Sustainable materials in design projects

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Abstract

New types of sustainable materials are introduced in our markets every year to minimise the environmental impact of products. The search for more environmentally benign materials is crucial in reducing the depletion of non-renewable material resources. Recent literature indicates that there is a growing interest and rapid technological progression from various industry stakeholders on this matter. Nevertheless, the sustainability issues pursued by designers and other material developers are still ambiguous. The overall aim of this research is to develop new understanding of the sustainable materials being developed and applied in product design. Seventy-two material-centred design projects are analysed in terms of resource renewability and resource origin. The data obtained are further classified according to the material group and products produced with such materials. Renewable materials make up half of the materials used. Moreover, waste materials comprise up to half of the materials used. Three materials groups were found to be more frequently used, namely natural composites, synthetic polymers and organic materials. Most of these materials are being made into furniture, household objects and clothing and accessories. Within the natural composites and organic materials, various extraordinary materials were used, reflecting the dynamicity of designers' work and experimentation with materials. As for synthetic polymers, recycled plastics are the main materials used and this is not surprising given their abundance in the environment. In general, the application of sustainable materials seems to be at its infancy but explorations are vibrant and progressive. The impact of these materials in the mainstream market is unknown and other sustainability factors need further evaluation. As such, design as a discipline is yet to facilitate the uptake of these materials.

Keywords

Sustainable materials, sustainable design.

Every year millions of products are sent to landfills due to a throw-away culture. This rate of consumption will continue to grow, thus putting a strain on material resources and the environment (OECD, 2013). As a result, product developers have a growing interest in moving towards use of sustainable materials. Current initiatives to introduce sustainable materials are still in their early days with sustainability principles only starting to affect product development strategies. At a consumer level, while there is evidence that purchase decisions are influenced by companies' commitment to positive environmental impact, information made available to consumers on environmental friendly products remains limited and ambiguous (Brécard, 2014). For example, emphasis is placed on environmental and social attributes of products but the actual scientific proof of many claims is unknown (Hoek, Roling, & Holdsworth, 2013). Further to this, in a material context sustainability is dependent on many factors, which make any argument about the sustainability of materials complicated.

This research aims to characterise sustainable materials used in design projects and explore what products are being made with them. The results of this research reveal the breadth of materials developed and applied. The characterisation of materials proposed in this research is useful to improve the quality of the discussion on sustainable materials and particularly the sustainability argument made. Furthermore, this research helps identify distinct efforts to overcome the depletion of non-renewable materials and reflect on the emphasis and attention that these should be given.

Materials and sustainability

While global resources are further stressed by a push for faster consumption of short lifespan products (Rivera & Lallmahomed, 2015; Agrawal, Kavadias, & Toktay, 2015) and the rapid growth of developing countries (Fiksel, 2006) sustainability concerns remain in the fore. As Miller (1972) highlights, the critical boundary of resource consumption is beyond the shortage of reserve and includes the adverse impact on the environment. The sustainable use of resources (i.e. materials) then needs to be addressed if we are to realise the vision presented in the Brundtland Commission's report *Our Common Future*, in which current use does not adversely affect future generations (World Commission on Environment and Development, 1987).

The central theme of materials and sustainability is to minimise the adverse impact of materials to humans and the environment through well-planned management. However, even defining sustainability can be complicated since it is dependent on multiple stakeholders' views and contexts (Arroyo, Tommelein, & Ballard, 2016). For instance, the meaning materials convey changes with use and can lead to less favourable consumer appraisals or behaviours in terms of sustainability (Baxter, Aurisicchio, & Childs, 2015, 2016). It is also often too simplistic to regard certain materials as (un)sustainable as perfect data on the reserve of non-renewable materials is often difficult to obtain (Graedel et al., 2012). The result has been the development of several objectives and guidelines to move toward more sustainable use of materials. McDonough and Braungart (2002) have emphasised the need to manage material resources through efficient lifecycles including closed-loop processes in which waste is avoided. Ashby and Johnson (2010) have placed a time to this management suggesting that the timescale of sustainability concern should be fifty years into the future . Achieving these objectives is aided by the concepts of detoxification and dematerialization. Detoxification describes the attempt to reduce toxic materials used in material production or manufacturing processes, which includes the use of renewable resources for chemical substance (Weenen, 1995). Dematerialisation is concerned with the substitution of virgin materials with recycled materials, (Fiksel, 2006) and resource intensive materials with sustainably harvested and renewable materials (OECD, 2010) .

Assessment of sustainable materials is aided by several metric based tools that have emerged such as life cycle assessment and ecological footprinting (Robèrt, 2000). Typical considerations are environmental impact, resource efficiency, waste minimisation, life-cycle cost and performance capability. Some industries move beyond assessments to also place labels on products to try to communicate various types of sustainable solutions. For example, the textile industry features a host of eco-labels including: compostable, degradable, designed for disassembly, extended product life, energy recovery, pre or post-consumer materials, recycled materials, reduced energy, reduced water consumption and reduced use of resources (Targosz-Wrona, 2009).

Sustainable materials exploration

Designers are continuously tinkering to expand their knowledge and find new materials and manufacturing processes. In recent years, this activity includes the exploration of sustainable materials. This work is partly driven by the democratisation of knowledge and production technology (Rognoli, Bianchini, Maffei, & Karana, 2015; Mota, 2011) the output of which is an increasingly large category of 'DIY' materials (Rognoli et al., 2015). This is further facilitated through maker communities

(Thilmany, 2014). Importantly material research is 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) are also contributing to the dissemination of materials knowledge to the public.

Within design, materials with sustainable credentials are variously referred to as environment-conscious materials (Utsugi, Yiyin, Abe, & Shiraishi, 2007), materials with high sustainable potential (Rognoli, Salvia, & Levi, 2011) and eco-sensitive materials (Karana & Nijkamp, 2014).The difference between these terms is not always clear but the breadth of these terms is not altogether surprising since the area of sustainable materials is growing and is still divergent in thinking. Consolidating current work in this area into a general term in order to better understand the types of materials considered sustainable is central to the aim of this work.

One prominent theme found in the literature is the utilisation of abundant waste materials in new forms. Examples of this include: discarded wet blue leather remainders in the huge leather industry in Brazil used to produce oven gloves (Júnior, Cândido, & Guanabara, 2008); clay soil from rural areas in Spain used to make unfired-bricks for the construction industry (Miqueleiz et al., 2012); and *xylan* and *mannan*, widely available from the side-streams of agriculture and forestry and used to make sustainable packaging products (Mikkonen & Tenkanen, 2012).

The use of unconventional materials with peculiar surface characteristics in which imperfection is embraced and considered an appealing aesthetic is another emergent theme. 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); and seeds' tablets and pots based on coffee waste, which were designed using a tool known as Material Driven Design (Karana, Barati, Rognoli, & Laan, 2015).

Another theme is the exploration of living materials, i.e. materials embodied in products which possess additional 'interactive' features. These materials are often called smart materials as they sense and respond to environmental stimuli in a predicted manner (Tao, 2001; Stamhuis, 2015). Living materials are unique since they benefit from how the 'living' features contribute to additional facets of sustainability. Examples include: the oxygen-breathing 'silk-leaf' by a Royal College of Art graduate (Melchiorri, 2014), responsive bacterial based 'bio-skin' fabric by MIT Media Lab (Biologic, 2015), and bacterial mineral precipitation 'self-healing' concrete by TU Delft (Jonkers, 2007). The future of everyday living with these interactive materials or products that mimic living organisms were speculated by Johanna Schmeer from the Royal College of Art in a project called Bio-plastic Fantastic (Schmeer, 2014).

Research methodology

The literature review provided useful insights on the vast spectrum of sustainable materials explored by designers. In order to fulfil the aim of characterising sustainable materials, material projects were analysed and classified. This section presents information about the dataset of materials collected during this research and explains how the data was analysed and classified.

Data collection

Seventy-two material-centred design projects were collected from various sources including design websites and design fairs. Projects were selected for consideration if they had: i) a focus on sustainability; ii) an objective to research and implement a sustainable material; and iii) a goal to output a consumer product. For each project, the following information was collected: material, end-product produced, and developer. Materials ranged from creative explorations to industry-led projects. Products included both semi-developed and commercial objects. Developers included academia, designers, start-up companies and established companies.

Results

The materials in the data set were classified into three categories, namely resource renewability, resource origin and material group, see Table 1. The resource renewability category distinguishes if a material is from a renewable, non-renewable or semi-renewable source. The resource origin category characterises if a material is from a virgin or waste resource. The material group category classifies materials in five types, namely organic, bio-polymer, synthetic polymer, natural composite, and synthetic composite. This category, initially informed by the work of (Ljungberg & Edwards, 2003), has evolved following a data-driven approach, in which data was analysed to identify patterns and classes have emerged based on the data interpretation. The two composite material classes deserve a special note to explain how materials have been assigned to them. In a composite the matrix material surrounds and supports the reinforcement material by maintaining their relative positions. Typically, the matrix material is significantly higher in volumetric percentage than the reinforcement material, and therefore it affects more its sustainability. On this basis the distinction between a natural composite and a synthetic composite was made depending on whether the matrix is from a natural or synthetic material.

Category	Class	Definition	Example
Resource renewability	1. Renewable	Material made from natural organic resources.	Bio-plastic from corn starch, bacterial cellulose based material etc.
	2. Semi-renewable	Material made from two or more constituent materials of which at least one is renewable.	Wood wool and cement composite, bio-plastic reinforced fiberglass composite, etc.
	3. Non-renewable	Material made from a finite natural resource.	Synthetic polymer from petroleum, etc.
Resource origin	1. Virgin	Material made from a resource that has not been previously used or consumed.	Bamboo, wood plank, etc.
	2. Waste: by-product	Material made from waste that is a left-over of a production process.	Pineapple leave fibre-based material, agriculture residue, etc.
	3. Waste: second life	Material made from waste that is obtained from a product which has reached its end of life.	Expired meat, spoiled milk etc.
Material group	1. Organic	Material derived from biological substances.	Wood, cotton, bio-film, etc.
	2. Bio-polymer	Polymer-based material derived from biological substances.	Bio-plastic from plant cellulose, bio-plastic from corn starch, etc.
	3. Synthetic polymer	Man-made polymer from artificial components.	Polyethylene terephthalate (PET), high density polyethylene (HDPE), etc.
	4. Natural composite	Material formed by the combination of natural or synthetic reinforcement and natural matrix.	Natural fibre reinforced bio-polymer, e.g. composite of hemp fibre and bio-resin; natural fibre reinforced organic material, e.g. composite of wood and mushroom; natural fibre reinforced inorganic material, e.g. composite of natural fibre and clay; synthetic fibre reinforced bio-polymer, e.g. carbon fibre reinforced bioplastic.
	5. Synthetic composite	Material formed by the combination of natural reinforcement and synthetic matrix.	Natural fibre reinforced synthetic polymer, e.g. composite of cotton yarn and resin.

Table 1. Sustainable material categories

The products were also classified into categories including: furniture, household object, clothing and accessories, packaging, building material, and others, see Table 2.

Household objects	Packaging	Furniture	Clothing & accessories	Building Materials	Others
Plate, mug, bowl, pot, clock, toothbrush, vase, basket, mat, toys, hoover.	Bottle, plastic bag, void fill packaging, fruit-carrier bag, razor packaging.	Stool, chair, bench, lighting, side table, table, outdoor seating.	Dress, shoes, textile, dress, necklace, sneaker, bag, sunglass.	Acoustic panel, bricks, tiles, flooring.	Musical instrument, car interior finish, surfboard. 3D printer filament.

Table 2. Product categories

Sustainable materials classified

The materials used in the data set were mapped according to the previously introduced categories, see tree in Figure 1. The numbers in brackets along the branches of the tree represent the frequency of the materials in the dataset in term of actual instances. At the bottom of the tree, material percentages for the classes of each category are provided.

The classification includes three main branches, which follow the classes of the resource renewability category. Results show that 50% of the materials are renewable, 18% semi-renewable and 32% non-renewable, see Figure 1. The classification further splits materials into sub-branches dependent on the resource origin category. This shows that 42% of the materials are virgin, 50% waste, and 8% a mix of virgin and waste. Waste can be a by-product of a consumption process, or a material which can have a second life. Finally, the classification identifies five material groups (see Figure 1) the largest of which are: natural composites (35%), synthetic polymers (29%) and lastly organic materials (18%).

The first branch of the classification is ‘renewable materials’. Within this, *virgin* materials lead to organic materials (9), bio-polymers (4) and natural composites (10). An example of an organic material is cork leather. Examples of bio-polymer and natural composite are plastic from corn-starch and a natural fiber composite from hemp, respectively. *By-products waste* materials lead to organic materials (3) and natural composites (4). Fibre from pineapple leaves is an example of organic material, whereas a composite of wood shave and a bio-resin is an example of a natural composite. *Second life waste* materials consist of organic materials (2), natural composites (3), and bio-polymers (1). Examples of these are expired meat, a composite of coffee waste and a natural binder, and plastic from spoiled milk, respectively.

The second branch is ‘semi-renewable materials’. Within this branch, *virgin-virgin composite* materials lead to natural composites (7). An example is a composite of eco-cement and hemp fibre. *Virgin-waste composite* materials are further split into materials with a *by-product waste* and *second life waste*. *Virgin-by product waste* materials lead to synthetic composites (2). An example is denim offcut from manufacture and resin. *Virgin-second life waste* materials consist of natural composites (4) and an example is a composite of bacteria, urea, sand and calcium.

The third and last branch is ‘non-renewable materials. Within this branch, *second life waste* materials lead to synthetic polymers (21) and synthetic composites (2). An example of the first material type is weaved seatbelt and discarded fabric and resin is an example of the second material type.

The five material groups, namely organic materials, bio-polymers, synthetic polymers, natural composites and synthetic composites, are now examined.

<u>Organic materials</u>: this group includes virgin materials from plants and extraordinary examples of utilised waste including second life materials such as expired meat and by-product materials such as

salmon skin and pineapple leaves. Some of these materials have an established process to convert them into products (e.g. salmon skin leather, bamboo), whereas others are still at conceptual level and require further research before the materials can be considered fully developed and feasible for commercial production (e.g. mycelium mushroom fabric, beetle's chitin film).

Bio-polymers: this group includes plastics from virgin renewable resources such as corn starch. Some of these materials are already in the mainstream market, were sourced from companies with high-tech production technology and used as surrogate materials. The complexity of polymeric materials and the constraints of manufacturing facilities seem to hinder designers' exploration thus making these materials among the least used. Still, there are early attempts to develop new bio-polymers from second life waste materials such as spoiled milk.

Synthetic polymers: recycled plastics make up the largest share of this group. This is expected since plastic waste from consumer goods is often abundantly available. Some of the plastics were reused, whereas others were recycled, i.e. they were broken down into their raw state and reprocessed into new products. The former type requires that technical properties such as rigidity are utilisable. As for recycled plastics, the production process requires uncomplicated procedures, compatible with existing plastic production methods thus providing ample opportunity for self-explored small scale production. For instance, high-density polyethylene (HDPE) bottle were converted into new products with self-made extrusion and injection moulding.

Natural composites: waste is the dominant origin of the resources used in this group. Among natural composites, there are predominantly natural fibre reinforced bio-polymers. However, natural composites were found to also include natural fibre reinforced organic materials, natural fibre reinforced inorganic materials, and synthetic fibre reinforced bio-polymers. The reason for this variety of composites is the ease of production of these materials. As such, many unusual materials were utilised within this material group, e.g. seaweed, algae, urea, manure etc. Several applications tend towards creative expression in which the combined materials were explored for new aesthetics as much as improved utility.

Synthetic composite: materials in this group are predominantly by-product waste and second life waste materials. In terms of production, these materials require simple procedures similar to the aforementioned natural composites. They are mostly post-industrial and post-consumption products that were combined with industrial resin. These materials are the least used in the dataset indicating that a bio-based matrix is typically the preferred option. Several applications portray the reinforcement materials in their original and unprocessed state, creating unique surface properties.

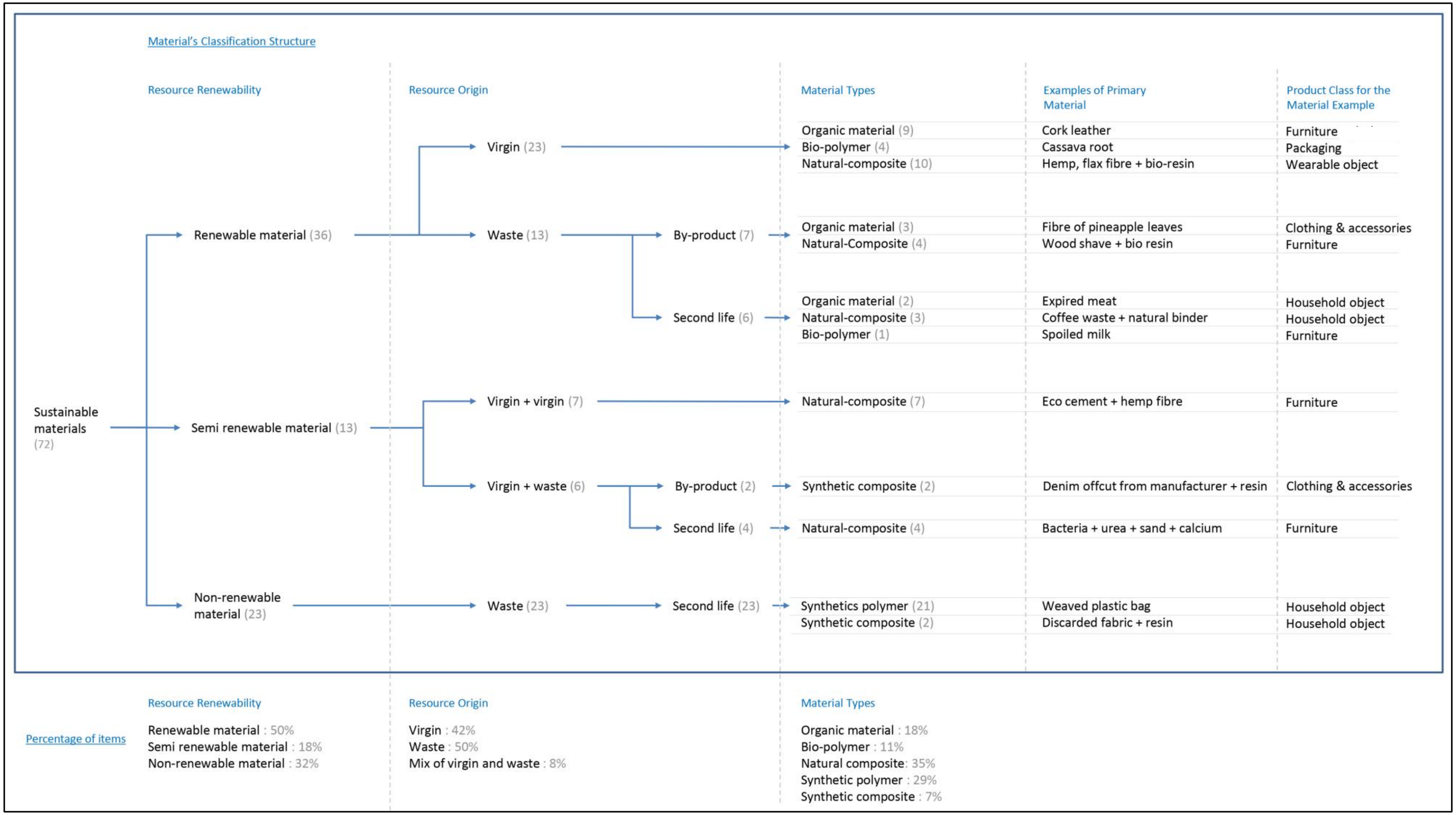

Figure 1. Classification of sustainable materials

Sustainable materials in practice

A closer examination of the seventy-two projects highlights the types of products made with the proposed materials. The types of products being developed are mainly furniture (37%), household objects (25%), clothing and accessories (18%) and packaging (11%). Figure 2 shows the breakdown of product types and Figure 3 examples of products in the dataset according to their materials types. Further analysis revealed which materials were used to make a particular product type, see Figure 4. The following trends were identified:

- <u>Furniture</u> was found to be increasingly made of natural composites and recycled plastics. The furniture products developed the most are seating items such as stools, chairs and benches. For example, a chair was made from a composite of wood fibre and fish oil, and an outdoor stool was made from discarded milk and detergent bottles. The reason for making seating furniture is that these products are simple creations that allow materials' technical properties (e.g. strength) to be easily tested and variation of surface qualities to be artistically embraced such as the concept of *wabi-sabi* (unique imperfection).
- <u>Household objects</u> were found to be predominantly made of recycled plastics and natural composites. Examples are bowls made from particles of recycled melamine, and a lamp cover made from coffee waste and a natural binder. Similar to furniture, household objects made from recycled plastics and natural composites are limited to simple products and the design indicates that basic moulding processes were adopted for production.
- <u>Clothing and accessories</u> were found to be made of recycled plastic and organic materials. Recovered PET and HDPE bottles were recycled into fabric and toothbrushes. In another case, waste plastics were reused to make bags adopting craft methods such as weaving. The utilisation of organic materials for clothing and accessories is still at the initial stages of material exploration. Although organic materials are still not fully developed for this application, attempts were made to convert them into products based on their technical properties (e.g. the flimsiness of bio-films is being associated with the softness of fabric thus the material is proposed to be used in making garment).

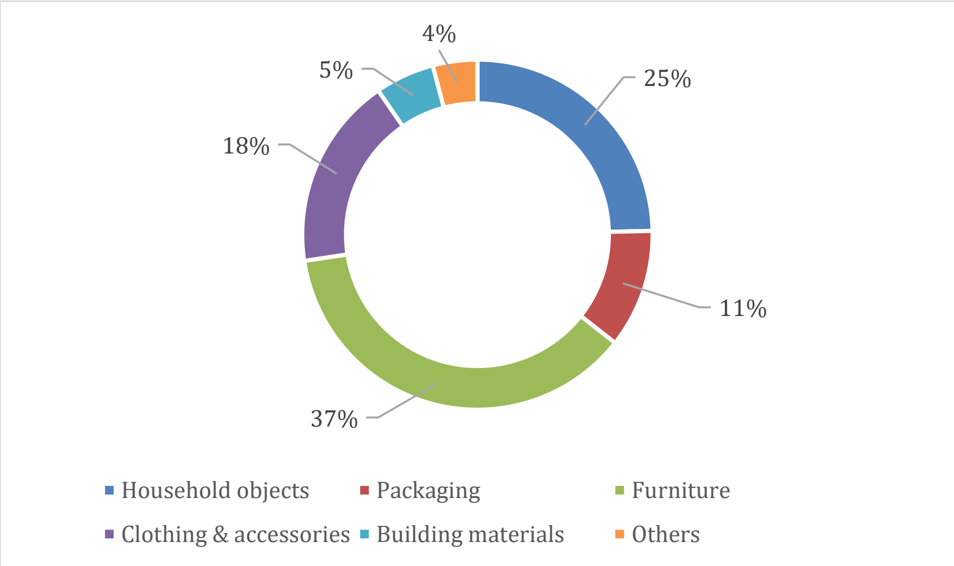

Figure 2. Product types

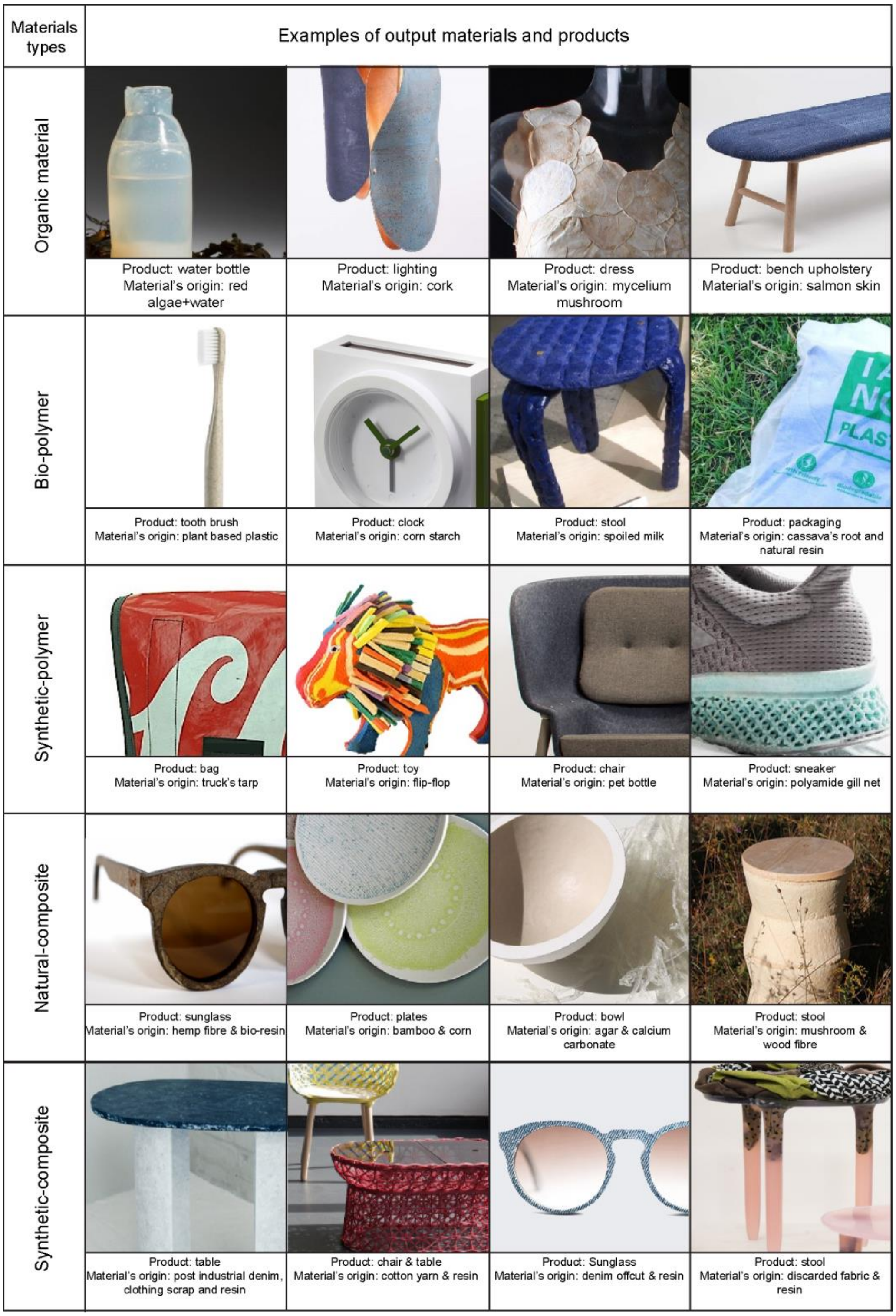

Figure 3. Sustainable materials and products

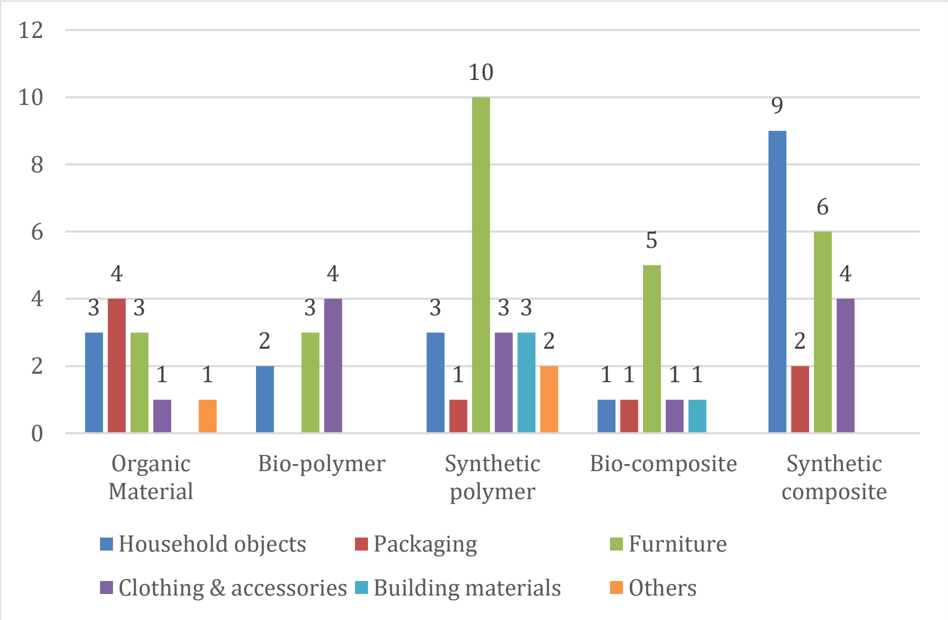

Figure 4. Sustainable materials and products application

Discussion

This research has shown that the majority of the materials were renewable and play a prominent role in balancing the depletion of non-renewable resources. They are predominantly based on virgin plant cellulose, agricultural by-products and food industry waste and the main outputs are natural fibre composites. The search for renewable materials is also focusing on the exploration of extraordinary living organism materials and uncommon waste materials. These materials portray the richness of the exploration undertaken within design communities. Although some materials are highly conceptual, it is noteworthy that a few extraordinary materials have progressed towards commercialisation. An example is a jacket made with bio-engineered bacteria by a well-known outdoor clothing company.

Non-renewable materials frequently originate from waste but waste also included various instances of renewable materials. Hence, the research has demonstrated that a culture for waste-reuse is progressively entering product design. The abundance and proximity of a waste resource provided a solid justification for its use. Interestingly, if a waste resource was collected from polluted environmental areas, e.g. the ocean, that resource was perceived as having an additional sustainability element which was often used to market the proposed product.

Due to its abundance, plastic waste is the most typical example of resource reuse or recycling. This is a way in which the destination to landfill of plastics is diverted back into the usage loop. Some recycled plastics were mixed with virgin bio-plastics; this is to attempt to improve the technical properties of the end material as well as to reduce the volume of plastic waste in the environment. This practice is expected to induce partial degradation of the inert material at the end of its life. With sufficient amount of biodegradable component in the mixture, the non-biodegradable component is expected to disintegrate and decay while the biodegradable component is consumed by microorganism (Wojtowicz, Janssen, & Moscicki, 2009). Other practices to induce synthetic polymer degradation include use of bacteria and fungi (Kim, 2003; Kyaw, Champakalakshmi, Sakharkar, Lim & Sakharkar, 2012; Sivan, Szanto & Pavlov, 2006).

The products studied vary significantly in terms of size, primary function and conventional materials that they are made from. Nevertheless, the products developed are limited to simple objects and only a case of material application in an electronic product is found. In general, various applications of sustainable materials were meant for material substitution and improved technical properties.

Interestingly, a significant number of unusual materials in the dataset were developed to support creative expression and provide new sensorial experiences to users. For example, the expired meat project which was exhibited at a design fair indeed provoke users' emotions during the interaction with the material.

In the Sustainable Materials Exploration section, we argued that terms such as environment-conscious materials, materials with high sustainable potential, and eco-sensitive materials are increasingly used to refer to materials with varying sustainable credentials. We also suggested that there is a need to consolidate current terminology used in the field. Departing from an analysis of materials used in practice, this research has shown important differences in sustainable materials and has proposed classes to characterise them. We have not looked at the thorough environmental footprint analysis of these materials. Renewable materials, for example, are often thought of as an ideal resource offering great potential for biodegradability. However, renewable virgin materials have to be grown, harvested and processed prior to usage. In contrast, waste materials exist in a ready-to-use state or semi-finished state. These facts do not necessarily have to favour waste materials since it is unrealistic to fully rely on them. Another intricate issue that has to be considered is the social impact of sustainable materials as in some contexts, the commercialisation of sustainable materials create jobs, help clean sluggish areas and revamp a material culture.

Limitations and further work

The research is based on seventy-two material centred design projects and on publicly available data about them. A larger data set of materials and richer data are necessary to develop a deeper understanding of the breath of sustainable materials. Future studies could expand the focus to understand the experience of users with these materials particularly those with peculiar surface characteristics and unusual origins as these aspects may possibly form the personality of the materials.

Conclusions

This research was undertaken with the aim to develop new understanding of sustainable materials developed within design projects. A dataset of seventy-two materials was collected and analysed using three categories, namely resource renewability, resource origin, and material group. Natural composites and recycled synthetic polymers are the materials predominantly used followed by organic materials. In order of frequency, the products produced with these materials are furniture, household objects and, clothing and accessories. Overall, this research has shown that the exploration of sustainable materials is vibrant and progressive but the market impact is still ambiguous. The development of sustainable materials was found to be at its infancy but undergoing a dynamic development. Proper strategies are needed to make these materials become commercial and design can play an important role in facilitating their uptake in the market.

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