Exploring the design applications of key emerging materials from natural sciences through a design ideation workshop

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The design direction is shifting towards new design landscapes with alive and adaptive aesthetic features and functions and confronting natural alternative designs. Designers, architects, and artists have proposed the exploration of emerging materials by exploiting synthetic biology, bionics, chemical technology, and material science to create new design alternatives with natural aesthetic features and functions. In practice, however, designers are not properly familiar with the potential applications of these emerging materials and their alive and adaptive aesthetic and functional features in product design. Thus, particularly in traditional product design development, the applications of these materials are untouched resulting from three hindering factors. First, knowledge regarding potential applications of emerging materials for product design is lacking. Second, designers' creativity is restricted because they are not able to disconnect from established product design solutions. Third, the current product design scope does not allow designers to go beyond traditional product design processes. The present study conducted a design ideation workshop by employing a design-led problem-solving process with eight design graduate students from product design and intelligent system design majors. The purpose of the workshop was to explore the three factors and understand the requirements, constraints, and opportunities for new product design concepts with alive and adaptive aesthetic features and functions by exploiting and integrating emerging materials from natural sciences into product design.

Keywords: emerging materials; alive and adaptive feature and function; aesthetic creativity; product design

1 Introduction

Designers, architects, and artists have proposed the use of synthetic biology, chemical technology, living technology, biotechnology, and bionics to examine and utilize natural materials for new design opportunities (Speck et al. 2015; Tokuc et al. 2018; Graeff et al. 2019). Some design researchers argue that new artistic ways of interacting with the users and their surroundings might emerge from the exploration of various materials in nature, material, and chemical sciences (Ceschin and Gaziulusoy 2016). They further added that the environmental and sustainable performance, together with its many input and output flows across its various life cycle stages, should inform the selection of these materials for assembly in the design of new products (Allione et al. 2012).

With the rapid development of science and technology in the early 19th century, two separate areas have been identified as ready for the new era of integration in the 21st century. Video art, which is a combination of art and science, is the best example of this integration. The MIT Media Lab, founded in 1985 by media scientists Negroponte and Wiesner, pursues the convergence of science and technology, and media art. It provides a visual and voice-based interface, digital broadcasting, and virtual reality in leading the field of cutting-edge convergence technology (Li et al. 2014). The smartphone, which has become a necessity of the day, has attracted the attention of consumers by securing aesthetics and functionality through the integration of art, science, and technology. Recent advancements in technology are the result of the complementary nature of science and technology—the realm of pursuing beauty through imagination and the pursuit of objective fact. In aesthetic creativity, beauty through imagination is pursued with an attempt to imagine with insight and intuition. Scientific creativity, on the other hand, tends to pursue truth rather than imagination. Thus, scientific creativity has yielded convergent and critical thinking abilities. The aesthetic design of digital media devices has enhanced the value of products by adding various forms of aesthetic creativity and attractive analog sensibility (Pagliarini et al. 2000).

The Bavarian Motor Works (BMW) has introduced an inspirational and futuristic design of geometry and functions in the 'N' adaptations concept for a car that has a shape-shifting fabric, allowing its shape to transform according to exterior conditions and car speed (Allen 2012). The car not only has a lightweight body but a form of material intelligence that reacts automatically to its surroundings. The future of this astonishing atmosphere, where everyday artifacts behave as living entities, is a real ambient interaction experience between humans and artifacts. Because of the visual perception of aliveness and adaptiveness in this real interaction, various emerging materials that can make this prospect possible need to be explored for new product design development. Furthermore, this exploration will broaden the design space and guide design researchers and practitioners to a new horizon of design practice with aesthetic creativity and will open new design directions presenting new design landscapes confronted with natural alternative designs of alive and adaptive aesthetic features.

Given the importance and omnipresence of design integration in the future, it is important to research the potential applications of emerging materials and propose their integration patterns to create new product design opportunities. This study seeks to find plausible applications of emerging materials in natural science, chemistry, and materials science and their integration with product design. At present, designers are not sufficiently familiar with the potential applications of these emerging materials and their alive and adaptive aesthetic and functional features in product design. Until now, little research has been done on the exploration and integration of emerging materials from natural sciences into the product design domain. In traditional product design development, however, the use of emerging materials is untouched resulting from three hindering factors. First, knowledge regarding potential applications of emerging materials for product design is absent. Second, designers' creativity is fixated on certain aesthetic parts because most designers are not able to disengage from established product design solutions. Third, the current product design scope does not allow designers to go beyond established product design processes. To further explore these three factors, we conducted a design ideation workshop by employing a design-led problem-solving process with eight design graduate students from the product design and intelligent system design fields. The workshop intends to explore the requirements, constraints, and opportunities for new product design concepts with alive and adaptive aesthetic features and functions by exploiting and integrating emerging materials.

2 Key emerging materials in natural sciences

This section presents some of the key emerging materials from natural sciences and reports their potential applications in design. First is a thermoelectric (TE) paint (Park et al. 2016a) that converts heat flux into electrical energy. Conventional TE generators are made of solid-block shapes while TE paint is shape-engineerable and geometrically compatible with the surface of any shape (See Figure 1).

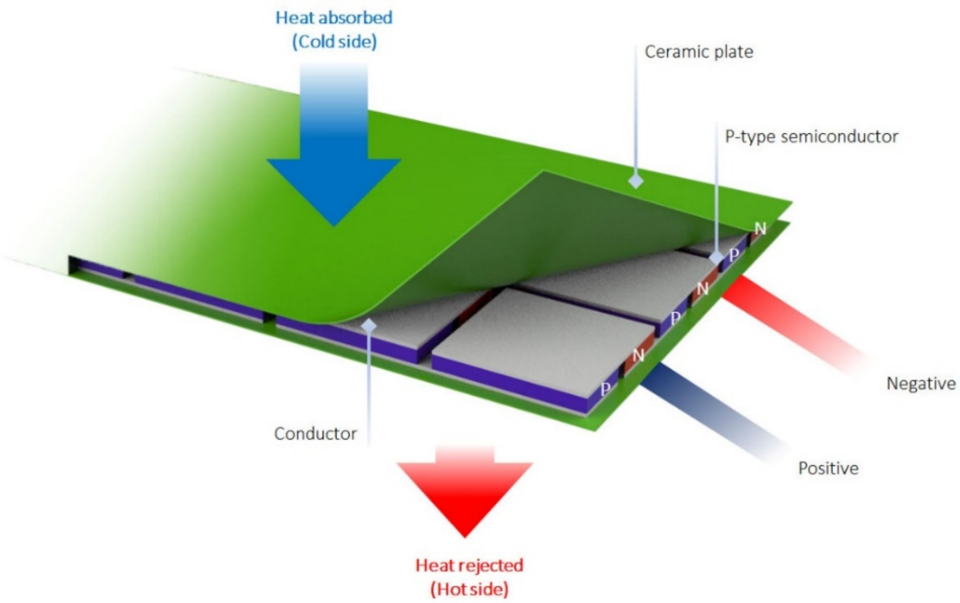


Figure 1. Structure of the Thermo-electric generating paint

Second, a printable secondary battery (Choi et al. 2017; Kim et al. 2015) that is easily fabricated through a simple, low-cost, and scalable printing process. It stores electric power produced by TE generators and uses it as a design feature, such as form factor, shape conformability, and its monolithic integration with other products (See Figure 2).

The third key emerging material is a conductive material used in printed electronic circuits that represent an emerging artistic electronic technology and a typical art activity embodying aesthetics. The scalable process of this thin-film printed circuit is achieved through the roll-to-roll (R2R) printing process (Noh et al. 2015) with a printable form of silicon and flexible thin-film transistors (Jung et al. 2015). Choi et al. (2016) introduced a new class of all-inkjet-printed solid-state malleable supercapacitors on normal paper with remarkable aesthetics for a printed electronic circuit. The printing process maximizes the technological functionality of printed electronic components, such as printed supercapacitors, transistors, and resistors that feature artistic patterns with other integrated power sources (See Figure 3).

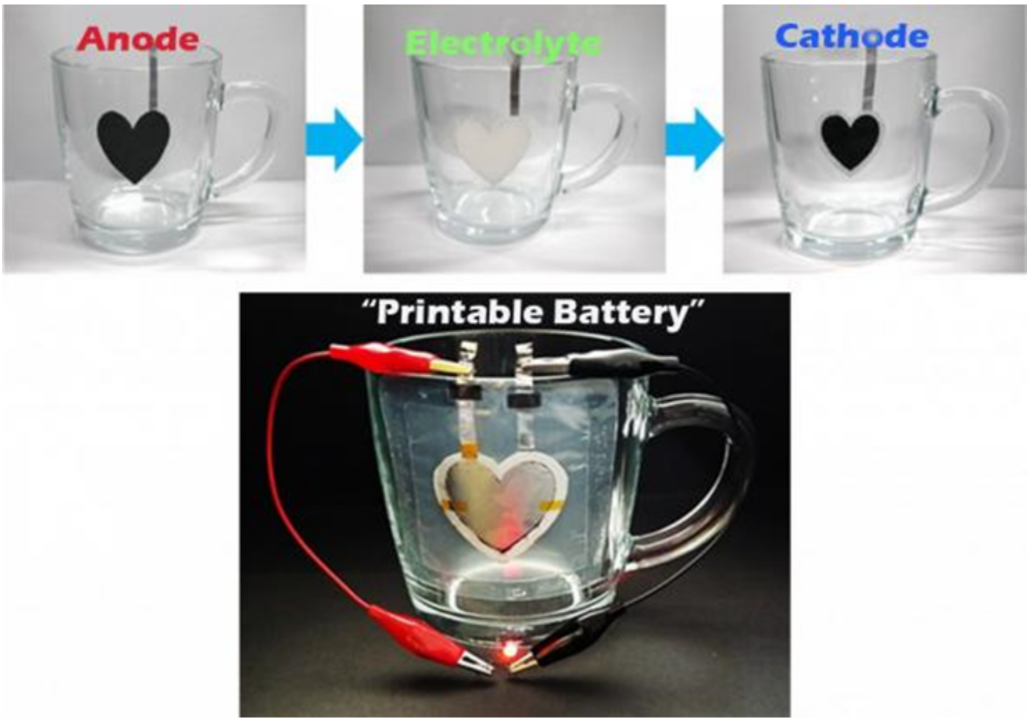


Figure 2. Energy storage paint for printed battery (Source: Kim et al. 2015)

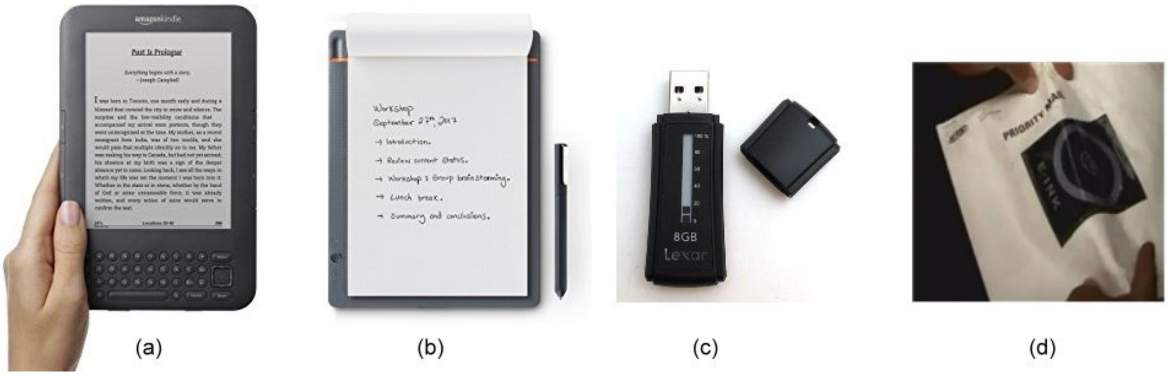


Figure 3. Printed electronic applications (a) Amazon e-ink-based eBook Kindle, (b) Digital notebooks using Wacom e-ink, (c) USB memory showing space with Lexar e-ink, and (d) Reusable and addressable e-ink envelopes

Fourth, a color and texture-changeable electronic paint that is used as an aesthetic element in display terminals. This is designed using electromorphic, photochromic, and electrochromic materials. The combination of these materials provides color changes over flexible photo switches amid two different states with distinct properties (Zhang et al. 2012). A reversible color shifting occurs upon electron flow if an electric current is passed through electrochromic materials (Mortimer et al. 2006). These materials offer enormous potential in the rapidly developing area of plastic electronics because of their flexibility, low power consumption, and ease of processing. They are utilized in anti-glare car rear-view mirrors, sunglasses, smart windows, frozen-food monitoring, and light-reflective or light-transmissive displays (See Figure 4).

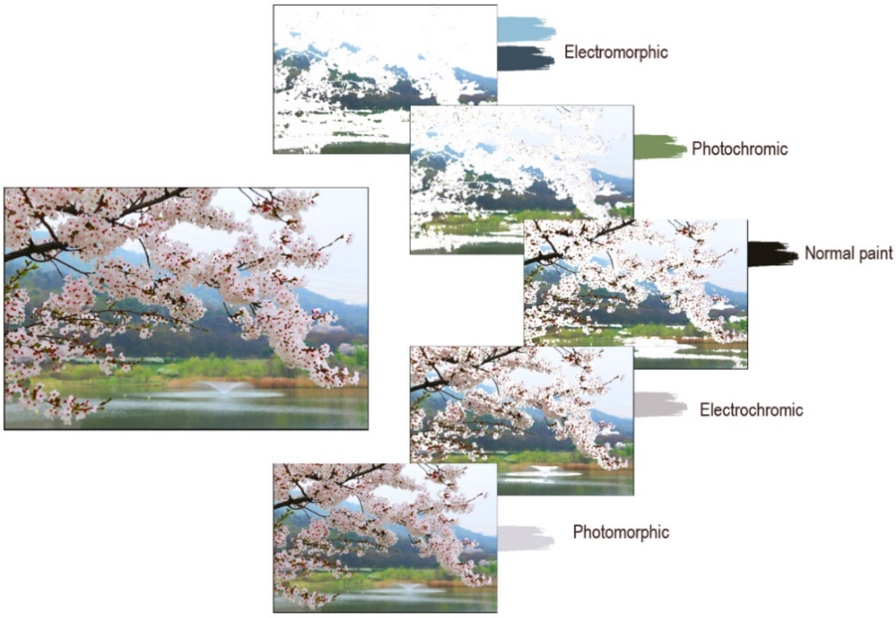


Figure 4. Electronic painting using morphic and chromic techniques

The fifth emerging material is the living bacterial material in biotechnology with various bio-inks to harvest functional composite materials using 3D-Printed Bacterial Minifactories (Kyle 2018). These materials show huge potential in bioremediation, sensors that can sense toxic substances, and wound plasters in medical settings. The fabrication procedure of the living materials using 3D-Printed Bacterial Minifactories is shown in Figure 5 below.

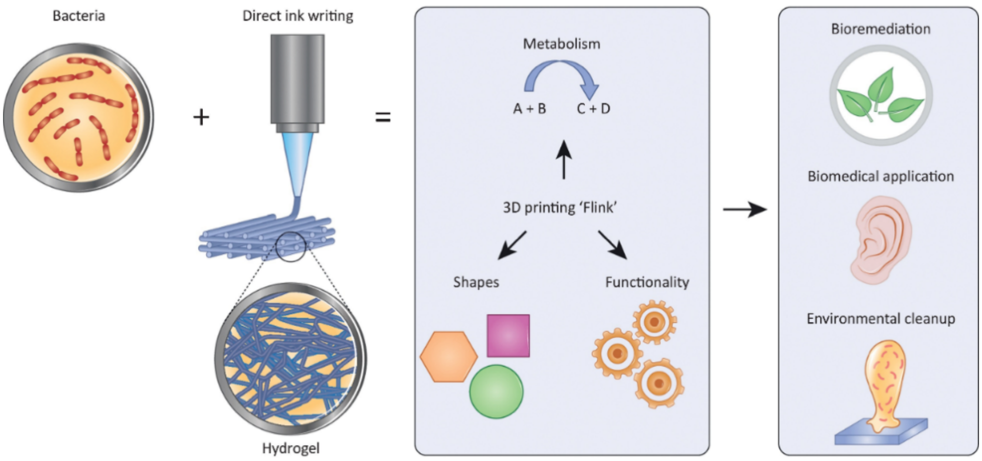


Figure 5. Fabrication procedure of living materials and their applications (Source: Kyle 2018)

The above materials are promising for sustainable and aesthetic performance in product design and their use is immensely prevalent in the design area. However, the applications of these materials are still beyond the scope of designers' objectives. In addition, each material has its conventional use and futurity in its area. For example, TE paint is used on the object's heated or frozen surface to control heat loss. Printed batteries are used to store electric power. Printed electronic circuits are used to replace currently present circuits. Electronic paints are used in liquid crystal display (LCD), organic light-emitting diode, and thin-film transistor (TFT) screens. 3D printing of bacterial minifactories materials has its conventional use in biomedical applications.

3 Design approach

We arranged a design ideation workshop by employing a design-led problem-solving process put forward by Stempfle and Badke-Schaub (2002). The purpose was to explore the three basic factors that hinder designers from using and applying emerging materials from natural sciences in product design. The first factor is a lack of knowledge of emerging materials on design applications. The second factor is the designers' lack of intention and motivation to go beyond the established product design solutions. The third factor is the current scope of product design, which is limited to the traditional product design processes. The design-led problem-solving process consists of three basic constructs: analysis, ideation, and assessment. In the analysis construct, the focus is mainly on the design problem, and considerating the requirements, constraints, and opportunities for a design solution. In the ideation construct, an emphasis is made on the design solution, producing ideas and creativity. The assessment construct focuses on the evaluation, justifying and linking, and synthesizing the design ideas or solutions. According to Knight et al. (2019), these constructs are accountably distinct but contribute to moving from an unstructured design problem to a feasible design solution.

We applied the three constructs with three sessions in the design ideation workshop: an analysis session, an ideation session, and an assessment session. Before commencing the sessions, our design team reviewed and identified key emerging materials from natural sciences literature. Second, we conducted a study visit to two local institutes' science laboratories, mainly material science, biological science, and chemical science. The purpose was to observe and understand emerging materials for their structure, features, and applications. Third, we prepared a list of key emerging materials from the literature review for participants' inspiration in the workshop. The following subsections guide the detailed process of the workshop.

3.1 Procedure and participants

The workshop was conducted in a design workshop laboratory setting at our institute. The workshop lasted for two to three hours and commenced with male and female design graduate students (n = 8) who majored in product design and intelligent system design. All participants were given a brief introduction for 10 - 15 minutes concerning the challenges in identifying and understanding key emerging materials and producing their potential applications in product design. The facilitator of the workshop distributed a list of key emerging materials along with their features, structure, and conventional applications to the participants (See Table 1). They were given 10 minutes to read from the list and choose one or two particular materials for consideration in design. Besides, the facilitator provided images of these materials on wall posters. Subsequently, the facilitator asked the participants to start brainstorming activities. These activities were divided into three main sessions: analysis, ideation, and assessment.

Table 1. List of the key emerging materials

Material	Feature	Structure	Conventional use
Thermoelectric generating paints	Absorb light of a wide spectrum to convert it into thermal energy	A CMYK color-based paint produced through an inorganic pigment and combined with TE elements	Generate energy to reduce heat loss on a curved heat source where conventional TE devices failed to reduce heat loss

Printable batteries and energy storage paint	Energy storage paint for secondary batteries, such as Lithium-ion to store power from TE generators	Stencil printing process, electrolyte filling pore space, lithium-ion, active material, and conductive additive binders	A reliable and scalable battery with a shape and aesthetic adaptability as conventional rechargeable batteries retain size and shape limitations
Printed electronic circuits	Printed circuit with a thin coating of conductive material	Inlet ports, capacitive sensors, microheaters, and electrowetting electrodes	For flexible and wider surface applications, especially plastic electronics
Flexible pressure sensors	Transduce exterior pressure from compression into electrical signals	Flexible substrate, sensor array, series capacitor, a source-drain electrode, and a gate electrode	Applied on flat surfaces to get more accurate data
3D electro chromic soft photonic crystals	200-micron thick material that combines force-changing color for thermal radiation management	Nanostructured materials with RGB colors, polymer and MXene	Color adaptability in visible and infrared regions
3D printing of living functional bacteria	A multi-scale material combining self-healing and organism adaptability with physiochemical properties	Living bacteria in direct ink writing with hydrogel using metabolism	Bioremediation, biomedical applications, and environmental cleanup

3.2 Analysis session

In this session, participants were asked to focus on the problem to understand the requirements, constraints, and opportunities of applying emerging materials in product design. They were asked to share their opinions openly during the workshop. The participants were asked to focus on the following key points to understand the current problems with the use of the materials.

1. The channels of accessing and approaching the key emerging materials from the list
2. The shortcomings and obstacles in applying these materials in product design
3. Interesting and satisfying features do these materials have that could be applicable in new product design
4. Emerging materials have complex structures that prevent their integration with product design
5. The relationship between the innovative transformation of product design and the iterative development of new materials
6. Designers' previous experience to incorporate emerging materials into product design projects
7. Emerging materials impacting the field of material science in the coming years could then provide channels to access these materials by designers
8. Emerging materials currently being used in material science can be integrated with the product design development
9. Designers' information about currently ongoing research projects that investigate the use of emerging materials in product design
10. Advances in material science impact the development of new technologies and processes for product design

11. A recent breakthrough in materials science and its implications for various fields, especially product design.

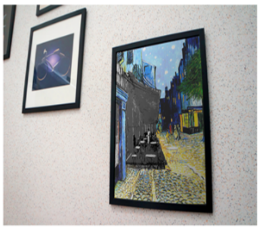
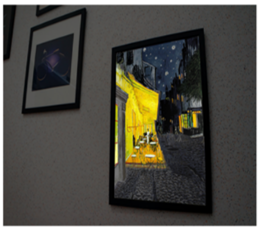
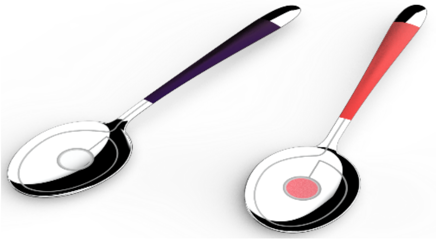
3.3 Ideation session

After a thorough discussion and brainstorming in the analysis session, participants were provided with a few concept designs that our design team prepared for the workshop (See Figure 6). Our design team showed these concept designs in which different emerging materials were conceptually integrated to shape a product with alive and adaptive aesthetic features and functions.

Figure 6. Concept design examples and their explanation

These concept designs are explained in Table 2 below.

Table 2. Concept designs of products with alive and adaptive aesthetic features and functions

Concept	Material Composition	Concept image
A bowl design that provides food contamination information	Printed electronic circuit with organic RF tags and flexible universal NFC circuit	 
A reactive photo frame design with alive color/texture changeable frame design (daytime design and design for the dark)	Light luminance displays and electronic painting with photo-morphic, electromorphic, and electrochromic polymers	 
An alive and adaptive spoon that detects food composition and temperature information by changing its handle color	Color and texture changeable materials, printed circuit, and printed battery	

RF edible toast to preserve it from contamination	RF and NFC tags/sensors with edible Graphene	
Alive and adaptive ambient display on the walls with color/texture changeable features based on outside weather	Color and texture changeable materials, photomorphic materials and printed electronic circuits, and TE paint	
Reactive car steering surface with color and texture changeable features for rough, bumpy, and smooth road tracks information	Printed electronic circuit, printed battery, flexible sensors, GPS connection, and electrochromic polymers	

After a detailed discussion on concept designs, participants were asked to choose a material from the list of key emerging materials (See Table 1) and propose a potential application that can be applied to a new product or an existing product design. Participants' activities and discussions for idea generation during the ideation session are presented below in Figure 7 as an example.

Figure 7. Participants' activities and discussions for idea generation during the ideation construct

3.4 Assessment session

In the assessment session, participants were asked to assess the key emerging materials and their limitations for design applications. In particular, they were asked to describe the challenges faced by designers while dealing with emerging materials and restrictions based on their structure and features that hurdle the product design process. They were further asked to envision the future of product design with alive and adaptive aesthetic features and functions influenced by the development and availability of emerging materials from natural sciences.

Each participant followed a different process and produced a different type of output. They mainly followed their brainstorming with discussion sessions and then initiated work in collaboration with other participants on the solutions. The participants' activities in all the sessions, including analysis, ideation, and assessment are shown in Figure 8 below.

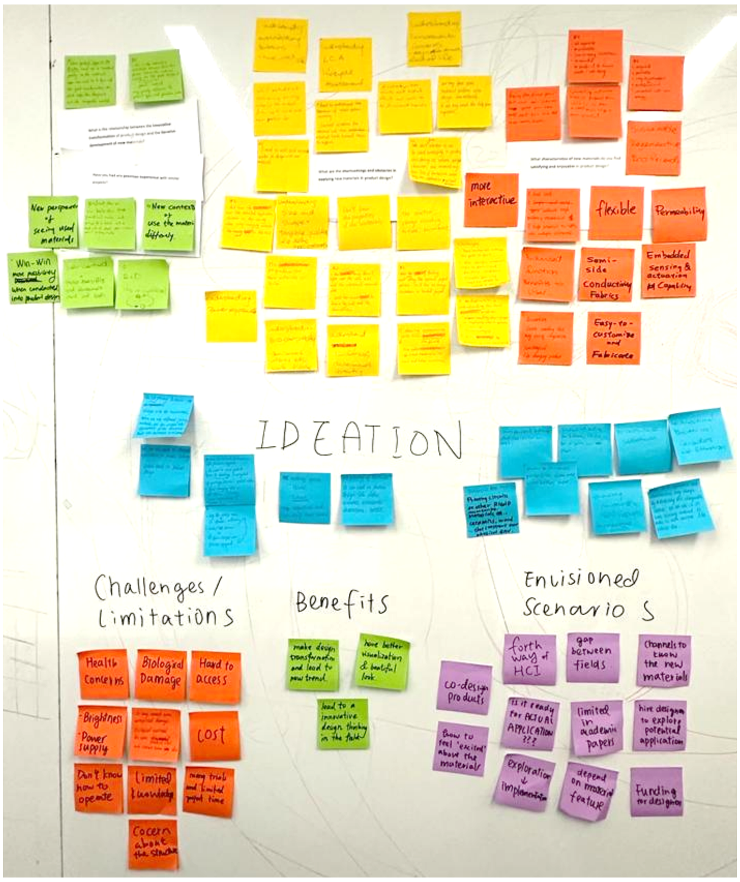


Figure 8. Participants' activities and responses in all the three sessions

4 Results and design insights

4.1 Results of the analysis session

In this session, the participants presented their views on the application of emerging materials in product design, including channels of access to new materials, deficiencies and barriers in applying new materials in product design, aesthetic and novel features of new materials in product design, and the relationship between novel product design transformation and the iterative development of new materials for product design. Based on participants' views, the main obstacles and shortcomings in the design applications of the emerging materials are as follows:

- From the actual project investors' point of view, the use of new materials in design projects may have time and investment constraints due to which there are chances of massive failures and delays in the project schedule.
- From the project manager's perspective, the use of new materials often requires additional employees with expertise in hardware and related technology, which adds personnel management costs.

- From the designer's point of view, there is a need to acquire alternative technologies and procedures to handle the materials to minimize perceived limitations in different conditions of the new materials while fabricating products. Most products have a high degree of interaction with the users and there is direct contact between the product material and the human body. If designers have limited knowledge about the composition of the materials, the chances of the hazard caused by these materials are even more critical. Thus, the materials from science labs used in product design can pose potential risks to human health and safety. For example, nanotechnology can have unknown or unintended effects on the biological systems of the users or the environment. New materials can be expensive or inaccessible to some groups of individuals, creating a material divide. These materials can also disrupt existing product industries or markets that rely on common raw materials, causing unemployment or unfair competition. In addition, materials with alive and adaptive features and functions can also harm the environment or other living beings. For example, these materials may consume natural resources, generate waste, or discharge hazardous gases and may also affect the welfare of animals or plants that are used as sources or affected by their production processes.
- Designers also need to consider the challenges and limitations of applying new materials in product design, such as higher costs, limited availability, technical complexity, or environmental concerns. Therefore, designers need to carefully evaluate the benefits and trade-offs of using new materials for their product design projects based on various criteria such as functionality, aesthetics, sustainability, and user needs and requirements. Overall, the use of new materials in product design projects faces high costs and unknown hazards, making their implementation in the field challenging.

Participants reported the following main characteristics of new materials with aesthetic and novel features in product design:

- Applying emerging materials in product design can reduce the environmental impact of products by replacing more polluting or resource-intensive materials such as plastic, concrete, or leather materials. For example, seaweed, mycelium, and latex are some of the natural materials that designers can use to create more biodegradable and renewable products.
- Emerging materials can create new possibilities for product innovation by enabling new forms, functions, or interactions and improve the performance, efficiency, or durability of products by offering superior mechanical, electrical, or thermal properties.
- A product design composed of emerging materials from natural sciences can improve the performance and functionality of the products by using materials that offer superior properties, such as strength, durability, flexibility, or responsiveness and reduce the manufacturing costs and material waste of their products by using materials that are lighter, more efficient, or more sustainable. For example, a lightweight product design makes an object weightless without compromising its strength or performance, which can save money and energy.
- Employing new materials with alive and adaptive aesthetic features and functions in product design can create new possibilities for product innovation and differentiation by using materials that offer novel aesthetics, interactions, or experiences and enhance the

environmental and social impact of their products by using materials that are biodegradable, renewable, or circular.

The participants' output in the analysis session is presented below in Figure 9.

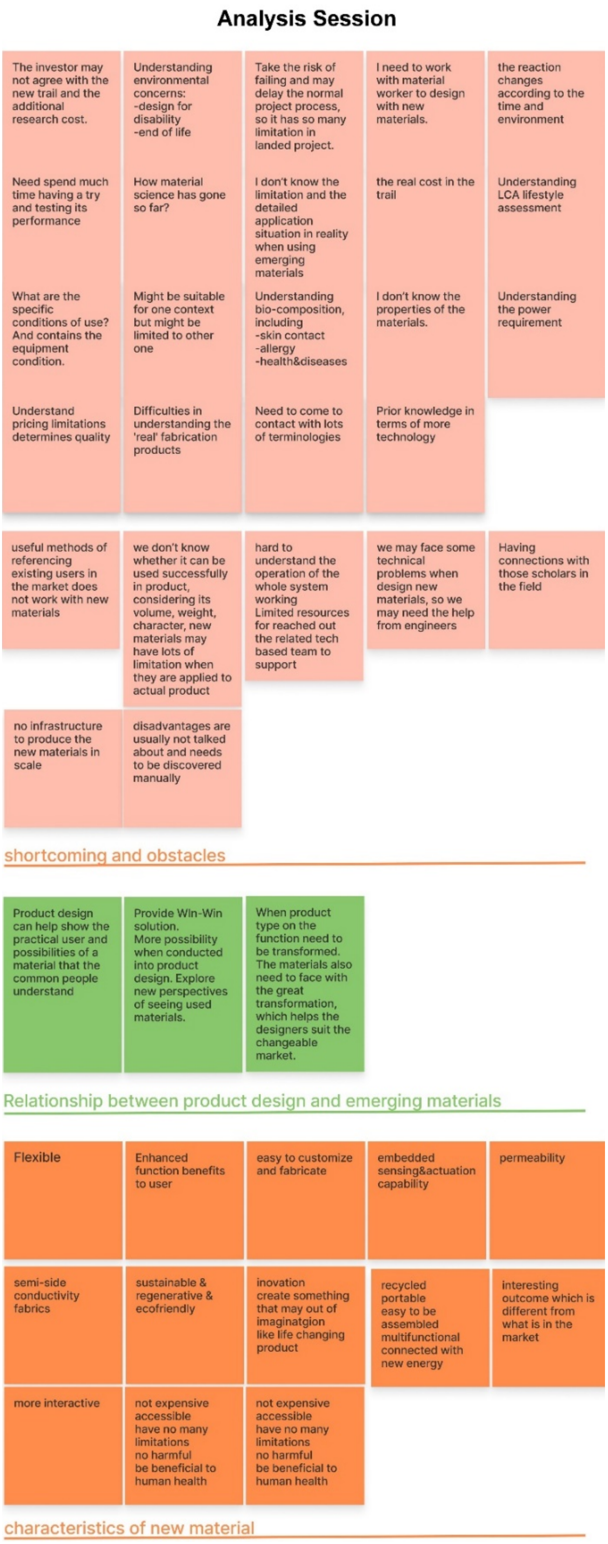


Figure 9. Analysis session output

4.2 Results of the ideation aession

During the ideation session, participants shared their views on the potential applications of various emerging materials and considered their advantages and disadvantages in product design. The participants mainly chose the following materials and their possible design applications.

4.2.1 3D printing of bacteria

Participants suggested various innovative applications for the 3D printing of bacteria. One example of a structure with self-repair and regenerative growth capabilities might involve incorporating bacteria into concrete to create a "bio-concrete" that could heal cracks as they are formed thereby increasing the structure's durability. Bacterial facades for purification could be employed in urban settings, where living walls of plants and microorganisms work together to purify the air and combat pollution. For microbiome substrates, 3D-printed bacterial structures might be used to change personalized probiotics tailored to an individual's specific health needs. In the realm of automation, sensory materials rooted in bacteria could allow advanced prosthetic extremities that provide users with sensitive wisdom of touch. Finally, in fashion design, bacteria-infused cloths could change color or yield fragrances in response to environmental factors, creating dynamic, customizable fashion design features.

4.2.2 Flexible pressure sensors

Participants proposed flexible pressure sensors for use in home-based smart service systems. For instance, these sensors could be embedded in furniture, carpets, or appliances to monitor and respond to users' movements and behaviors. A smart mattress could mechanically regulate determination based on a user's sleeping position, while a smart carpet could detect a situation in which a person has fallen and send an alert for assistance. However, potential drawbacks include privacy concerns regarding the collection of personal data, technical issues related to sensor accuracy and integration, and the possibility of overreliance on technology.

4.2.3 3D electrochromic soft photonic crystals

Participants generated ideas for the use of 3D electrochromic soft photonic crystals with various applications. For example, stress-relief toys made from these materials could change color when squeezed, providing visual feedback and promoting relaxation. Flexible AR devices, such as smart glasses or contact lenses, could incorporate these crystals to display information or notifications directly to the user's field of view. In the realm of fitness, force change color equipment could help users envision their energy levels, providing motivation and helping to ensure proper exercise form. However, challenges such as breakage risk, material durability, and technical difficulties in producing and integrating these crystals must be considered before their design applications.

4.2.4 Printed batteries and energy storage paint

Participants suggested printed batteries and energy storage paint for several design applications. For example, aesthetic integration into product design could involve incorporating printed batteries into glossy and unobtrusive shapes that blend flawlessly with the design of electronic devices. Disposable products, such as single-use medical devices, could be powered by these batteries, ensuring a consistent and reliable energy source. Large-scale energy storage could be achieved by creating a grid of small printed batteries, which could be interconnected to store and distribute energy from renewable sources. Despite their innovative and versatile nature, challenges such as proper disposal, environmental impact, and implementation hurdles need to be addressed during the product design processes.

The results of the ideation session are presented below in Table 3.

Table 3. Results of the ideation session for materials usage and their potential applications, benefits, and drawbacks

Material	Application	Benefits	Drawbacks
3D Printing of Bacteria	Self-repairing structures	Innovation	Health concerns
	Bacterial facades for filtration	Sustainability	Material durability
	Microbiome substrates	Adaptability	Complex implementation
	Sensory materials for robotics	Customization	
Flexible Pressure Sensors	Fashion design	High responsiveness	Privacy concerns
	Home-based smart services	Convenience	Technical issues
Three-Dimensional Electrochromic Soft Photonic Crystals	Stress-relief toys	Adaptability	Overreliance on
	Stress-relief toys	Versatility	Breakage risks
	Flexible AR devices	Interactivity	Technical difficulties
Printed Batteries and Energy Storage Paint	Force change color fitness equipment	Potential for recycling	Implementation challenges
	Aesthetic integration into product design	Innovative	Environmental concerns
	Powering disposable products	Versatile	
	Grid of small batteries for large-scale	Potentially sustainable	

By focusing on the potential design applications of each material, the ideation process enabled participants to explore diverse opportunities for product design and share their insights. The exchange of ideas between the participants broadened their understanding of the opportunities offered by emerging materials and technologies, inspiring further innovation and creativity in their respective fields. Figure 10 illustrates the participants' output in the ideation session.

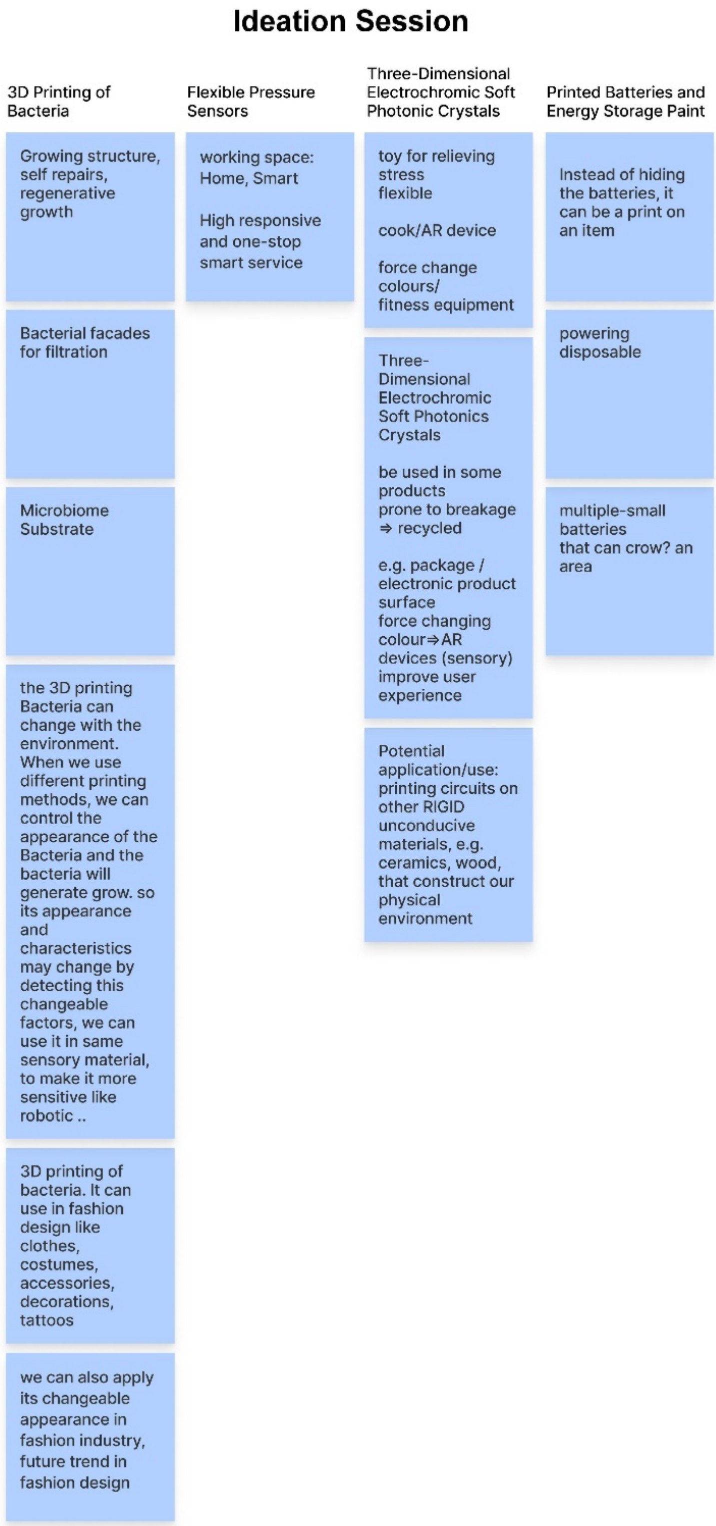


Figure 10. Ideation session output

4.3 Results of the assessment session

The results of the assessment session are divided into limitations, benefits, and envisioned scenarios of key emerging materials with their design applications. Figure 11 illustrates the participants' output during the assessment session of the workshop.

4.3.1 Limitations

Emerging materials have great potential in the integration with design for the functional advantages into product design but several risk factors associated with these materials cannot be resolved without proper knowledge or the lack of personnel who are experts in handling such materials for design applications. For example, materials that have health concerns cannot be taken into account without specialized expertise. Designers may require to develop certain expertise related to the materials or co-create with scientists from the materials fields. Sometimes designers face a complex design situation or scenario where they have a lack of understanding, they work with professionals in other fields over time to understand its working principles. Both cases may require cost and time to understand the potential application of a material and its integration into product design. Although designers need time to access relevant knowledge, the limited time and cost constraints of the design project may not support designers' co-creation activities with material scientists and professionals in other fields.

4.3.2 Benefits

Integrating emerging materials into products is a good way to initiate co-design and innovation in the product design field. Designers may need more opportunities to have discussions with materials scientists and increase the time taken to explore multiple perspectives in product design. If the product type based on the features and functions needs to be transformed, the materials also need to face great transformation, which may ultimately help designers suit the unpredictable product market trends. If the materials industry has great developments in providing various design applications, both the products and materials may greatly influence the product types and presentation patterns. There is a need for a platform that can support designers' and material scientists' co-creation initiatives and to better connect to their mutual resources. This co-creative and co-design environment will achieve a win-win situation leading to the design and emerging materials transformation and new trends in product design because designers have the know-how to design products with the human or environmental experience that will be the most convenient and aesthetically pleasing design situation.

4.3.3 Envisioned scenarios

Participants shared their expectations of engaging more designers to explore potential design applications and co-design situations for products with innovative and aesthetic features and functions. They further added that these design opportunities could also benefit the human-computer interaction areas that could be combined with these emerging materials, such as printed electronic circuits and sensors to generate innovative future scenarios. For example, how the highly responsive fabric force sensors can work on a smart home and smart office areas through hand motion sensing for operation commands.

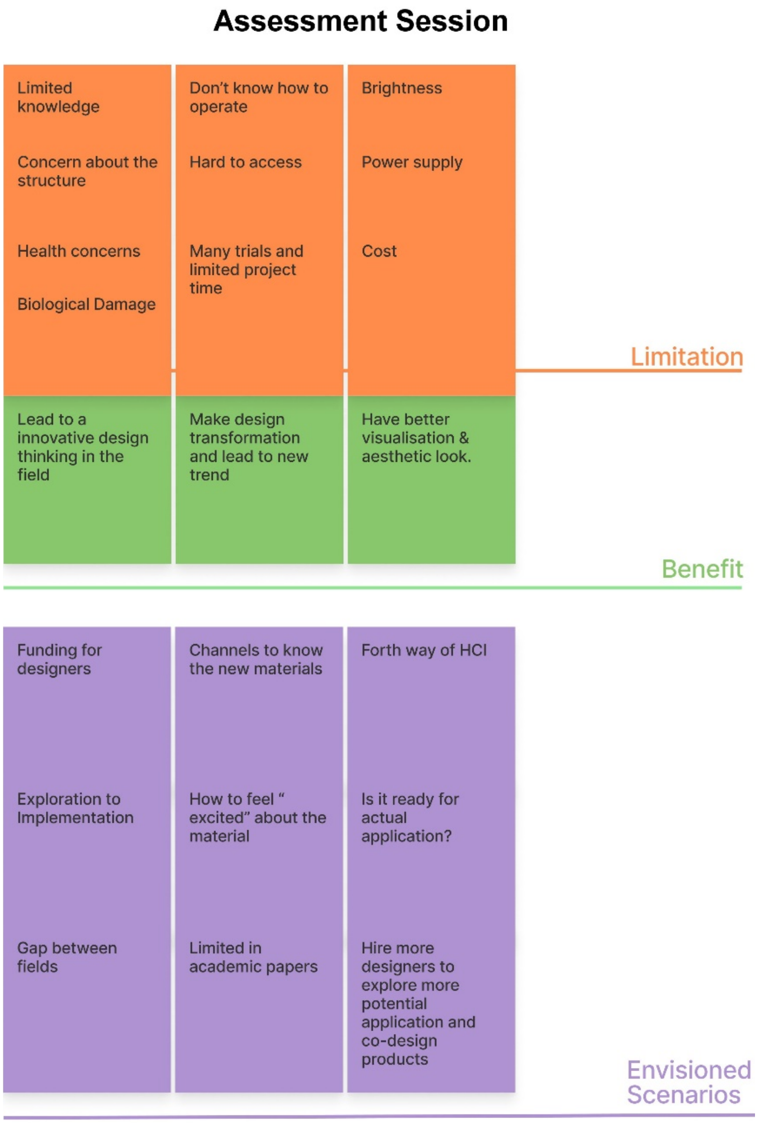


Figure 11. Assessment session output

5 Conclusions and design impacts

This study intended to conceive design applications of key emerging materials in natural science, chemistry, and materials science and opportunities for design integration. In traditional product design situations, the use of these emerging materials is neglected due to a lack of knowledge of their potential design applications. Designers usually focused on certain aesthetic parts using established product design solutions because of which the product design scope is limited to its traditional design processes. This study explored these hindering factors through a design ideation workshop with eight design graduate students by employing a design-led problem-solving process. Therefore, the study's main contribution was to understand how these design students could apply the design-led problem-solving process with three main sessions: analysis, ideation, and assessment. These sessions explored the design problems, requirements, constraints, and opportunities for design applications. In particular, the analysis session explored the channels to access emerging materials, deficiencies, and barriers in applying these materials in product design. Furthermore, the aesthetic and novel functional features of these materials in product design were also explored. The ideation session revealed various potential design applications of key emerging materials along with their advantages and disadvantages in product design. Finally, the assessment session demonstrated the limitations, benefits, and envisioned scenarios of the key emerging materials and their future design applications. From these sessions, we concluded that designers are highly required to expand their understanding of handling emerging materials to improve novel aesthetic and functional features in product design. Owing to the unique structure, features, and properties of these emerging materials, designers could bring new product experiences with alive and adaptive aesthetic creativity to the product design. There is a need to develop a platform that could encourage collaborations and co-creations between design teams and scientific laboratories. In general, these laboratories produce various emerging materials, such as artificial materials, ceramics, metals, glass, polymers, and semiconductors that could be highly required in products. Because most of these materials have their conventional applications in particular areas. Designers cannot deal with products of these materials alone because it is difficult to manage their functional features in terms of interdependencies between the appearance and interior design of the products. Handling such materials for product design will enhance the role of designers as the creator of technology instead of their traditional role of designing conventional products.

The availability of emerging materials with various design applications is pervasive in our future design experiences. New forms of product designs with alive and adaptive aesthetic features and functions will open new design landscapes which will promote the technical and aesthetic dimensions of the composition of emerging materials for interdisciplinary education in design. Products with alive and adaptive features and functions prevailing in our environment will allow the adoption of material-based design that will encourage future iterations of products bearing no resemblance to available conventional products. Based on the thorough review of current emerging materials, we assumed to develop a single alive composition that could be adaptive to our surroundings. At this point, an alive composite means a design with energy generation, consumption, and conservation for its own use, and one that can possibly interact with the outside world, such as a user, adjacent peripheral systems, or the environment for various applications. Based on the foregoing, the presence of the system will be autonomous in nature and reside on a single surface, which is different from conventional systems that rely on three-dimensional (3D) objects. We conceptualized a design by integrating emerging materials to redesign a surface into a living object in a 2D design.

In our future study, we will conduct various field studies and co-creation workshops with scientific laboratories to explore further design applications of emerging materials and address the limitations and constraints of applying and integrating these materials in product design. These workshops will be supported through theories and frameworks in problem-solving areas to provide detailed insights into the applications of emerging materials in complex design problem situations. In addition, we will explore the design applications of emerging materials in interaction design and ambient interactions, artistic representations, and architecture design fields. From these activities, our design team intends to formulate design principles for material-based design and design methodologies for co-creations with natural sciences for new product design experiences.

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