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The Development of Bacterial Cellulose Biomaterials Using the Material Design-Driven Approach for Packaging Industry

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ABSTRACT

Alternative renewable materials are a possible solution to the rapid depletion of non-renewable resources. Within the renewable materials category, living organisms have been utilised in sustainable material projects. Although the projects are currently speculative, the possibility of utilising living organisms offers an appealing sustainability advantage for product design. Notably, their ability to 'self-build' enables them to become the co-maker of the output materials or products effectively. One of the promising lab-grown materials developed and utilised in product design is bacterial cellulose. Many researchers and designers have focused on improving the cultivation process and the feasibility of the materials for targeted product applications. However, much research is still needed to fill the void of knowledge in developing biomaterials for product design. This paper presents an early development of novel bacterial cellulose biomaterials and their applications using the Material Design Driven (MDD) framework. In this research, three bacterial cellulose biomaterials with unique experiential qualities have been produced through the approach. Notably, the research highlights the innovative potential of bacterial cellulose as a packaging material by incorporating plant fibres as the reinforcement agent and imprinting artificial texture on the material surface.

Keywords: *Sustainable Material, Biomaterial, Material Experience, Packaging, Circular Economy*

1. INTRODUCTION

The environmental impact of our production and consumption activities is sobering. A tremendous amount of waste is sent to landfills due to a throw-away culture. Single-use plastic is the primary culprit due to the tremendous waste it produces. Initially driven by innovation for economic benefit, petroleum-based plastic products provide convenience and create massive waste in landfills (Meikle, 1997; Mhd Nor Osman et al., 2018). Furthermore, the unchecked overconsumption of such products leads to severe environmental and social consequences (Packard, 1960).

A great deal of literature indicates a growing interest from various industry stakeholders in developing more environmentally benign materials. Such materials are developed and utilised as an activity to counterbalance the depleting of non-renewable materials. Although the prospect of renewable and recycled industrial materials is hindered by the strong position of petrochemical-based materials and the locked-in nature of other materials in the market, opportunities for a genuinely sustainable materials economy remain extraordinaire (Geiser, 2001).

The implications of overconsumption and the adverse impact of the take-make-use-dispose approach have long been highlighted (Ellen MacArthur Foundation, 2013; Papanek, 1972; Rogers, 2005). In recent years, product stakeholders and the general public are becoming aware that if this linear economy prolongs, some ecosystems will collapse even before resources are completely exhausted. The current rate of raw materials consumption puts a strain on material resources and is detrimental to the environment (OECD, 2013). Further, planned product obsolescence has worsened the adverse environmental impact of production and consumption (Agrawal et al., 2015; Andrews, 2015). Hence, a more viable alternative production approach is required, and product industry stakeholders are under increasing pressure to shift towards circular practices to close the loop of material usage efficiently.

In response to the above challenge, designers and product developers are showing a growing interest and distinct efforts to develop and utilise more environmentally benign materials. Designers and product developers inspired by natural resources such as tropical organism in make a variety of materials (Donna Angelina, 2020). The development of sustainable materials is seen as crucial to minimising the environmental impact of products and reducing non-renewable material resource depletion. Hence, recycled and renewable materials that are commonly complemented with sustainability claims are emerging in the market.

Within the spectrum of sustainable materials, living organisms are used in speculative material projects. The developers in these projects were optimistic that living organisms could revolutionise the way materials are produced. The material's ability to 'self-build' or replace other necessary compounds in making the material it substituted is considered an advantage to minimise environmental burden. Lab-grown materials such as Kombucha, mycelium and tissue culture were perceived as a unique source of sustainable materials. The living cells effectively become the co-maker of the materials, thus blurring the boundary between man-made and nature (Hilal Mazlan, 2020). For instance, the Kombucha based material developer stated that the idea is to trigger a bacterial colony to produce a textile material to provide an alternative to conventional animal leather fraught with ethical and environmental issues. The idea of having nature as the co-maker of products is currently seen as the way forward to sustainable production and consumption. Such a strategy will help minimise the adverse impact of non-sustainable material and reduce reliance on finite, non-renewable fossil-based material.

Substantial progress has been made in the past concerning research findings on the cultivation of Kombucha biomaterial, but current development is stagnant. In particular, existing research has predominantly explored the production process (Jurgita Domskiene et al., 2019; Torres et al., 2012; C. Zhu et al., 2013). Also, researchers are focusing on the feasibility of the materials at molecular levels, e.g., relating to composition, structure, and processing of materials to their properties and uses, conducted by material scientists and researchers (Vincent, 2011). However, it is still necessary to improve the output material in terms of its technical and experiential properties. For instance, the kombucha film without oil or wax coating crumbled easily and even with coating; the material is not as durable as animal leather. Thus, in general, the current understanding of how to further develop the biomaterial to be embedded in functional products is inadequate. Therefore, a new design direction that counterbalances the material's technical qualities and experiential qualities is essential. It is also noteworthy to highlight that this research mirrors a new emphasis on developing and utilising novel and sustainable biomaterial in Malaysia.

2. SUSTAINABLE MATERIAL

Material industry stakeholders posit diverse sustainability dimensions, but they convene around similar themes, minimising materials' adverse impact on humans and the environment through efficient management. (Arroyo et al., 2016) asserted that defining sustainability can be complicated since it is subject to multiple stakeholders' views and contexts.

By definition, 'sustainable' means 'conserving an ecological balance by avoiding depletion of natural resources (*Oxford Dictionary of English (3d.)*, 2010). In literature, the word 'sustainable' is typically is used with no consensus meaning. It has no precise definition and is composed of three fragments of aspiration: economic, social, and environmental well-being (Allwood, 2016). It is also understood as a vague concept concerning holistic well-being at the societal level (Kattwinkel et al., 2018).

When the word 'sustainable' is linked to materials, it explains a more viable material that fulfils specific sustainability attributes regardless of the material's type. For example, In the book 'Sustainable Materials with Open Eyes', (Allwood & Cullen, 2012) reviews the sustainability attributes of five materials, namely steel, aluminium, cement, paper and plastic. Of course, the attributes that define sustainable materials vary depending on the context. However, the essence of the terminology encapsulates the well-being of humans and the environment. 'Sustainable materials' are those that reduce hazards in processing, secure public health and minimise environmental impact throughout their life cycles (Geiser, 2001).

Also, 'sustainable material' is often used interchangeably with 'eco-materials to explain the environmental credentials, e.g., `Eco-tyres that are made of sustainable methods and materials' (Luchs et al., 2010). In the Rio de Janeiro Earth Summit, the concept of 'eco-materials was proposed by which all materials should be developed and utilised in harmonic sync with the eco-sphere (Halada & Yamamoto, 2001). Historically, "eco-friendly" was originated in 1989, while "sustainable" has been around since 1727 (*The Merriam-Webster Dictionary*, 2013). Nevertheless, the two terminologies are widely used (Campbell et al., 2015) and are prominent in 1,570 labels of sustainable products in 2009 (Greenbiz, 2009). More broadly, both material groups are associated with similar attributes, e.g., materials designed employing lifecycle assessment, hazardous substance-free, higher material recyclability and having a low environmental impact (Umezawa et al., 2014, Halada et al., 2003), and bio-derived, renewable and bio-degradable (Grant & Mason, 2013).

In the science and engineering domain, 'sustainable materials' are prevalently used to describe alternative renewable materials (Cunha et al., 2013; Mikkonen & Tenkanen, 2012; Poletto et al., 2016). Furthermore, the word 'sustainable' is often used as the prefix to material types such as sustainable polymers (Y. Zhu et al., 2016) and sustainable bio-composites (Mohanty et al., 2002), describing the end-of-life (biodegradability) and the resource origin attribute (renewability). Within the design domain, various other terminologies are used, such as 'environment-conscious materials' (Utsugi et al., 2007), 'materials with high sustainable potential' (Rognoli et al., 2011) and 'eco-sensitive materials' (Karana & Nijkamp, 2014) which all of these are referring to either renewable or recycled materials. However, the difference in sustainability attributes confined by these terms is not always clear. The breadth of the terms indicates that the area of sustainable materials is growing and is still divergent in thinking. As a matter of fact, there is no consensus yet on the usage of 'bio-based plastic' terminology in the industry (Álvarez-Chávez et al., 2012).

3. MATERIAL DESIGN DRIVEN (MDD) APPROACH

Historically, research and exploration of materials as a substance having beneficial properties were exclusive to material scientists as the discipline of chemistry progressed faster during the Industrial Revolution (Miodownik, 2007). The focus back then was on utilising the performative aspects of the material and converting them into valuable products. Interdisciplinary collaboration was encouraged in the 1960s, and industry-academic partnerships were initiated in the 1980s to escalate material commercialisation (Vincent, 2011). As a result, material exploration and development discourse spread to other disciplines such as product design. Within the same period, sustainability consideration was incorporated in the fore of the design industry as part of their environmentally conscious design solution (Ramirez, 2012). The trend also emerged in academics where sustainability issues are being taught in design courses (Ramirez, 2012). The Cumulus International Association of Universities and Colleges of Art, Design and Media further posed sustainability issues as opportunities for design, design education and design research (Cumulus, 2008).

Thus, currently, sustainable material exploration and development is not unusual in design practices. This trend is also partly driven by the democratisation of knowledge and production technology (Rognoli, Bianchini, Maffei, & Karana, 2015; Mota, 2011), producing an increasingly large output category of 'DIY' materials (Rognoli et al., 2015). It is also noteworthy that material exploration within this spectrum is further facilitated through maker communities (Thilmany, 2014). The exploration projects are not limited to self-exploration, as multidisciplinary knowledge sharing platforms (e.g., the open workshops on bio-materials held by the Co-Lab at the Institute of Making, University College London) contribute to disseminating materials knowledge to the public.

The use of unconventional materials with peculiar surface characteristics in which imperfection is embraced and considered an appealing aesthetic is one of the designer's emergent themes in material projects. Examples of such projects are Tomas Gabzdil Libertiny's bees hive vase (Parsons, 2009); Suzanne Lee's bacterial cellulose jacket; Gingers Krieg Dosier's microbial-induced bricks (Ginsberg, 2014); a tissue-cultured jacket (Catts & Zurr, 2014); alternative textile production from mycelium (Collet, 2017) and seeds' tablets and pots based on coffee waste, (Karana, Barati, Rognoli, & Zeeuw Van Der Laan, 2015).

Although inclined towards conceptual application that is purely design-based, i.e., explored through material tinkering or trial and error, materials explored by designers have contributed to the body of knowledge. The outputs of material exploration by designers are pushing the boundaries of the design discipline and challenging the capabilities of the current technology. However, they are indeed shaping the future of the material field (Ginsberg et al., 2014). The exploration of materials by designers in this century has reached the ultimate peak, including the creation of futuristic materials (Lee, 2015). The oxygen-breathing 'silk-leaf' by a Royal College of Art graduate (Melchiorri, 2014) and 'Bio-plastic Fantastic' (Schmeer, 2014) can be considered as iconic examples that indicate the progressiveness of the materials explored by designer, to the extent that future living with interactive and living materials are conceptualised. Significantly, the features of the materials contribute to an additional facet of sustainability (e.g., renewability, self-heal). Not limited to conceptual products, even luxury brands have utilised sustainable materials to comply with the sustainable standard in sourcing and producing products. For example, Gucci launched a handbag collection made of leather sourced from Rainforest Alliance Certified ranches, and Stella McCartney developed biodegradable leather (Ki & Kim, 2016).

Further, the Material Driven Design framework has been developed to facilitate designers in designing products with materials as the clear departure point in the design process (Karana et al., 2015). Also, this tool is beneficial in designing or developing non-conventional materials in which the embedded meaning of the materials is unknown. As shown in Figure 1, attention is given to the technical and experiential qualities of materials. Therefore, designers need to go through four main steps as follows: (i) Understanding the Material: Technical and Experiential Characterisation, (ii) Creating Materials Experience Vision, (iii) Manifesting Materials Experience Patterns, and (iv) Designing Material/Product Concepts. The first and second steps are crucial as designers need to analyse the nature of the materials, how users go about appraising materials and formulate ideas on the possible application where unique technical qualities and experiential qualities of materials are relevant to be incorporated (Karana et al., 2015).

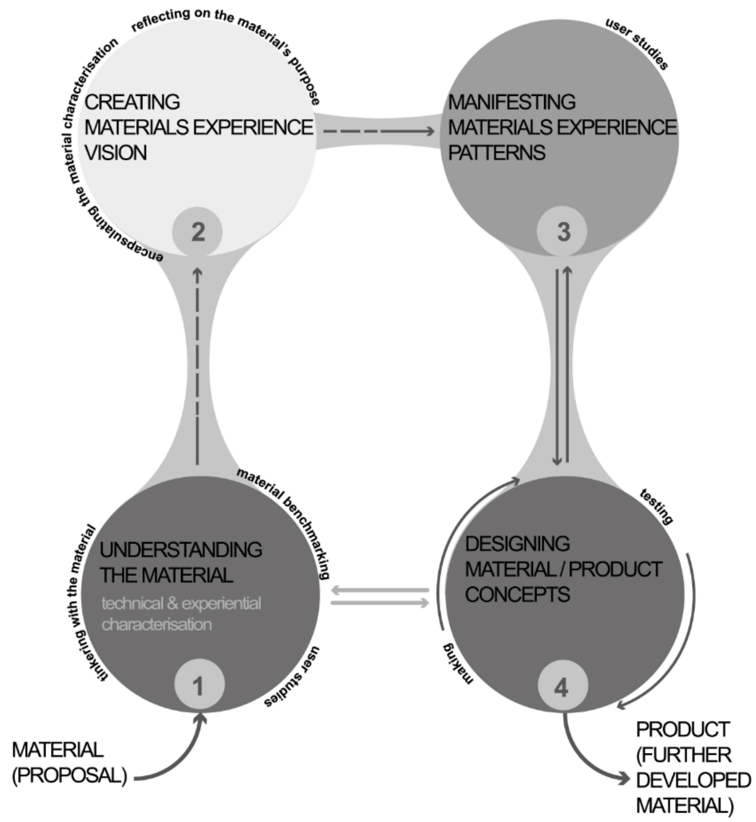


Figure 1: The Material Driven Design Framework (Karana et al., 2015)

4. BACTERIAL CELLULOSE BIOMATERIAL

Bacterial cellulose is a biological material with impressive physical properties and low cost of production that is an attractive substrate for the development of sustainable materials for product application. As previously mentioned, the main idea of utilising living materials for products is to harness the ability of the materials to be self-built. Thus, the output material or the product is relatively more sustainable because it requires little energy and resources in its production.

One of the most common bacterial cellulose materials used in product design is the Kombucha bio-film. The material is a membrane created through a symbiotic fermentation process by consortium bacteria, yeast and Kombucha tea (Alkhalifawi, 2014). Principally, the bacteria are fed with agricultural waste as the grow medium, forming a sheet of skin-like material. Usually, it would take about two weeks for a thin, flexible and organic film to form. At its end of life, Kombucha biomaterial will easily disintegrate and decompose.

Figure 2: Samples of semi-developed Kombucha biomaterial (Emma Sicher, 2018)

Many product designers have developed Kombucha biomaterial to substitute plastic, textile and animal leather (see the above Figure). As the biomaterial is entirely grown from cellulose film, no animal is exploited in the production. Also, water and energy use are less intensive than the production of mainstream materials. Hence, the carbon footprint of Kombucha biomaterial is relatively low. However, developers are still refining the finishing treatment for the biomaterial. For sustainability reasons, they opt not to use harmful chemicals typically used to treat material surfaces.

To date, much research has explored the engineering and design aspects of cellulose materials. For example, (Sicher, 2017) and (Cohen et al., 2020) investigated food waste as a growth medium for bacterial culture, (Chawla et al., 2009) describe the structural properties and speculate current and potential applications of bacterial cellulose. Previous studies (e.g., Stefano Parisi, 2021; LoreVeelaert, 2020; Ghalachyan, 2018) explored user perceptions and experiential characterisation towards bio-inspired cellulose material application in design. In addition, researchers are exploring the various dimensions of bacterial cellulose materials to look for alternatives in substituting the non-renewable resources typically used in the conventional linear economy.

5. METHODOLOGY

This paper presents a project to develop bacterial cellulose composites variation using the Material Driven Design (MDD) framework (Karana et al., 2015). The project focuses on the early stage of material development encompassing the first two steps of MDD, (i) Understanding the Material, (ii) Creating Material Experiential Vision, (iii) Manifesting Materials Experience Patterns, (iv) Designing Material/ Product Concept. It is noteworthy to highlight that the MDD guides designers to envision a material application based on its experiential and technical qualities. Like the typical practice of a product design development process, designers rely on a reflective approach and act on intuitive interpretation, knowledge and experience in using MDD.

In the first step of MDD, as part of the alteration and tinkering process, a mini-laboratory of biomaterial cultivation and processing system was set up to output several samples of bacterial cellulose materials. Then, the researchers interacted and manipulated the samples to understand their technical and experiential characteristics thoroughly. In addition, selected samples were benchmarked against several conventional materials.

In the second step, the purpose of the materials was defined. Relevant material applications based on their experiential characteristics were projected. The step also consists of an evaluation of the materials by a panel of product design experts. The study participants were asked to appraise the materials using a think-aloud protocol. The aim was to understand users' perceptions of the material samples. A semi-structured interview with two product design experts was conducted in the third step of MDD. The interview further investigated the material-users relationship, and the findings provide a basis for envisioning the material application. Finally, a meaningful and feasible embodiment of the material samples in products were proposed. The overall MDD process conducted in the study is summarised in Table 1 below.

Table 1: The MDD steps and approaches in each step

MDD Steps	Approaches
1. Understanding the Material	● Alteration and tinkering -samples cultivation -physical manipulation - think-aloud protocol and physical interaction by two product design experts ● Material benchmarking
2. Creating Material Experiential Vision	● Reflection on experiential and technical qualities of the material samples
3. Manifesting Materials Experience Patterns	● Understanding of how the materials will be used and experienced -think-aloud protocol with two product design experts
4. Designing Product Concept	● Packaging Design Proposals

6. FINDINGS

The following sections present the outcomes of each step of the MDD. In this project, approaches within each step of the MDD facilitate the output of new variants of bacterial cellulose material and envision their applications.

6.1 Understanding the Materials

6.1.1 Alteration and Tinkering

The tinkering process is started with the production of the material samples. The process aims to make changes and improve the characteristics of the material. Through exploratory experiments, one 'control' (unaltered sample), one 'film' (altered sample), and two composites (altered samples) were produced, as shown in Figure 3.

Figure 3: Four material samples

All material samples were grown at room temperature in a controlled growth medium. Table 2 presents the brief record of the material samples cultivation. Examples of the scene of the cultivation and material processing are shown in Figure 4.

Table 2: Record of material samples cultivation control

Cultivation Process	Control (Unaltered Sample)	Biofilm (Altered Sample)	Biocomposite 1 (Altered Sample)	Biocomposite 2 (Altered Sample)
Growth Duration	Four weeks	One week	Two weeks	Four weeks
Fibre Reinforcement	NA	NA	Coconut husk & rice straw	Coconut husk
Impurities Removal Treatment	NA	Water, Betaines and Sodium Laureth Sulfate	Water	Water, Betaines and Sodium Laureth Sulfate
Surface Treatment	NA	Silicone texture imprint	NA	Silicone texture imprint
Colour Treatment	NA	NA	Food grade dye	NA
Water-Repelling Treatment	NA	NA	Coconut oil	NA
Drying Method	Sun-dry	Sun-dry and heat press	Sun-dry and heat press	Sun-dry and heat press

Figure 4: Bacterial cellulose in growth medium (left) and sun-drying and texture imprinted process (right)

Several sessions of physical manipulation were conducted on the materials after the cultivation and processing were complete. The tinkering process allowed the designers to develop a comprehensive understanding of the materials, including their sensorial, performative, affective, and interpretive aspects. Specifically, the tinkering studies were conducted with the materials to understand their properties, behaviour under different manipulation, and opportunities. As shown in Figure 5, the material samples were bent, cut, weaved, pulled, soaked and moulded. The step enables material developers to be intuitive, like an artisan, relying on cognitive process and physical-experiential capacity to read the behaviour of the materials.

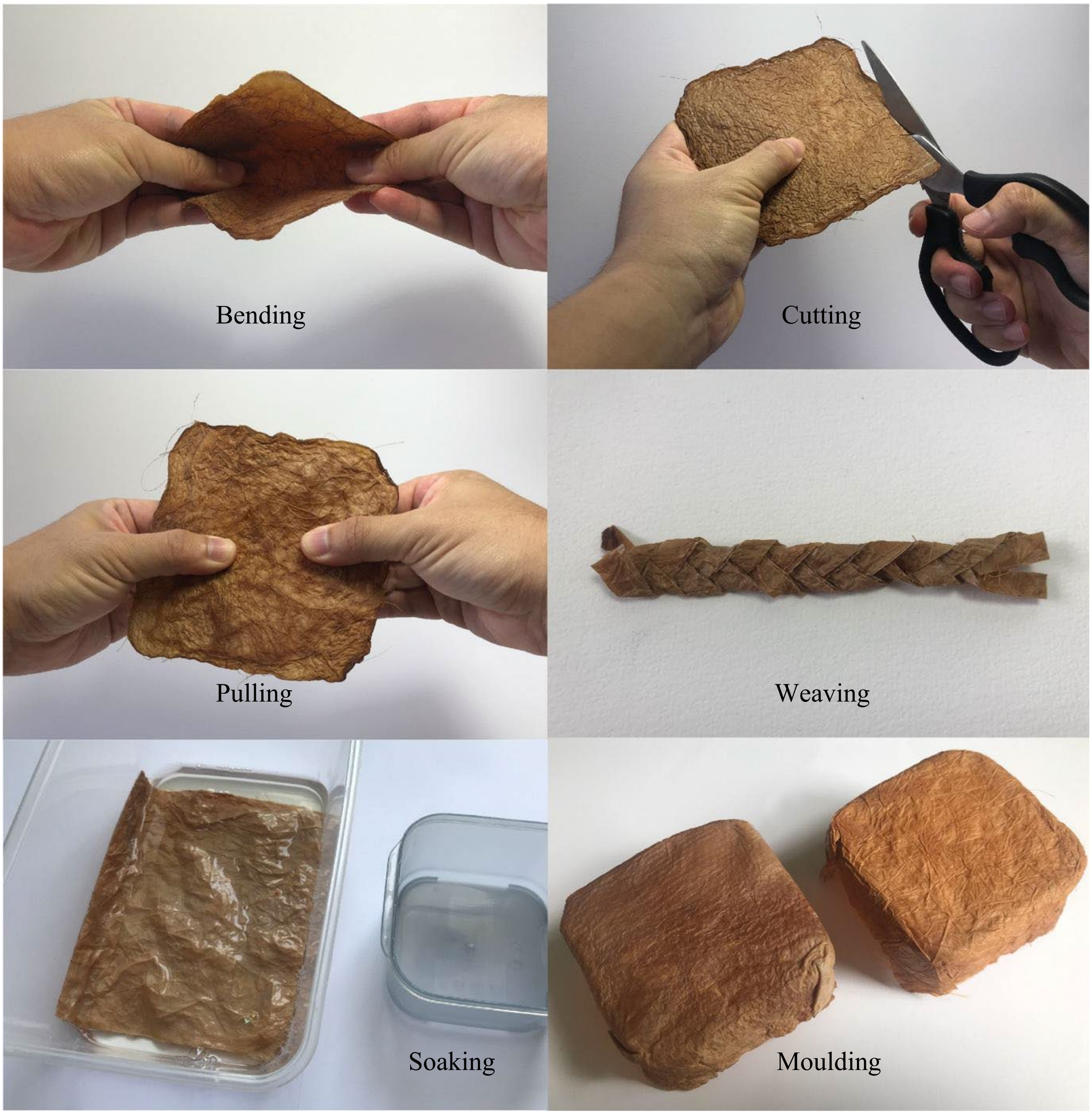


Figure 5: Tinkering Studies with the Bacterial Cellulose Materials.

The procedures mentioned above validate the materials' technical qualities. However, the researchers also simultaneously focused on the materials' experiential qualities by having a think-aloud protocol session with two product design experts. This approach aims to simulate a users' perception and experience study, to understand the evoking emotions and appraisals of the materials. It is found that the materials elicited a range of emotions from surprise, pleasant, joy to disgust. Mainly, the second composite is potentially seen as an untreated animal skin. Hence users may be revolted to touch it. Then, the product design experts associated the material samples with everyday objects such as wood, leather, film and edible material. The appraisals were done while touching, grasping, folding, caressing, and pinching the materials' samples. The translucency is deemed a unique characteristic of the film sample, and the imprinted texture makes the material look high quality. The following table shows a breakdown of the various reactions and emotions elicited when the researchers cum appraisers interacted with the material samples.

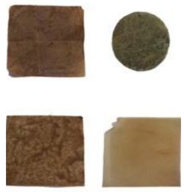
Table 3: Experiential Quality Studies

Experiential Quality	Control	Biocomposite 1	Biocomposite 2	Biofilm
Sensorial	A pungent smell, wavy contour	Coconut-like smell, see layers, structural, moss green	Pleasant smell, natural look	Paper-like, translucent, structured pattern, feel smooth, soft, plastic sheet-like,
Performative	Fold, bend, pinch, press, stroke	Caress, fold, bend, pinch, press, grasp	Fold, bend, pinch, press, roll	Fold, bend, pinch, press, caress, roll
Affective	Unpleasant, surprise, disgust, shudder	Surprise, pleasant	Joy, happiness, surprise, fascination	Surprise, fascination, confuse
Interpretive	Wood bark-like, low quality, wrinkled leather, cheap and strong, parchment-like,	Crafty, wall deco, natural, beautiful,	Leather-like, packaging, strong, biobased material,	Film-like, rice paper, inner packaging, food packaging, high quality, flimsy, filler packaging, ready to use, edible, food-safe

6.1.2 Material Benchmarking

Further, the material samples were benchmarked against related mainstream and innovative materials available in the market. This step is essential in strengthening our insights on the characteristics of the designed materials.

Table 4: Material Benchmarking

Benchmark criteria	Recycle Brown Paper & Corrugated Box	Cowhide Leather	Mycelium Leather	Altered Bacterial Cellulose Materials
Sample picture				
Technical properties	Non-water resistance, easily torn	Resistant to tear, puncture, wet and dry abrasion, elastic	Low density, thermal and acoustic insulation,	Resistant to tear, paper-leather flexibility, humid resistant
Experiential qualities	Established meaning depending on the sensory quality e.g., temporal, throw-it away, single-use	Established meaning depending on the sensory quality e.g., warm, sophisticated, classic	Natural, leather-like, flexible, imperfection surface quality	Natural, leather-paper-like, no established meaning
Applications	Durable and robust packaging for various industries	Clothing, furniture upholstery, bag, leather goods.	Leather substitute, footwear, fashion accessories, bag,	Filler packaging, toiletries packaging, food packaging, coffee cup sleeves, wall and interior finishing, soft board
Sustainability attributes (resources origin and lifecycle)	Renewable resources, recyclable	Renewable resources, environment impact (tannery)	Renewable resources, biodegradable, low carbon footprint,	Renewable resources, biodegradable, low carbon footprint, high cultivation rate
Sustainability attributes (water consumption in production)	Approximately 10 litres for an A4 sized	Approximately 160 litres for 1 kg of leather	Approximately 1% of the water used in leather production	Approximately 2 litres for an A4 sized

6.2 Creating Material Experiential Vision

6.2.1 Reflection on Experiential and Technical Qualities of the Material Samples

Based on the experiential study, technical evaluation and mapping above, the outstanding quality of bacterial cellulose material is its paper-leather-like characteristics. Compared to paper, composite samples with natural fibres showed better water and tear resistance. The fibres help to disperse the water quickly hence maintaining the integrity of the matrix. In addition, the incorporation of natural fibre in the material reinforces the structural strength of the material. The leather-like sample (composite 2) is slightly rigid, but the fibered composite is as highly flexible and malleable as parchment leather. Also, the less adhesion of the reinforcement fibre with matrix would speed up the biodegradability process at the material' end of life'.

Notably, despite the sensorial and technical quality, the perceived sustainability is a solid value-added in the experiential dimension of the material. The sustainability information can be communicated to users through the narrative of materials, including the resource origin, place of origin, developers, manufacturing process and the end-of-life state (biodegradability). However, the challenge is to formulate harmonic sync between the sensorial quality, technical quality and the biographical story to enable an engaging and pleasant experience in using the materials.

6.3 Manifesting Materials Experience Patterns

6.3.1 Understanding of How the Materials will be Used and Experienced

In conceptualising the material application, we foresee that it is feasible in packaging due to its technical, experiential and sustainability attributes. The product design experts speculated that users would have no repulsion towards the materials. They will perceive the control sample as wood bark-like or parchment-like materials, composite 1 as a natural fibre composite, composite 2 as a leather-like material, and the film as a wax paper. Meaning they are familiar with the sensorial properties of the materials, especially the visual and tactile. Furthermore, the design experts appraised the crafty look of composite 1, which resulted from the fibre reinforcement as beautiful, natural, and suitable for wall finish. Meanwhile, the leather-like composite 2 material is versatile for leather goods such as wallets, keychains, bags and purses.

The design experts expressed diverse visions on the film sample. Its flimsiness, imprinted patterns, and translucency were associated with rice paper, flat noodles, gift wrappers, lampshades and *wayang-kulit* (shadow puppets). Notably, the predicted vast area of application for the material is in the packaging industry. Due to its properties, the film is feasible for inner packaging, food packaging, filler packaging, edible packaging and food safe wrapper.

The designed materials in this project are cost-effective and utilise easy up-scalable production techniques. Notably, local feedstocks can be used as the growth medium and substances of the materials. Hence, it is feasible to manifest the production of the materials in Malaysia as the small and medium enterprises (SMEs) are the backbone of the manufacturing industry. Also, there is an emerging cluster of microenterprises consisting of young designers and independent product makers. Such stakeholders could further develop and commercialise the materials, either for everyday functional product application or as a medium for creative and artistic exploration.

6.4 Designing Product Concept

6.4.1 Packaging Design Proposals

Based on the previous three steps of MDD, the researchers have envisioned three packaging concepts for the three bacterial cellulose materials. The proposed concepts took advantage of the experiential and technical qualities of the materials. While the main aim is to solve the fundamental problem of the wasteful and negative impact of mass plastic and paper-based packaging, the researchers also intend to support a counter-movement of artisanal making or craft industry. Hence, the proposed packaging design adopts a simple and effective manufacturing process

The embodiment of bio-based materials in such products is central to the contemporary conversation about environmentally aware consumption. Consumers are becoming more eco-conscious in Malaysia, and companies are beginning to see that sustainability makes sense economically. It is also an asset that helps to leverage a responsible brand image.

The following Figures show the proposed packaging design made of the designed materials. The packaging concepts for the material samples are as follows:

1) Biocomposite 1- Gift box
2) Biocomposite 2- Biscuits and pastries serving box, fruits bag, soap sleeve packaging
3) Biofilm- Alternative' bubble wrap'.

Figure 6: Proposed packaging design: (a) gift box, (b) fruits bag, (c) alternative 'bubble wrap', (d) biscuits and pastries serving box.

7. DISCUSSION

The novel output materials for this project are two variants of bacterial cellulose – plant fibre-reinforced composites and a bacterial cellulose film. At a glance, the first composite may be perceived as a natural fibre composite, a combination of plant fibre as reinforcement and a natural binder as the matrix. The second composite is potentially be seen as a leather-like material. On the other hand, the film can be considered as a thick baking sheet or rice paper. However, upon initial interaction or close examination with the three materials, they can be appraised as parchments with paper-to-leather characteristics. The plant fibre reinforced composites feel rough, and they make slight rustling when folded. Notably, the composites' uneven thickness, 'stain' colours, abstract pattern of veins, subtle scars and bruises, and shrunken surfaces evoke natural meanings. The surface of the film is silky smooth but structurally stiff. The imprinted texture on the material's surface brought the meaning of 'manufactured' hence elevating the perceived robustness of the material.

In terms of technical qualities, by nature, bacterial cellulose is hydrophilic. However, although it has a strong affinity for water, the material stays intact, and the surface layer of the material is hygroscopic (not easily dissolved by water). Therefore, oil or wax treatment helps to control the water-vapour permeability. Also, the reinforcement of plant fibres, including the types and techniques of incorporation, is a novel finding of this research. Less adhesion between the plant fibres and the matrix contributes to the flexibility and biodegradability rate of the material.

Based on the experiential and technical qualities of the designed materials, the researchers deem that the materials are feasible to be used as packaging. Notably, the unique main character of the materials is that it is more robust than paper and do not last forever as plastic. Moreover, the desired technical qualities of the materials can be controlled during their growth process. For example, for more structural packaging, rigid and brittle fibres can be incorporated. Also, a thin and untreated version of the material fits for fillers or plastic wrap-like packaging, of which the materials' lifespan can be shortened for sustainability.

Another significant sustainability aspect of the bacterial cellulose material is the potential to establish a network of local stakeholders that develop and utilise the materials. For example, universities or research centres can provide the 'blueprint' of the materials. Then, start-ups, micro-enterprises or craft companies can cultivate the materials, using growth medium from much by-production waste such as used coffee and tea powder from cafes and restaurants in Malaysia. Similarly, reinforcement fibres can be obtained from food industry waste. Finally, the finished materials may be passed to third parties producers to turn the materials into products. Such stakeholders are part of the material's story. Narrating the biography of the material to the consumers would elevate the perceived value of the materials. Expectedly it will create an engaging material experience, more appreciation of the material and ultimately lead to progressive uptake of sustainable materials in the local market.

Nevertheless, expansion of approaches within each step of MDD can lead to product diversification. Future investigations are necessary to validate the experiential and technical properties of the materials. Apart from commercialising the materials as packaging products, we believe that future research could look for crafts and creative applications. For instance, the materials can substitute mengkuang or bemban to be weaved into everyday items such as baskets, containers, and lampshades. Also, future research is needed to understand how users' perceptions change when the materials are applied in different types of products.

8. CONCLUSION

An approach gaining popularity among product designers and material developers is called Material Design Driven (MDD). The framework offers a systematic step to qualify materials in terms of their technical and experiential qualities. Such an approach assists designers in developing novel and non-mainstream materials, aiming to embed desirable characteristics to the designed materials. Importantly, it triggers material's sustainability consideration as projecting how the material will be used and experienced is a prominent agenda of MDD. In this project, the researchers have produced three types of bacterial cellulose materials, i.e., composites and film, proposed to be used as packaging materials. It is anticipated that the 'parchment' or 'paper-leather'-like characteristics of the materials provide advantages in product protection, sensorial experience and meanings. The materials potentially can be developed by small and medium enterprises and the crafts industry in Malaysia as the cultivation process is not complex. Additionally, waste materials are the primary resources used in the materials' cultivation. Further improvement of the material variants by expanding the approaches of MDD would unfold new dimensions of the material characteristics and applications.

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AUTHOR CONTRIBUTIONS

The three authors are experts in sustainable materials and product design. The first and second author developed the materials, conceptualised and conducted the experiments. The third author helped to perform the experiential studies. All authors discussed the findings and contributed to the final version of the manuscripts.

CONFLICT OF INTEREST

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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