How Natural Are the “Natural” Materials? Proposal for a Quali-Quantitative Measurement Index of Naturalness in the Environmental Sustainability Context

Original
How Natural Are the “Natural” Materials? Proposal for a Quali-Quantitative Measurement Index of Naturalness in the Environmental Sustainability Context / Dal Palu', D.; Lerma, B.. - In: SUSTAINABILITY. - ISSN 2071-1050. - STAMPA. - 15:5 - This article also belongs to the Special Issue "Sustainability and Circularity: New Material Scenarios for Product Design"(2023). [10.3390/su15054349]

Availability:
This version is available at: 11583/2976505 since: 2023-05-03T12:26:51Z

Publisher:
MDPI

Published
DOI:10.3390/su15054349

sustainability

MDPI

Article

How Natural Are the “Natural” Materials? Proposal for a Quali-Quantitative Measurement Index of Naturalness in the Environmental Sustainability Context

Doriana Dal Palù * and Beatrice Lerma *

DAD—Department of Architecture and Design, Politecnico di Torino, 10129 Torino, Italy
* Correspondence: doriana.dalpalu@polito.it (D.D.P.); beatrice.lerma@polito.it (B.L.)

Abstract: The overall purpose of the paper is overcoming the misunderstanding of the “naturalness” attribute of materials. This is due to the always-increasing innovative materials considered “environmentally sustainable” and “natural” by producers, material libraries, and designers. The investigated research problem is: how to simply and effectively evaluate the degree of naturalness of a material, preventing a complete and complex LCA analysis? The basic design of the study was focused on (i) creating a multicriteria quali-quantitative method—Material Naturalness Index (MNI)— in order to assess materials’ naturalness scientifically, and (ii) test it by running the evaluation on 60 innovative materials. MNI was set considering the least number of parameters of the Material Life Cycle (i.e., resource kingdom, material resource, material processing, post-use processing). The 60 latest materials selected from the “natural” material family of six international material libraries were selected to test the index. The data analysis was based on the Theory of Attractive Quality, considering attractive, must-be, or reverse qualities. Major findings concerning the index utility were found as a result. MNI was demonstrated to support different actors with different aims: (i) designers, in independently evaluating naturalness of materials using real evidence and pursuing a critical point of view not influenced by marketing claims; (ii) producers, in facing the challenge of naturalness; (iii) material libraries, which are collocated between the two other actors, in proposing measurable information concerning naturalness. In conclusion, the study demonstrated how the key-concept of “naturalness” should be assumed as an attribute rather than as a material family.

Keywords: material life cycle; naturalness; materials libraries; innovative materials; environmental sustainability; life cycle assessment; product design; materials naturalness index; design for sustainability; materials hyper-choice

Citation: Dal Palù, D.; Lerma, B. How Natural Are the “Natural” Materials? Proposal for a Quali-Quantitative Measurement Index of Naturalness in the Environmental Sustainability Context. *Sustainability* **2023**, *15*, 4349. https://doi.org/10.3390/su15054349

Academic Editor: Asterios Bakolas

Received: 30 November 2022
Revised: 1 February 2023
Accepted: 5 February 2023
Published: 28 February 2023

1. Introduction

1.1. Motivation: The Overabundance of “Environmentally Sustainable” and “Natural” Materials

In the last decades, an overabundance of environmentally sustainable—and so labelled—materials have been developed. Italy, Germany, and Spain are the most productive countries in the EU [1]. The environmental sustainability of material is pursued following different approaches [2–5]. In this context, a key role is played by the definition of *environmentally sustainable materials*, as there is no univocal point of view amongst practitioners, especially material producers. In fact, producers frequently adopt this definition in order to qualify their products as more appealing and closer to Nature, for a mere marketing purpose [6], also adopting other terms considered as synonyms, such as *natural materials*.

From the Oxford Languages dictionary entry, “natural” could be defined as “existing in or derived from nature; not made or caused by humankind” and “in accordance with the nature of, or circumstances surrounding, someone or something”. Therefore, although the term “natural” is widely used [7], for example, to define a material, a clear and objective definition still lacks.

Nevertheless, according to many authors [8,9] the so-called “natural” materials are preferred over unnatural ones in many contexts. In the wide world of environmentally sustainable materials, characterised by various explanations, definitions, and categorizations [10–14], this paper investigates the “natural” materials family observed in the material libraries.

1.2. Significance: The “Natural” Materials Family in the Materials Libraries

The diffusion of sustainable products, or products tending towards environmental sustainability, has led to a great effort by producers and researchers to develop innovative materials or solutions strictly connected to natural resources or to natural processes. The material journey starts in and through Nature by surrounding humans [15] with a great variety of what is already defined as natural material substances [16]. This trend meets the definition of “supernatural” materials [17] (i.e., materials from renewable resources, recycled materials made from production and end-user waste, biodegradable and/or compostable materials).

Material libraries represent the principal place where designers and companies should find clear, correct, updated, and impartial information about materials, as they represent a window on materials innovation [18]. The so-called “natural” materials are well represented in the materials libraries, although their classification is not always approached consistently, especially in the “natural” materials family, characterised by blurred and trans-familiar borders (Figure 1). A particular bias is caused by the fact that materials’ naturalness is frequently adopted as a marketing lever by producers. The transition towards sustainability also implies marketing tactics by companies to project an ecologically responsible image despite continuing environmentally harmful practices [19,20] (i.e., “greenwashing”). Greenwashing is defined as “the act of misleading consumers regarding the environmental practices of organisations or the environmental benefits of a product or service” [21]: it, thus, becomes crucial to establish the framework within which a material can be defined as environmentally sustainable. As material libraries derive information on materials from producers, inaccurate, inflated, or tendentious information on the naturalness of a material provided by the manufacturer can lead to an inaccurate and misleading transfer of information to the designer, if a clear and scientifically robust classification is lacking.

1.3. Novelty: Measuring the Naturalness of Materials

Naturalness has been defined as: “the probability that a material or object is perceived as being natural, i.e., perceived as being derived from nature” [22]. However, many authors [8,23] analyse the perception of materials and products, considering the aspect of naturalness, and define naturalness as crucial for product environmental sustainability perception: in fact, it is often associated with positive qualities, and it probably makes a difference in the decision processes of consumers. Naturalness has also been used as an added value of physical food products [24,25] or as a validation tool of the effectiveness of ecosystem management [26], but no prior studies have defined a method to measure the materials’ naturalness. Starting from this controversial situation caused by the aforementioned issues, the present contribution addresses the need to evaluate the materials’ naturalness, which is so far lacking in the scientific literature. A validated, scientific, rigorous, and already existing tool for similar assessments is Life Cycle Assessment (LCA); nevertheless, the limitations of this approach are extensively shared amongst practitioners and the scientific community [27].

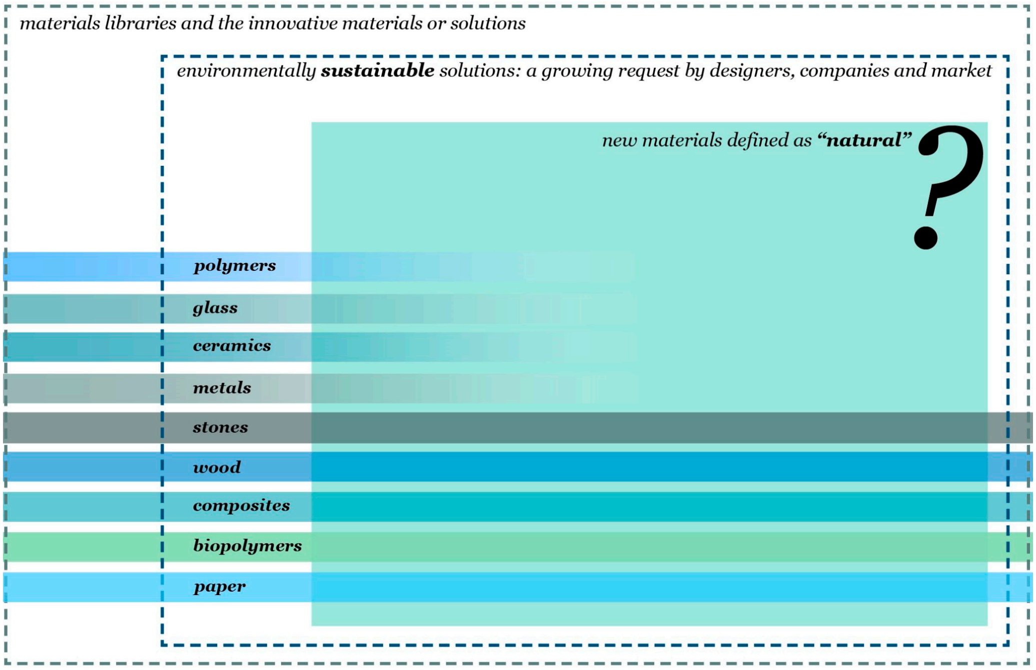


Figure 1. The family of "natural" materials within material libraries: it is shown how this family is characterised by blurred and trans-familiar borders. The first four material families represented in gradient colours are less frequently found in the family of natural materials, but are catalogued by some material libraries as such.

In order to reply to the research question: How to simply and effectively evaluate the degree of naturalness of a material, preventing a complete and complex LCA analysis?, the objective of this contribution (Figure 2) is to propose an index able to consider the least number of parameters necessary for the assessment of this aspect, in order to allow designers, material libraries, and material producers to independently evaluate naturalness of materials starting from real evidence, and pursuing a critical point of view not influenced by marketing claims.

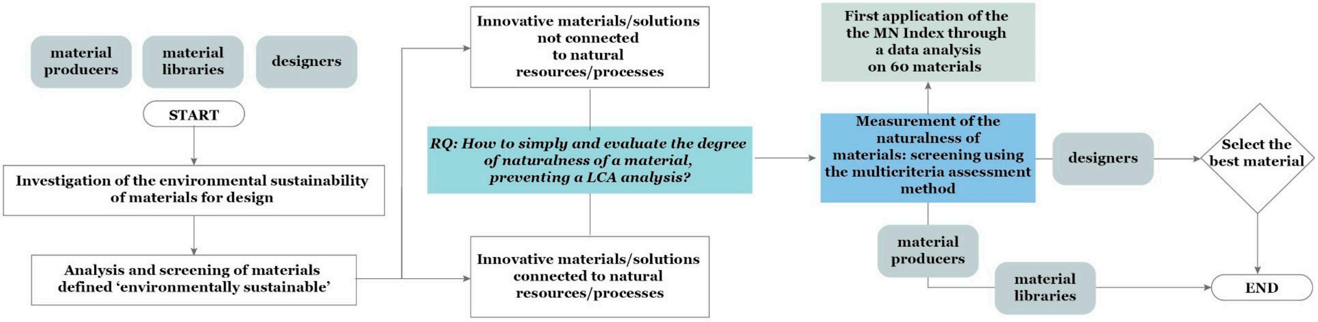


Figure 2. Conceptual framework for the evaluation of the materials' naturalness.

2. Materials and Methods

2.1. The Source of Information: The "Natural" Materials Family in Different Materials Libraries

An analysis of different classification methods adopted by several material libraries for cataloguing the "natural" materials was carried out.

A selection of six materials libraries based in Europe and worldwide was made, considering five free database access material libraries (Materfad (http://es.materfad.com/, accessed on 18 November 2022), ES; Material District (https://materialdistrict.com/material/, accessed on 18 November 2022), NL; Make it London (https://www.make-it.london/materials-library, accessed on 18 November 2022), UK; Circular Material Library (https://circulardesignco.com/circularmateriallibrary/, accessed on 18 November 2022), AUS; SML—Sustainable Materials Library (https://sml.pidc.org.tw/product_en_1.php, accessed on 18 November 2022), TW), and one closed database access material library (MATto (http://www.matto.design/en/home/, accessed on 18 November 2022), IT).

An investigation was performed, in order to understand each classification system adopted by the selected material library (in particular, concerning the topic of “natural” materials), as shown in Table 1.

Table 1. An overview of different classifications of “natural” materials families within different international material libraries.

Material Library Name	Family Organisation (and Number of Collected Items up to November 2022)	Particular Notes
Materfad	Natural materials, 336 (animal origins, 103; vegetal origins, 46; mineral origins, 187).	A subdivision by living kingdoms is adopted.
Material District	Other naturals, 685; Wood, 300; Natural stones, 72.	The “other naturals” materials family comprises bioplastics.
Make it London	Timber and construction boards, 25; Plastics, 8; Stones and composites, 11; Naturals and organics, 10; Paper and print, 9; Metals, 8; Textiles, 13.	Commonly considered natural materials, such as stone or wood, are ascribed into other materials families than “naturals and organics”. Furthermore, materials families and applications are mixed.
Circular Material Library	TechCycle, 37; BioCycle, 60.	All items are circular materials. There is no specific session dedicated to “natural” materials. In the” TechCycle” family are collected metals, plastics, etc., and in BioCycle woods, bioplastics, etc.
Sustainable Materials Library	Organic materials, 543 (plastic, 244; fibre, 160; natural, 32; rubber, 68; others, 39); Inorganic materials, 46 (metal, 14; mineral, 32).	There is no distinction between “natural” and other materials. All materials are brought back to nature.
MATto	Natural materials, 33; Wood, 90; Metals, 50; Paper, 136.	“Natural materials” include materials such as leather, cork, basalt, etc. Bioplastics are not included in the “natural materials” family.

Table 1 demonstrates two different phenomena:

- The naturalness attribute is perceived in a non-homogeneous and non-consistent way when used to classify materials; for example, materials commonly recognised as “natural” such as wood or leather, are often separated from the “natural materials” family;
- The “natural” materials family comprises, in some cases, materials with a high degree of artificiality defined as “natural” by their manufacturers or because they include materials from natural resources.

This inconsistency, as well as the overuse of the attribute "natural" to define more environmentally sustainable materials, generates a complete linguistic and conceptual misunderstanding. The present work is conducted to face and overcome this misunderstanding, proposing a new method to quali-quantitatively assess the "naturalness" of materials.

2.2. A Multicriteria Assessment Method

A multicriteria assessment method set on several variables of the material life cycle was created to overcome the misunderstanding and scientifically assess the "naturalness" attribute. The following aspects (Figure 3)—subdivided along the main phases of the Product Life Cycle, and, consequently, on the Material Life Cycle (respectively: "production" for the variables in paragraphs 2.2.1-5; "end of life" for the variable in paragraph 2.2.6)—were considered. The intermediate phase between these two, i.e., the "use", was excluded from this multicriteria analysis because it relied on the end consumer behaviours.

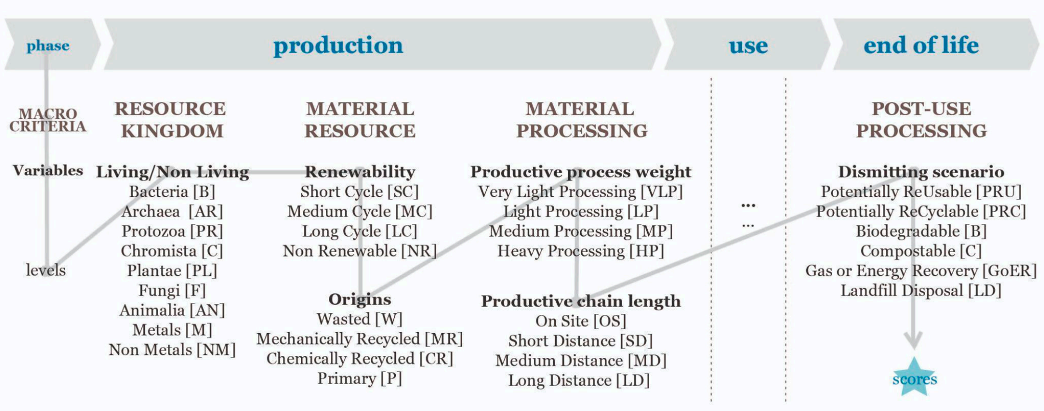


Figure 3. A flowchart of the variables and levels adopted to evaluate the materials' naturalness.

All the variables explained in the next sub-paragraphs, and the related levels, constitute the columns of Appendix A.

2.2.1. Resource Kingdom

The first variable is based on the living or non-living attribute of the resource [28].

The classification into seven living kingdoms proposed by Cavalier-Smith [29] was adopted for categorising the living resources along the following levels:

- *Bacteria [B];*
- *Archaea [AR];*
- *Protozoa [PR];*
- *Chromista [C];*
- *Plantae [PL];*
- *Fungi [F];*
- *Animalia [AN].*

Similarly, the non-living resources were classified according to the scientific literature [30,31] on the following two levels:

- *Metals [M];*
- *Non-Metals [NM].*

2.2.2. Renewability of the Resource

The age-structured discrete time modelling of a renewable resource is found in the scientific literature and is by now thoroughly discussed [32]. Nevertheless, the reference to discrete levels [33]—well consolidated in the field of Design for Sustainability [34]—remains the most easily understandable and applicable for designers. In this contribution, this variable is articulated on the following four levels:

- *Short Cycle [SC];*
- *Medium Cycle [MC];*
- *Long Cycle [LC];*
- *Non-Renewable [NR].*

Specifically, according to ISO 14021, the term "renewable" is referred to as "a material that is composed of biomass from a living source, that can be tree or crops, and that can be continually replenished", and renewability as "depends upon both the specific regrowing speed and the extraction frequency" [13]. All the resources that cannot be regenerated in a lifespan compatible with human life can be considered non-renewable. Therefore, fossil resources as well must be considered non-renewable.

2.2.3. Origins of the Resource

The substitution of raw materials for sustainable resources is required in order to attain global sustainability [35]. The origins of the resource variable can be evaluated on four levels, as follows:

- *Wasted resources [W] [17];*
- *Mechanically recycled resources [MR] [10];*
- *Chemically recycled resources [CR] [36];*
- *Primary (i.e., virgin) resources [P].*

2.2.4. Productive Processes Weight

There is a further investigation concerning the "artificiality thickness" concept [37], and it is about the productive processes' weight, i.e., the complexity of the resource transformation. This variable was investigated on four different levels:

- *Very Light Processing [VLP]*: The resource is taken directly from nature and introduced in the same configuration into the material layout; this is the case of materials that do not change their macro or micro shape during processing or that only change their shape spontaneously.
- *Light Processing [LP]*: The resource is usually processed with just a few traditional production processes, frequently just one, in some cases inspired by handcraft process or involving light and/or very simple technologies, such as melting, intertwining, spinning together, etc. In materials characterised by light processing, the resources are usually quite recognizable, at least with one of the five senses, because the link with their original shape is still quite strong.
- *Medium Processing [MP]*: The resource is processed, usually by steps, with several different technologies or with a few complex technologies; the productive process strongly affects the resource characteristics and deeply changes its mechanical properties. This approach entails a re-engineering of the material, frequently involving a natural or biologically inspired engineering approach; in this case, the resource can be recognisable, but with a completely different aspect, or it can be hidden and no longer recognizable because of the high number of undergone processes.
- *High Processing [HP]*: The resource is more than processed, it is entirely re-designed by a deep artificial process going back to its chemical structure; this is the case of synthetic biology, of materials created in the laboratory, generated—partially or totally—from a redesign of their intrinsic DNA, of their molecular structure.

2.2.5. Productive Chain Length

Controlling the productive chain length means reducing the distribution impacts of resources from the extraction site to the transformation site. In order to provide an estimate of productive chain length, four levels have been set for this variable:

- *On Site [OS]*: The resource extraction site coincides with the resource processing site [38];
- *Short Distance [SD]*: The transformation happens in the same country of extraction as the resource;
- *Medium Distance [MD]*: The transformation happens in the same continent of extraction as the resource;
- *Long Distance [LD]*: The transformation happens on a different continent of extraction than the resource.

2.2.6. Dismitting Scenarios

In order to answer the complex and multidimensional waste management problem [39], the European Commission defined through the Waste Framework Directive [40] the main guidelines and basic principles to prevent waste production. According to this waste hierarchy [40], the most recent Circular Design Strategies [41] and the International Organization for Standardization, the material demitting scenario variable was evaluated on six levels:

- *Potentially Reusable [PRU]*: The material can be separated and prepared to be re-used without any other pre-processing;
- *Potentially Recyclable [PRC]*: The material can be reprocessed by a recycling process to recover secondary recycled material with high/low performances for the original or other purposes;
- *Biodegradable [B]*: The material waste can be biologically degraded by living organisms down to the base substances such as water, carbon dioxide, methane, basic elements, and biomass [42];
- *Compostable [C]*: The material waste can be transformed into compost within a specific time frame; it requires specific conditions (home or industrial composting facilities) [43,44];
- *Gas or Energy Recovery [GoER]*: The material waste can be subject to an energy recovery treatment, through their combustion in fossil fuel power plants, or to gas recovery;
- *Landfill Disposal [LD]*: The only possible end of life scenario for the material is landfill.

2.3. Data Analysis

A multicriteria analysis inspired by the Theory of Attractive Quality [45], commonly adopted in new products and service development [46] and considering quantitative discrete and qualitative ordinal variables, was performed.

Each variable level was categorised, following Kano's theory applied to sustainability [47], as *attractive quality* (*attractive* involves all the functions which are normally not present, but ones which would increase the quality perceived by the final user), *must-be quality* (*must-be* involves all the aspects required by a product without which the product would be perceived as low quality), or *reverse quality* (*reverse* involves all the aspects that, if they exist, lead to dissatisfaction; if they do not exist, they do not lead to satisfaction (See Appendix A)), following the consumer's attitudes towards the current environmental sustainability issue of materials.

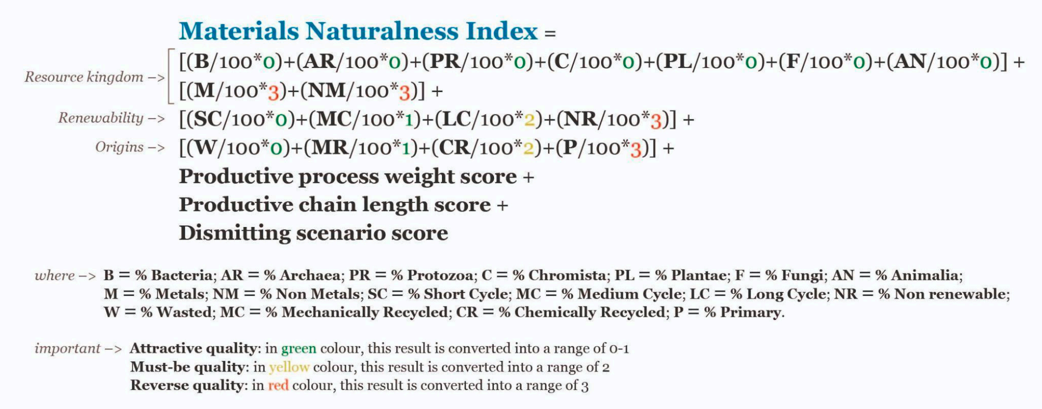
A standardisation of the evaluation following the principle "less is better", i.e., the lower the value of the indicator, the better the evaluation of the materials on that particular criterion, was performed, with a score level ranging from 0 to 3. Specifically:

- *Attractive quality*: If the analysed material fulfils the quality, this result is converted into a range of 0–1 (excellent; in green colour in Appendix A);

- *Must-be quality*: If the analysed material fulfils the quality, this result is converted into 2 (good; in yellow colour in Appendix A);
- *Reverse quality*: If the analysed material fulfils the quality, this result is converted into 3 (poor; in red colour in Appendix A).

Data concerning the discrete quantitative variables of *Resource kingdom*, *Renewability of the resource*, and *Origins of the resource*, as they were expressed as percentage, were multiplied by the aforementioned coefficients in order to obtain the specific scores. Data concerning the qualitative ordinal variables of *Productive process weight*, *Productive chain length*, and *Demitting scenarios* were just converted into a score, as indicated. Finally, the sum of the scores obtained for each variable was calculated.

A score representing the naturalness level of each material was calculated adopting the following formula (Figure 4), in order to express the result of this multicriteria assessment method as a new index, named the Materials Naturalness Index (MN Index).



Materials Naturalness Index =

Resource kingdom –> [(**B**/100*0)+(**AR**/100*0)+(**PR**/100*0)+(**C**/100*0)+(**PL**/100*0)+(**F**/100*0)+(**AN**/100*0)] +
[(**M**/100*3)+(**NM**/100*3)] +

Renewability –> [(**SC**/100*0)+(**MC**/100*1)+(**LC**/100*2)+(**NR**/100*3)] +

Origins –> [(**W**/100*0)+(**MR**/100*1)+(**CR**/100*2)+(**P**/100*3)] +

Productive process weight score +
Productive chain length score +
Dismitting scenario score

where –> **B = % Bacteria; AR = % Archaea; PR = % Protozoa; C = % Chromista; PL = % Plantae; F = % Fungi; AN = % Animalia; M = % Metals; NM = % Non Metals; SC = % Short Cycle; MC = % Medium Cycle; LC = % Long Cycle; NR = % Non renewable; W = % Wasted; MC = % Mechanically Recycled; CR = % Chemically Recycled; P = % Primary.**

important –> **Attractive quality**: in green colour, this result is converted into a range of 0-1
Must-be quality: in yellow colour, this result is converted into a range of 2
Reverse quality: in red colour, this result is converted into a range of 3

Figure 4. The formula adopted to calculate the Materials Naturalness Index (MN Index).

2.4. A First Run of the Assessment: The Implementation on Several "Natural" Materials

Sixty materials identified from the most recently collected materials in the "natural" materials family by material libraries, presented in Table 1, were selected to run the multicriteria analysis method for the first time.

Materials were equally selected from materials of resources from living and non-living kingdoms, considering the Renewability (Short Cycle, Medium Cycle, Long Cycle; Non-Renewable) and the Origins (Wasted resources, Mechanically Recycled resources, Chemically Recycled resources, Primary) of these resources. Moreover, differences in the Productive processes weight (Very Light, Light, Medium, and High Processing), the chain length (On Site, Short, Medium, and Long Distance) and in the Dismitting scenario (Potentially Reusable, Potentially Recyclable, Biodegradable, Compostable, Gas or Energy Recovery, Landfill Disposal) were criteria for choosing the materials to be analysed. As example, materials derived from fruit peel, cork, animal fibres, flexible stones, and many others were analysed.

The collected data are systematised in Appendix A. The materials are presented on the rows through a concise description, without indicating the names of the product and/or the manufacturer since the purpose of the analysis is research and not commercial; however, the material library from which the material was selected is reported. The variables are presented in the columns.

3. Results

3.1. The Materials Naturalness Index

The standardisation of the variables based on a three-value scale allowed us to establish a quali-quantitative method to assess the naturalness degree of the so-called "natural" materials. Nevertheless, even if this assessment method was developed in order to quali-quantitatively assess the naturalness attribute for those materials belonging to or ascribed to the "natural" materials family, it can be applied to whatever materials, without any distinction within material families.

Aggregating the values concerning the macro-criteria allowed us to create a single dimensionless value describing this specific attitude toward the topic of naturalness, an index named Materials Naturalness Index (MN Index), graphically represented in Figure 5.

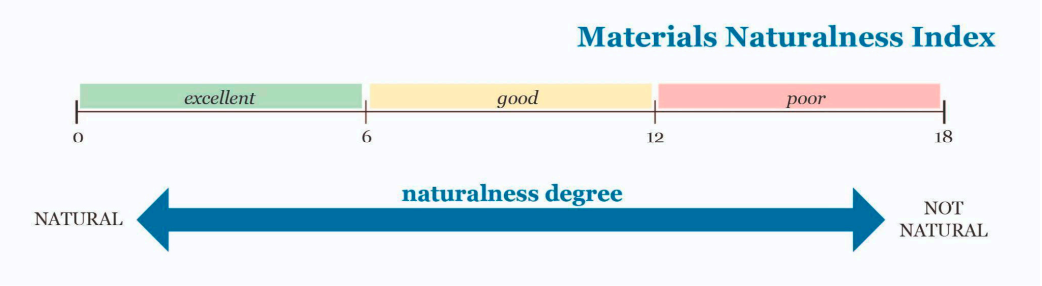


Figure 5. A graphical representation of the Materials Naturalness Index (MN Index).

Having a single dimensionless value facilitates, on the one hand, the integration of the evaluation of the materials' naturalness in the meta-design process of the final product, but on the other, it means forcibly simplifying a complexity which, in fact, enhances the index.

The value describing the specific Material Naturalness Level was segmented into three different ranges of values:

- *Excellent value (of Material Naturalness)*: The analysed material was assessed with a value ranging from 0 to 6 (the evaluation is placed in the area with a light green background in the figure);
- *Good value (of Material Naturalness)*: The analysed material was assessed with a value ranging from 7 to 12 (the evaluation is placed in the area with a light yellow background in the figure);
- *Poor value (of Material Naturalness)*: The analysed material was assessed with a value ranging from 13 to 18 (the evaluation is placed in the area with a light red background in the figure).

It must be noted that this score does not mean that a material is better or worse than another for a specific design project. The MN Index is simply designed to compare different materials with a multi-criteria approach, taking into consideration various aspects that have a direct effect on their effective degree of naturalness. The score must, therefore, be read as *"The XY material is rated as Z* (e.g., 5) *on a scale from 0 to 18 of the Materials Naturalness Index, meaning that it has an Excellent/Good/Poor* (in this case, Excellent) *level of naturalness"*.

Finally, as the MN index groups different criteria, the resulting value represents a balanced score. In other words, the index does not elevate one criterion as more important than the others. A material can obtain the *Excellent* rating despite having one criterion assessed as significantly less natural (e.g., a high score on a "reverse" quality) than the others.

3.2. The Analysed Materials in Relation to the "Natural" Materials Family

Some conclusions can be also drawn from the collected data (See Appendix Table A 1) adopted to first run the Material Naturalness Index. However, it should be noted that the objective of this analysis is not drawing conclusions on the selected materials but rather to verify if the index can be helpful in clarifying the misunderstanding of the "naturalness" attribute and, more precisely, assessing it.

Amongst the selected 60 "natural" materials, a preponderance (40 items on 60) of vegetable resources can be noticed. This could highlight a strong relation between "naturalness" and living resources, even if there has been, until now, less interest in resources from the other living kingdoms (e.g., *Animalia*: 14 items of 60; *Bacteria*: 3 items of 60; *Protisti*: 2 items of 60; *Chromisti*: 2 items of 60; Fungi: 2 items of 60; *Archae*: 1 item of 60). In the next decades, the involvement of living resources other than plants is likely to grow, especially boosted by bioproduction and other new material processing trends currently on the rise [38]. This fact could entail a consequent possible shortening of the productive chain length; currently, *On site* and adopting natural (i.e., biological) productive processes is found just for 10 items of 60.

Materials made of non-living resources are, rather than being defined as "natural", frequently ascribed to ad hoc material families (e.g., metals or stones), instead of to the "natural" materials family. This fact explains the limited number of items found adopting these resources (only 24 items of 60), if compared with those from living resources (53 items of 60). This evidence could be due to a more consolidated taxonomy that sees high-performance materials (e.g., metals) more investigated from a physical-mechanical point of view than from a sensory-expressive one. Therefore, for such materials, the attribute of "naturalness" could be judged as less important.

The low presence of bioplastics in the "natural" materials family (3 items of 60), and the still lower presence of the traditional polymers (2 items of 60) should be highlighted. This fact appears to be controversial for traditional polymers, derived from natural resources, albeit non-renewable, but is still more controversial for bioplastics, which are directly derived from living and renewable resources. Probably, the preconception of bioplastics as substitutes for traditional polymers influences their classification, which still appears not to be homogeneous within materials libraries.

Renewability of the resource in "natural" materials is usually quite limited (37 items of 60), probably because of its relation to the living kingdom, even if the productive process weight can also significantly modify the resource expressiveness (*Medium Processing*: 18 items of 60; *Heavy Processing*: 11 items of 60), making the original matter no more recognizable to the end consumer. This fact negatively affects the identification of the correct end-of-life disposal scenario. An example is the issue of bioplastic disposal, which is frequently confused within traditional polymers and organic waste.

All the issues raised from the results of the analysis of Appendix A reinforce the focused need for an index to evaluate the material naturalness level. At the present time, the material family of "natural" materials neither responds to a robust criterion shared between material libraries, nor can it be delegated to designers to control and evaluate all these aspects on their own, without a systemic and guided view.

4. Discussion

4.1. A Comparison between MN Index and Other Studies Assessing the Material Naturalness

The Materials Naturalness Index was proposed to assess the naturalness of materials through a multicriteria assessment that considers aspects of the Material Life Cycle. The topic of measuring naturalness is not completely new for the scientific literature. In Landscape Studies, researchers studied how landscape patterns can be used as an indicator of naturalness and ecological sustainability [48]. In the Product Design field, other authors [49] analysed how the material perception of naturalness influences users' choice when selecting products, or [8,50] the perceived degree of naturalness through the sensory interaction (touch/vision) with materials (i.e., textiles), and others [9] investigated how colour compositions are perceived as natural. In studies related to the food field [24,25,51,52], naturalness has been defined as correlated to the perceptions of product quality; it has been also investigated [53] as a factor impacted by visual, tactile, and auditory cues or strictly correlated with elements such as how the food is grown and processed, the contagion of the raw material, or which ingredients that are used.

Moreover, the impact of packaging and the role of perceptual interactions have been defined as crucial in the food's expected naturalness [54]. In food colourant studies [55], naturalness has been evaluated in a simplified index (on a scale of 3 points; from 1 to 3), referring to the chemical structure of the pigments, considering the number of processing steps involved during food colourant production; nonetheless, naturalness was not further analysed as part of a complex set of indicators focused on the effect of manufacturing food additives and the consumers' expectations on production.

However, the mentioned studies did not provide a method to measure the "naturalness", and when the methods did investigate this aspect, it was by cross-correlating several psychophysical measurement methods and suggestions that can be used to express naturalness in design. Studies have so far been able to evaluate users' behaviour towards the concept of naturalness and have highlighted the primacy of certain elements strictly linked with the materials' environmental sustainability (i.e., synthetic yarns may be perceived as naturals when adequately combined with pure natural ones).

The main alternative to the MN index at the present time is represented by the LCA, which, even considering its limitations, is extensively used among practitioners and in the scientific community [27]. In particular, making the life cycle inventory more readily available (especially to non-expert practitioners) is one of the main limitations of to the tool [27]. Following one of the strategies theorised in literature to overcome the limitations of LCA, i.e., developing a hybrid analysis between an extension of LCA and the development of a toolbox including other types of impacts [56], the new quali-quantitative multicriteria method inspired by LCA was developed and proposed in this paper. The presented systematic procedure aims at being an exploratory tool to start the analysis on naturalness of materials, basing these evaluations on qualitative and quantitative data, mainly from the production and from the end-of-life phases of the Material Life Cycle.

4.2. The Impact of the MN Index on the Design Process, and the Adoption by Its Actors

The multicriteria method mapped out meets some of the Circular Business Model Archetypes [41], such as (i) Circular Supplies, (ii) Resource Value, and (iii) Product Life Extension. This research shows how materials respond to challenges, such as integrating environmental sustainability issues and consumers' perceptions. The MN index, therefore, meets the future scenarios for Product Design, especially supporting a triple typology of target, i.e., (i) designers, (ii) materials libraries, and (iii) material producers in facing the challenge of naturalness, as follows:

- *From the designers' perspective*, using the MN Index, the designer is aided in choosing the best materials through a method that is coherent with the Life Cycle Approach but agile and easily usable during the design process. Specifically, it can be adopted in the meta-design phase to choose the most appropriate material for a sustainable project. In fact, according to recent approaches to design culture, selecting suitable materials for a product should be done as early as in the meta-design stage because this supports its technical functions and shapes its personality [57]. However, the index can also be adopted to validate the designer's choices based on material technical, sensory, and environmental properties: the solutions can either be rejected or accepted by checking the naturalness level. Moreover, the MN index avoids using a priori preconceptions about materials' sustainable impact (e.g., biomaterials, materials from renewable resources) regarding sustainability and artificiality, interpreted as opposed to naturalness.
- *From the material libraries' perspective*, the classification of materials and their organisation in families represents a complex challenge. Through the analysis presented in this study, the "natural" term was proved needing to be considered as an attribute rather than as a family. This attribute, in fact, was demonstrated to be transversal to all material families; therefore, a new classification re-collocating the

currently so-labelled "natural materials" could be proposed, as well as a new layer of investigation of materials, adopting the proposed method.

- *From the material producers' perspective*, the MN index can also lead them to a reflection, especially on the use—and, frequently, abuse—of the naturalness attribute, often assumed as a marketing strategy. In fact, reflecting on the real variables that concretely lead to a higher degree of naturalness could help producers making the process being more "light", where possible, as well as meeting the wishes of the designer and, consequently, of the final consumer, for a truly more responsible production.

However, even if promising, the index is not without weaknesses that still need research, as pointed out in the next paragraph.

4.3. Future Challenges and Applications for the MN Index

In order to focus on the importance of the present contribution, as well as on its criticisms, a gap analysis based on a SWOT analysis (Table 2) was performed, highlighting strengths, weaknesses, opportunities, and threats of the MN index here theorized.

Table 2. A SWOT analysis of the MN index.

	Positive	**Negative**
internal	**S**TRENGTHS – To date, there is still no index to assess "naturalness"; – An emerging need for clarity on this topic is highlighted; – Simplicity of the MN index compared to LCA; – Objectifiable multi-criteria evaluation; – Applicability to any family of materials (not just for the "natural" materials family).	**W**EAKNESSES – LCA allows finer analysis (but also much more complex ones); – Lack of validation through a direct comparison between MN index and LCA; – The evaluation of the index may be partially inaccurate if the material producer provides unclear information (e.g., on raw materials, on the specific composition, on the production process, on the place of processing, etc.).
external	**O**PPORTUNITIES – (For designers): To support a design choice of materials with objective data; – (For material libraries): To give greater clarity to the user; – (For materials producers): To substantiate with objectively measured data the characteristic of "naturalness" of their materials (already in production or at the research stage), that is currently a marketing lever; – (For the authors): To propose this index as a method to evaluate the naturalness of	**T**HREATS – Uncertainty in business acceptance: the index could be rejected or opposed by companies that practise simple green washing, and have no interest in seeing the naturalness of their products denied; – The change in consumers' attitudes towards the environmental sustainability issues can modify the assessment, according to the Theory of Attractive Quality.

	materials at a higher level (e.g., at a national or international level).	

From this analysis, several challenges, as well as future applications for the MN index, can be foreseen.

Starting from the actors who could most benefit from the MN index, it is hoped that this method for assessing the naturalness degree of materials will be adopted in the future, primarily by material libraries. Material libraries represent, in fact, meeting places connecting designers and material producers, as well as being cultural hubs stimulating the debate on the most current topics in terms of materials [58].

Given the simplicity of calculating the MN index, it is desirable that the future cataloguing process of materials could also adopt this indicator, similarly to the indicators assessing the mechanical or sensory properties of materials, already taken into consideration in the material archives.

Furthermore, since the calculation method is very simple, and designers are now increasingly informed by scientific literature, it is hoped that everyone can freely calculate the naturalness of alternative materials (for example if different possible solutions are under evaluation for a project), starting from the method provided in this article, in order to support one's critical sense with reliable quali-quantitative data.

However, the present method is not free from defects, critical points, criticisms, and gaps and it needs to be further developed with recommended solutions.

Concerning the defects, users applying the method could need clarification on how to evaluate each variable. Therefore, it is desirable to develop an online calculation platform in which whoever enters the data is guided in interpreting the variables.

A current index limitation is represented by the "use" phase, which is currently excluded from the assessment because it relies on the end users' behaviours. It should be verified with an ad hoc study whether it heavily affects the MN level. Furthermore, a validation step could be hypothesised in a future contribution by comparing this method with a complete LCA analysis.

Finally, a similar application of the index to innovative materials belonging to material families other than "naturals" could be implemented, in order to verify its accuracy along different families of materials.

In the end, if all these validation and implementation steps demonstrate its effectiveness, the MN index could be proposed as a standard to correctly and scientifically inform stakeholders of a material's *real and measurable* naturalness.

5. Conclusions

With this contribution, an index named Material Naturalness Index was proposed, in order to respond to the research question "How to simply and effectively evaluate the degree of naturalness of a material, preventing a complete and complex LCA analysis?"

The multicriteria analysis proposed here was inspired by the Theory of Attractive Quality, commonly adopted in new products and service development, considering attractive qualities, must-be qualities, or reverse qualities, following the consumers' attitudes towards the current environmental sustainability issue of materials.

The benefits and utility of the presented Index can be synthetically summarised, as follows:

- The index allows overcoming the subjectivity and randomness with which the "natural" attribute is used in the world of materials;
- As it is based on the least number of parameters necessary for the evaluation of naturalness, it is easier to apply than a complete LCA;

- Designers could, therefore, independently evaluate the naturalness of materials starting from objective evidence and pursuing a critical point of view not influenced by marketing claims.

Providing designers with a method able to scientifically and robustly assess the materials' naturalness implies making them able to select the correct material in order to face big environmental issues, such as (i) recover the resource value of end-of-life matters by using them in new forms and avoiding the consumption of virgin resources, or (ii) extend materials and product life, through its reuse, repair, maintenance, and upgrade, in accordance with the Circular Business Model Archetypes [41] for future Design scenarios.

Even considering the current limits, it can be hypothesised that, thanks to future studies, the present criticalities of the MN index can be overcome, and its effectiveness proved. Then, the index could be proposed to designers as a method to support the material selection phase, to material libraries as a classification parameter, and to material producers as a self-analysis tool and guideline for developing new materials.

Author Contributions: Conceptualization, D.D.P. and B.L.; methodology, D.D.P. and B.L.; formal analysis, D.D.P.; investigation, B.L.; resources, D.D.P.; data curation, B.L.; writing—original draft preparation, D.D.P.; writing—review and editing, B.L.; visualisation, D.D.P. and B.L.; All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

The following table (Table A1) collects the data obtained from the 60 materials selected from the most recent ones in the "natural" materials family of each material library and analysed through the Materials Naturalness Index.

Table A1. Data from 60 "natural" materials from the selected materials libraries. Text in green colours refer to Attractive qualities; Text in yellow colour refer to Must-be qualities; Text in red colour refer to Reverse qualities. If the MN Index obtains an excellent value, the cell background is in light green; if the MN Index obtains a good value, the cell background is in light yellow; if the MN Index obtains a poor value, the cell background is in light red.

				Attractive Quality, Must-Be Quality, Reverse Quality - Theory of Attractive Quality [Kano, Seraku, Takahashi, Tsuji, 1984]																				
			MACRO-CRITERIA	RESOURCE KINGDOM									MATERIAL RESOURCE								MATERIAL PROCESSING		POST-USE PROCESSING	Materials Naturalness Index (MN Index)
			VARIA-BLES	Living [L;0]							Non Living [NL;3]		Renewability				Origins				Productive Process Weight	Productive Chain Length	Dismitting Scenario	
				Bacteria [B] / Archaea [AR] / Protozoa [PR] / Chromista [C] / Plantae [PL] / Fungi [F] / Animalia [AN]							Minerals Metals [M] / Non Metals [NM]		Short Cycle [SC;0] / Medium Cycle [MC;1] / Long Cycle [LC;2] / Non Renewable [NR;3]				Wasted [W;0] / Mechanically Recycled [MR;1] / Chemically Recycled [CR;2] / Primary [P;3]				Very Light Processing [VLP=0] / Light Processing [LP=1] / Medium Processing [MP=2] / Heavy Processing [HP=3]	On Site [OS=0] / Short Distance [SD=1] / Medium Distance [MD=2] / Long Distance [LD=3]	Potentially ReUsable [PRU=0] / Potentially ReCyclable [PRC=1] / Biodegradable [B=2] / Compostable [C=2] / Gas or Energy Recovery [GoER=2] / Landfill Disposal [LD=3]	
	SOURCE	MATERIAL DESCRI-PTIONS	LEVELS	B	AR	PR	C	PL	F	AN	M	NM	SC	MC	LC	NR	W	MR	CR	P				
1	MATto	biologically engineered banana leaf veneers						100					100				100				1	1	2	4
2	MATto	paper replacing up to 15% of virgin tree pulp with organic residues						100					100				15			85	1	1	1	6
3	MATto	innovative natural textile made from pineapple leaf fibre						100					100				70			30	2	2	2	7
4	Sustainable Material Library	non-wowen basalt fabric										100				100				100	2	3	3	17
5	Materfad	organic refuse biocompound						100					100				100				2	1	2	5

6	MATto	thin natural stone veneer over a cotton fleece					5				95	5			95				100	2	2	3	16
7	MATto	steel panels that house stabilized lichens					10			90		10			90		90		10	2	1	3	13
8	MATto	expanded insulation corkboard					100						100			100				0	1	1	3
9	MATto	innovative biological and healthy yarn obtained from milk					65		35			100				35			65	3	2	0	7
10	MATto	fibre by a blend of Chitosan (from crab shells) and viscose					95		5			100				5			95	3	2	0	8
11	Materfad	sheet of material from bacteria	50	50								100				100				0	0	2	2
12	MATto	alpine herb and flower veneers bonded with bio-resins					100					100							100	1	0	2	6
13	Materfad	cellulose fibre from Bamboo					100					100					50		50	3	2	1	8
14	Sustainable Material Library	fibre produced exclusively from wood and seaweed					100						100						100	3	1	1	9
15	Materfad	recycled textile waste and mycelium as a binding agent					95	5				5	95				95		5	1	0	3	6
16	MATto	very thin flexible sandstone					15				85		15		85				100	1	2	3	14
17	MATto	salmon skin leather							100			100				100				1	0	1	2
18	MATto	paper from algae of the Venice lagoon			100							100				30	70			1	1	1	4
19	MATto	biopolymer from PLA					100					100							100	3	2	2	10
20	Materfad	eco-leather from spoiled fruit and vegetables					100					100				100				0	0	1	1
21	Materfad	silk-like yarn from repurposed citrus juice by-products					100					100				100				3	0	1	4
22	Materfad	bio plastic composed of lignin, cellulose fibres, and natural additives					100						100			100				1	2	3	7
23	Materfad	floor covering of linseed oil, wood flour and mineral fillers					100					30	70			51			49	2	2	3	9
24	Sustainable Material Library	high-performing insulation material from the ocean					100					100				100				0	1	2	3
25	Materfad	flexible foams from algae biomass				100						100							100	2	1	2	8
26	Materfad	sound insulating material from sheep wool							100			100				100				0	1	1	2
27	MATto	recycled aluminum tiles for floorings								100					100	100				2	2	1	11
28	MATto	recycled leather					10		90				10	90		90			10	1	2	1	6
29	Sustainable Material Library	recycled polyamide for textile applications									100				100		100			3	3	1	14
30	Sustainable Material Library	bioplastic made from eggs							100			100				100				1	1	2	4
31	Material District	perforated poplar wood veneers					100						100						100	0	1	1	6
32	Circular Material Library	activated charcoal by upcycling non-edible food waste					60				40	40	60			60			40	3	2	2	10
33	Circular Material Library	textiles made by discarded wool from factory floor offcuts, deadstock yarn and post-consumer textiles waste							100				100			100				1	2	1	5
34	Circular Material Library	clay plaster for interior walls and ceilings					4			6	90		4		96				100	2	2	2	15
35	Circular Material Library	natural dye derived from bacteria and other microorganisms	100									100							100	2	1	2	8
36	Circular Material Library	precast concrete created by employing microorganisms to grow the bio cement	15								85	15			85	85			15	0	1	0	7
37	Circular Material Library	mimicry inspired vegan leather built on a formula of 8+ bio-based ingredients			5	5	80				10		90		10				100	1	2	2	10
38	Sustainable Material Library	oyster shell powder							100				100			100				2	1	2	6
39	Make it London	bio-based leather from chitin from shellfish waste and discarded coffee grounds					30	30	40			100				100				1	1	2	4
40	Make it London	recycled plastics from marine debris collected from the bottom of the ocean									100				100			100		3	2	1	14
41	Make it London	high performance cement mixed ultra-fine aggregates from recycled glass and polymers									100				100	50			50	2	2	3	15
42	Make it London	tree-free mineral-based paper					25				75		25		75	75			25	3	2	2	13
43	Make it London	paper board made from 100% recycled materials					100						100			100				1	1	1	4

44	Make it London	concrete made of hemp shiv and lime binder					30				70	30			70	30			70	1	0	1	8
45	Make it London	water-based, modified gypsum composite									100			100					100	1	1	1	11
46	Material District	vegan coated fabric					75				25	75			25	100				1	2	2	7
47	Material District	gypsum boards with fibrous reinforcement									100				100				100	2	2	3	16
48	Material District	panel from silkworm cocoons							100			100				100				0	0	1	1
49	Material District	100% merino wool							100			100							100	0	0	0	3
50	Material District	cork fabric					100						100			100				2	1	1	5
51	Material District	durable surface made of recycled content					25				75		100				75		25	1	2	3	11
52	Material District	textile fibre made from chemically recycled domestic cotton waste					100					100						100		2	1	0	5
53	Material District	cow stomach leather							100			100				100				2	2	1	5
54	Material District	sheep/cow/donkey dung paper					25		75			100				100				0	0	1	1
55	Material District	bonded leather by scraps					25		55		20	55	25		20	80			20	2	1	1	6
56	Material District	recycled wood chips terrazzo					80				20	10	80		10	90			10	1	1	1	5
57	Material District	decorative wood panels					90				10		100						100	0	1	1	6
58	Material District	high-density panel - freeform fiberboard					80				20	80			20	80			20	1	1	2	6
59	Material District	rice husk, salt and mineral oil composite					60				40					60			40	2	2	1	7
60	Material District	cement bonded particle board					63				37	10	63		27				100	3	2	1	12

References

1. Bontempi, E.; Sorrentino, G.P.; Zanoletti, A.; Alessandri, I.; Depero, L.E.; Caneschi, A. Sustainable Materials and their Contribution to the Sustainable Development Goals (SDGs): A Critical Review Based on an Italian Example. *Molecules* **2021**, *26*, 1407.
2. Silva, A.; Rosano, M.; Stocker, L.; Gorissen, L. From waste to sustainable materials management: Three case studies of the transition journey. *Waste Manag.* **2017**, *61*, 547–557.
3. Hofmann, M.; Hofmann, H.; Hagelüken, C.; Hool, A. Critical raw materials: A perspective from the materials science community. *Sustain. Mater. Technol.* **2018**, *17*, e00074.
4. Helbig, C.; Kolotzek, C.; Thorenz, A.; Reller, A.; Tuma, A.; Schafnitzel, M.; Krohns, S. Benefits of resource strategy for sustainable materials research and development. *Sustain. Mater. Technol.* **2017**, *12*, 1–8.
5. Arif, Z.U.; Khalid, M.Y.; Sheikh, M.F.; Zolfagharian, A.; Bodaghi, M. Biopolymeric sustainable materials and their emerging applications. *J. Environ. Chem. Eng.* **2022**, *10*, 108159.
6. de Freitas Netto, S.V.; Sobral, M.F.F.; Ribeiro, A.R.B.; da Luz Soares, G.R. Concepts and forms of greenwashing: A systematic review. *Environ. Sci. Eur.* **2020**, *32*, 19.
7. Rozin, P.; Fischler, C.; Shields-Argelès, C. European and American perspectives on the meaning of natural. *Appetite* **2012**, *59*, 448–455.
8. Overvliet, K.E.; Karana, E.; Soto-Faraco, S. Perception of naturalness in textiles. *Mater. Des.* **2016**, *90*, 1192–1199.
9. Sérgio, M.C.; Nascimento, A.M.A.; Gegenfurtner, K.R. Naturalness and aesthetics of colors—Preference for color compositions perceived as natural. *Vis. Res.* **2021**, *185*, 98–110.
10. Allione, C.; De Giorgi, C.; Lerma, B.; Petruccelli, L. From ecodesign products guidelines to materials guidelines for a sustainable product. Qualitative and quantitative multicriteria environmental profile of a material. *Energy* **2012**, *39*, 90–99.
11. Lerma, B. Materials in sustainable design. Characteristics and potential of materials for low environmental impact design. In *Towards Conscious Design. Research, Environmental Sustainability, Local Development Project*; Ceppa, C., Lerma, B., Eds.; Società Editrice Umberto Allemandi & C.: Torino, Italy, 2014; pp. 46–57.
12. Peters, S. *Material Revolution II: New Sustainable and Multi-Purpose Materials for Design and Architecture*, 1st ed.; Birkhauser: Basel, Switzerland, 2014; pp. 1–223.
13. Vezzoli, C. The "material" side of design for sustainability. In *Materials Experience: Fundamentals of Materials and Design*, 1st ed.; Karana, E., Pedgley, O., Rognoli, V., Eds.; Butterworth-Heinemann: Oxford, UK, 2014; pp. 105–121.
14. Whalen, K.; Peck, D. In the Loop—Sustainable, Circular Product Design and Critical Materials. *Int. J. Autom. Technol.* **2014**, *8*, 664–676.
15. Wilkes, S.; Wongsriruksa, S.; Howes, P.; Gamester, R.; Witchel, H.; Conreen, M.; Laughlin, Z.; Miodownik, M. Design tools for interdisciplinary translation of material experiences. *Mater. Des.* **2016**, *90*, 1228–1237.
16. Marschallek, B.E.; Jacobsen, T. Classification of material substances: Introducing a standards-based approach. *Mater. Des.* **2020**, *193*, 108784.
17. De Giorgi, C.; Lerma, B.; Dal Palù, D. *The Material Side of Design. The Future Material Design Cultures;* Società Editrice Umberto Allemandi & C.: Torino, Italy, 2020; pp. 1–144.

18. Fazil, A.; Pedgley, O. Sample Libraries to Expedite Materials Experience for Design: A Survey of Global Provision. *Mater. Des.* **2016**, *90*, 1207–1217.
19. Pimonenko, T.; Bilan, Y.; Horák, J.; Starchenko, L.; Gajda, W. Green brand of companies and greenwashing under sustainable development goals. *Sustainability* **2020**, *12*, 1679.
20. Seeram, R.; Rajan, J.; Addressing sustainability gaps. *Sci. Total Environ.* **2022**, *806*, 151208.
21. De Jong, M.D.; Harkink, K.M.; Barth, S. Making green stuff? Effects of corporate greenwashing on consumers. *J. Bus. Technol. Commun.* **2018**, *32*, 77–112.
22. Goodman, T.; Montgomery, R.; Bialek, A.; Forbes, A.; Rides, M.; Whitaker, T.A.; Overvliet, K.; Mcglone, F.; van der Heijden, G.. The measurement of naturalness (MONAT). In Proceedings of the 12th IMEKO TC1 & TC7 Joint Symposium on Man Science & Measurement, Annecy, France, 3–5 September 2008.
23. Karana, E. Characterization of 'natural' and 'high-quality' materials to improve perception of bio-plastics. *J. Clean. Prod.* **2012**, *37*, 316–325.
24. Damen, F.; Steenbekkers, B. Added value of physical food products as a stimulus during interviewing. *Appetite* **2022**, *169*, 105819.
25. Damen, F.; Verkerk, R.; Steenbekkers, B. Healthiness, naturalness and sustainability perception of adolescents toward chocolate snack bars. *Br. Food J.* **2022**, *124*, 200–218.
26. Barrette, M.; Dumais, D.; Auger, I.; Boucher, Y.; Bouchard, M.; Bouliane, J. Naturalness assessment performed using forestry maps to validate forest management sustainability. *Ecol. Indic.* **2020**, *119*, 106832.
27. Curran, M. Strengths and Limitations of Life Cycle Assessment. In *Background and Future Prospects in Life Cycle Assessment. LCA Compendium. The Complete World of Life Cycle Assessment*; Klöpffer, W., Eds.; Springer: Dordrecht, The Netherlands, 2014; pp. 189–206.
28. Srubar, W.V., III; Engineered Living Materials: Taxonomies and Emerging Trends. *Trends Biotechnol.* **2021**, *39*, 574–583.
29. Ruggiero, M.A.; Gordon, D.P.; Orrell, T.M.; Bailly, N.; Bourgoin, T.; Brusca, R.C.; Cavalier-Smith, T.; Guiry, M.D.; Kirk, P.M.; Thuesen, E.V. A higher level classification of all living organisms. *PLoS ONE* **2015**, *10*, e0130114.
30. Edens, B.; Di Matteo, I. Classification issues for mineral and energy resources. In Proceedings of the 11th London Group Meeting, Pretoria, South Africa, 26–30 March 2007, pp. 26–30.
31. Boubault, A.; Maïzi, N. Devising mineral resource supply pathways to a low-carbon electricity generation by 2100. *Resources* **2019**, *8*, 33.
32. Oubraham, A.; Zaccour, G. A Survey of Applications of Viability Theory to the Sustainable Exploitation of Renewable Resources. *Ecol. Econ.* **2018**, *145*, 346–367.
33. Vezzoli, C.A. *Design for Environmental Sustainability. Life Cycle Design of Products*, 2nd ed.; Springer London Ltd: London, UK, 2018; pp. 1–330.
34. Sassanelli, C.; Urbinati, A.; Rosa, P.; Chiaroni, D.; Terzi, S. Addressing circular economy through design for X approaches: A systematic literature review. *Comput. Ind.* **2020**, *120*, e103245.
35. Bontempi, E. *Raw Materials and Sustainability Indicators*; Springer: Cham, Switzerland, 2017; pp. 1–28.
36. Thiounn, T.; Smith, R.C. Advances and approaches for chemical recycling of plastic waste. *J. Polym. Sci.* **2020**, *58*, 1347–1364. https://doi.org/pol.20190261.
37. Lerma, B.; Dal Palù, D. Natural materials. A family on the move, but where is the last stop? In Running with Scissors, In Proceedings of the 13th International Conference of the EAD, Dundee, UK, 10–12 April 2019.
38. Raman, R.; Bashir, R. Biomimicry, Biofabrication, and Biohybrid Systems: The Emergence and Evolution of Biological Design. *Adv. Healthc. Mater.* **2017**, *6*, 1700496.
39. Rajendran, K.; Lin, R.; Wall, D.M.; Murphy, J.D. Influential Aspects in Waste Management Practices. In *Sustainable Resource Recovery and Zero Waste Approaches*; Taherzadeh, M.J., Bolton, K., Wong, J., Pandey, A., Eds.; Elsevier NV: Amsterdam, The Netherlands, 2019; pp. 65–78.
40. Directive (EU) 2018/851 of the European Parliament and of the Council of 30 May 2018 Amending Directive 2008/98/EC on Waste. Available online: https://eur-lex.europa.eu/eli/dir/2018/851/oj (accessed on 19 January 2023).
41. Moreno, M.; De los Rios, C.; Rowe, Z.; Charnley, F. A Conceptual Framework for Circular Design. *Sustainability* **2016**, *8*, 1–15.
42. Goswami, P.; O'Haire, T. Developments in the use of green (biodegradable), recycled and biopolymer materials in technical nonwovens. In *Woodhead Publishing Series in Textiles, Advances in Technical Nonwovens*; Kellie, G., Ed; Woodhead Publishing: Sawston, UK, 2016; pp. 97–114.
43. *ISO 18606:2013*; Packaging and the Environment—Organic Recycling. International Organization for Standardization: London, UK.
44. *ISO 17088:2021*; Plastics—Organic Recycling—Specifications for Compostable Plastics. International Organization for Standardization, London, UK.
45. Kano, N.; Seraku, N.; Takahashi, F.; Tsuji, S. Attractive Quality and Must-Be Quality. *J. Jpn. Soc. Qual. Control.* **1984**, *41*, 39–48.
46. Witell, L.; Löfgren, M.; Dahlgaard, J.J. Theory of attractive quality and the Kano methodology—The past, the present, and the future. *Total Qual. Manag. Bus. Excell.* **2013**, *24*, 1241–1252.
47. Dace, E.; Stibe, A.; Timma, L. A holistic approach to manage environmental quality by using the Kano model and social cognitive theory. *Corp. Soc. Responsib. Environ. Manag.* **2019**, *27*, 430–443.

48. Renetzeder, C.; Schindler, S.; Peterseil, J.; Prinz, M.A.; Mücher, S.; Wrbka, T. Can we measure ecological sustainability? Landscape pattern as an indicator for naturalness and land use intensity at regional, national and European level. *Ecol. Indic.* **2010**, *10*, 39–48.
49. Teixeira, F.M.; Pereira, A.F. Perception of naturalness in materials and user's choice: Hardwood and melamine foil finished products. *Strateg. Des. Res. J.* **2019**, *12*, 361–382.
50. Karana, E.; Nijkamp, N. Fiberness, reflectiveness and roughness in the characterization of natural and high quality materials. *J. Clean. Prod.* **2014**, *68*, 252–260.
51. Etale, A.; Siegrist, M. Food processing and perceived naturalness: Is it more natural or just more traditional? *Food Qual. Prefer.* **2021**, *94*, 104323.
52. Magnier, L.; Schoormans, J.; Mugge, R. Judging a product by its cover: Packaging sustainability and perceptions of quality in food products. *Food Qual. Prefer.* **2016**, *53*, 132–142.
53. Román, S.; Sánchez-Siles, L.M.; Siegrist, M. The importance of food naturalness for consumers: Results of a systematic review. *Trends Food Sci. Technol.* **2017**, *67*, 44–57.
54. Labbe, D.; Pineau, N.; Martin, N. Food expected naturalness: Impact of visual, tactile and auditory packaging material properties and role of perceptual interactions. *Food Qual. Prefer.* **2013**, *27*, 170–178.
55. Gebhardt, B.; Sperl, R.; Carle, R.; Müller-Maatsch, J. Assessing the sustainability of natural and artificial food colorants. *J. Clean. Prod.* **2020**, *260*, 120884.
56. de Haes, H.A.U.; Heijungs, R.; Suh, S.; Huppes, G. Three Strategies to Overcome the Limitations of Life-Cycle Assessment. *J. Ind. Ecol.* **2004**, *8*, 19–32.
57. Lerma, B.; De Giorgi, C.; Allione, C. *Design and materials: Sensory Perception_Sustainability_Project*; FrancoAngeli: Milano, Italy, 2013; pp. 1–177.
58. Wilkes, S.E.; Miodownik, M.A. Materials library collections as tools for interdisciplinary research. *Interdiscip. Sci. Rev.* **2018**, *43*, 3–23.