics is going to constitute an innovative development in the field of building science and sustainable development.

Appendix

Dear Sir/Madam

I hope this email finds you well. I am Manal Almutlaq, a Ph.D. student at the School of Architecture + Design, Virginia Tech. I am conducting research aimed at developing a knowledge-based framework that illustrates the intersection between material, process, and product to prove the possibility of creating an aesthetically pleasing exterior finish panel from recycled biopolymer waste that competes with the conventional finish materials in the Saudi market.

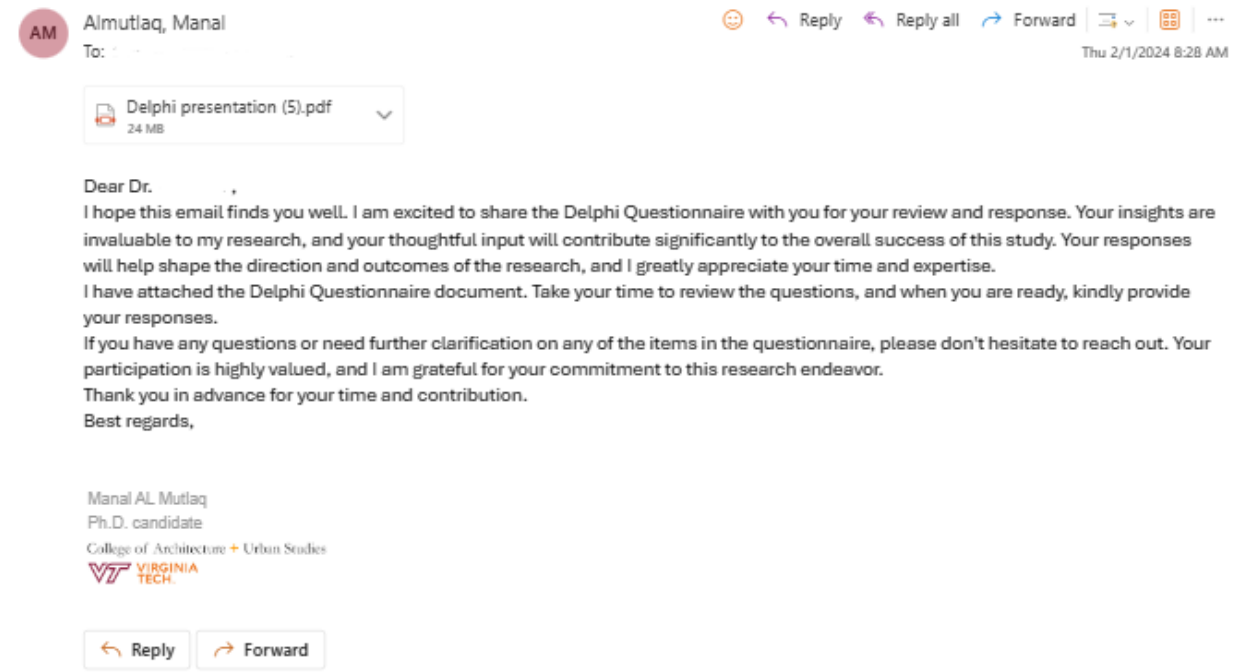
The Delphi method will be my primary strategy for carrying out consensus on the proposed framework. Skulmoski et al. (2007) state: Define the Delphi method as an adjustable research approach employed in situations where knowledge regarding a particular phenomenon is inadequate. This method is employed by researchers who are interested in gathering expert opinions regarding group decision-making (Skulmoski et al., 2007). This approach is a procedural framework comprising a sequence of consecutive "rounds" that are built up with defined feedback. Its objective is to attain the most reliable consensus view possible among a group of experts (Linstone & Turoff, 1975).

The Delphi technique was chosen as the research approach to obtain expert consensus regarding the proposed framework by analyzing their responses. In pursuit of this objective, I sought your assistance and involvement in the research. I intend to deliver a presentation incorporating a detailed explanation of the constructed framework and a brief introduction to the study. The presentation will be held for around 30 minutes, and it will be in person or via Zoom meeting. Upon completion, I will email you the presentation with the Delphi questionnaire. Participants will be required to respond to the questions about the proposed framework. The estimated time needed to finish the questionnaire is between 10 and 15 minutes. If necessary, a subsequent round will be conducted in consideration of your response. Your contribution will significantly impact the results of this study. Please do not hesitate to contact me should you have any inquiries about this matter. I appreciate your response and express my gratitude in advance.

Sincerely,

Manal Almutlaq

APPENDIX 1 DELPHI INVITATION LETTER



AM

Almutlaq, Manal

To:

Reply Reply all Forward

Thu 2/1/2024 8:28 AM

Delphi presentation (5).pdf
24 MB

Dear Dr. ,

I hope this email finds you well. I am excited to share the Delphi Questionnaire with you for your review and response. Your insights are invaluable to my research, and your thoughtful input will contribute significantly to the overall success of this study. Your responses will help shape the direction and outcomes of the research, and I greatly appreciate your time and expertise.

I have attached the Delphi Questionnaire document. Take your time to review the questions, and when you are ready, kindly provide your responses.

If you have any questions or need further clarification on any of the items in the questionnaire, please don't hesitate to reach out. Your participation is highly valued, and I am grateful for your commitment to this research endeavor.

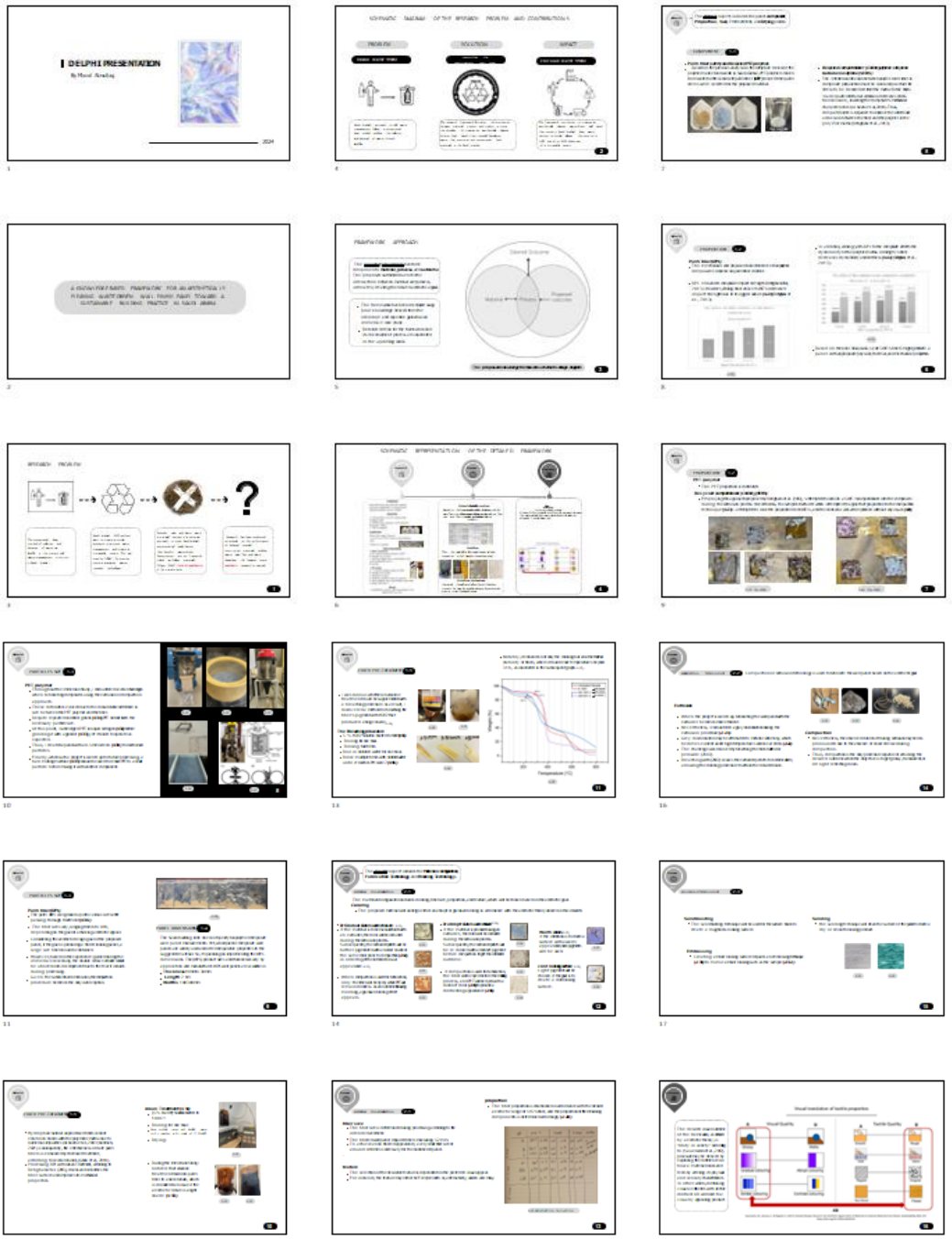
Thank you in advance for your time and contribution.

Best regards,

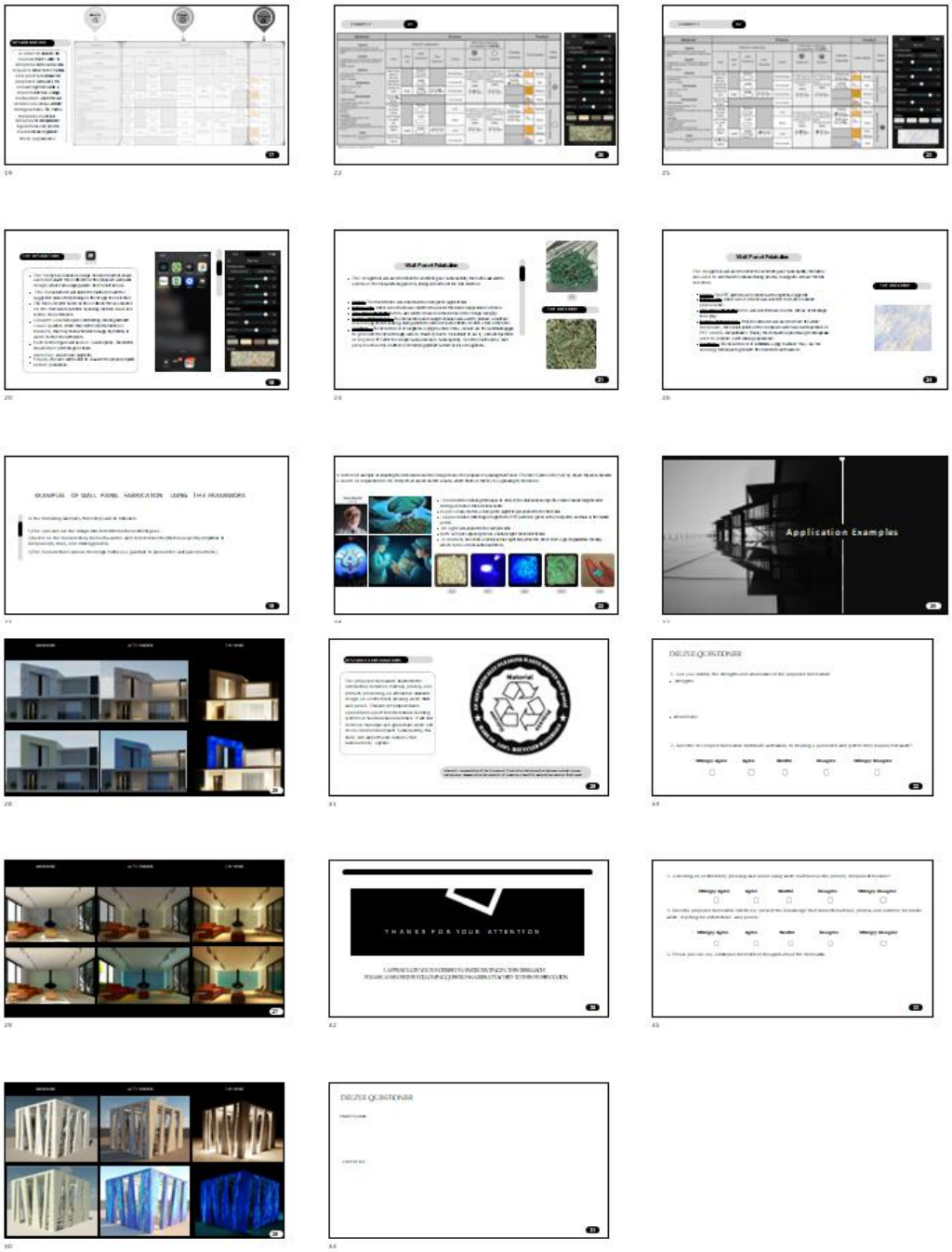
Manal AL Mutlaq
Ph.D. candidate
College of Architecture + Urban Studies
VIRGINIA TECH

Reply Forward

APPENDIX 2 DELPHI FOLLOW UP QUESTIONERS



APPENDIX 3 DELPHI PRESENTATION



APPENDIX 4 DELPHI PRESENTATION CONTINUED

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