Materials are the constituent of everything, the means that permit existence. Humans and living beings understand the world through their senses interacting with materials. The relationship between men and materials began between 1.8 and 1.3 million years ago with the first humans building their tools and has continued evolving and deepening. This relation marked the eras which usually took the corresponding material discovery name: from the Stone Age through the Bronze, Iron, Steel and Plastic Age. The close relation between the maker and the material has been a fundamental part of craftsmanship, without which culture would not be as we know it (Ashby 2008; Attfield 1999).

For ages, artisans have worked on different materials, from wood to clay, metals etc., developing high knowledge about potentialities and critical aspects (Bunn 1999). Touching and interacting with materials is the way to experience the three-dimensional world. As Gibson said, sensing is a process of exploring; whereas using the motor system to act or make is performative (Gibson & Carmichael 1966).

While this physical process of knowledge was taking place, specific rules and techniques for material processing were also defined over the years. Humans became more conscious, started exploring materials and developed artifacts and knowledge that have brought them to the present production system. Nowadays, there is a clear idea of the potentialities of the role of materials in our life: design, good design, is conscious of this, putting materials as one of the crucial points in its process (Ashby & Johnson 2003).

Functionality, usability, and aesthetics depend on the proper material's choice, meeting the technical, production safety and cost requirements. Material needs to ensure finishing, color and texture, to convey the right interaction message. Finally, the material defines the aesthetic and the perception aspects of the material, defining its personality and, consequently, its place on the market in product design, the character of architecture, and the style of a fashion item (Ashby & Johnson 2003).

It is now evident that the selection of materials becomes the central task of a project. However, it is not so simple because designing is an activity that constantly changes. Moreover, materials and technology are continuously evolving too (Papile et al. 2021).

Over the years, due to the increase in technical knowledge, the amount of information considered in material selection has grown. The materials themselves have increased in number, giving a great multitude of alternatives and entangling the activity of material selection. In the last 20 years, advances in research have led to the identification and synthesis of slightly more than 160,000 different materials, and this number is constantly increasing (Papile et al. 2021). Moreover, with the growing environmental emergency and limited resources, sustainability has now become a priority. When making the right choice of material, information about its extraction, processing, transport, use, recycling and general impact on the environment is relevant (Ljungberg 2007; Ashby & Johnson 2013; Papile et al. 2020).

The growing amount of information involved in the material selection with the vast number of materials available has led practitioners to face a complex decision-making task, an *iperscelta* ("hyperchoice"), as Manzini called it (Manzini 1989). To manage this "hyperchoice", several methodologies have been theorized. Material libraries, tools and platforms can efficiently support material selection. In recent years, many online tools and libraries have been implemented due to extreme digitization (Del Curto & Dantas 2009; Ramalhete et al. 2010; Papile & Del Curto 2021). Those can be divided mainly into two categories, the information tools and the inspiration tools: the first ones consider the technical properties in the selection process, while the seconds exploit perceptual and visual elements inspiring creative and innovative solutions. As Ramalhete et al. reported in their study, there is a tendency to create specific tools for designers or architects with less technical information and user-friendly interfaces (Ramalhete et al. 2010). However, the technical aspect must not be minimized but conciliated with other properties that designers may find interesting.

It becomes clear that nowadays and in the future the availability of materials will not increase and there will be critical issues in energy supply. Many production methods together with the system will change and so will the designers' choices. The attention to the origin and the recyclability of materials and the impact of their processing will be more and more relevant. In this context, the material selection will become an essential aspect of design to meet project requirements (Allione 2012; Papile et al. 2021).

Materials & sustainable architecture

Material science has been fundamental also in architecture for the construction sector and the evolution of housing well-being. However, the construction sector is one of the most environmentally impactful, equivalent to almost 50% of global material consumption and 20% of global greenhouse gas emissions (Gallego-Schmid 2020).

The attention to green architecture has increased, focusing on planning efficient and eco-friendly houses and building.

The main principles of green architecture concentrate on energy efficiency, water efficiency, resource supply and management, cost efficiency and respect for social values (Li 2011; Lembi et al. 2021). As Li said "sustainable architecture must not solely become a question of CO_2 emission-reducing. It is necessary to consider sustainability from a holistic point of view that considers financial, cultural, and social issues as well as wider ecological and environmental aspirations" (Li 2011). But the roots of this attitude go back a long way: from the very beginning, humans have tried to make the best use of nature for their convenience in life (Thackara 2017).

The spread of ecological thought in the 1970s and 1980s and climate awareness led to the first voluntary sustainable interventions since the beginning of the industrial revolution.

Humans began to act mainly on a large scale (urban design and architecture), with projects that involved the redevelopment of mostly rural buildings, trying to integrate them as best as possible into the territory.

As early as the 1960s, some professionals expressed the need to construct buildings that harnessed the free energy of the sun; however, it was only from the 1970s, with the oil crisis, that people have become conscious of limited natural resources. This trend has prompted architects to adopt solutions that have made homes increasingly energy-autonomous, thanks to the careful design of the materials used (Gauzin-Müller 2006).

Alongside the efficient development of the project, intensive research has been conducted on the materials' use. Materials have provided solutions to problems identified by engineers, architects and other construction sector specialists (Bechthold & Weaver 2017). Those innovations have permitted the creation of an efficient way of living, including effectively insulating interiors, creating new aesthetics, constructing glazing systems for efficient daylighting of interiors (Li 2011; Bechthold & Weaver 2017; Sahlol 2021).

The best materials according to the green architecture principles are those that best respond to the 4R rules (Li 2011):

Reduce
Reduce the needs for energy, water, land and materials used in buildings. It becomes significant to exploit materials and technologies that improve and optimize building performance, use clean and renewable energy systems and reduce water use (Lembi 2021). Materials that require less energy in their production and have less impact on the environment should be preferred.

Recycle
Recycle construction materials wherever possible. It becomes significant to prioritize the choice of materials that are recycled, recyclable and allow the recycling of resources used in the building (e.g. rainwater recycling).

Reuse
Reuse most materials. Building materials should be used in a much better way as a post-consumer resource to obtain: new materials, remanufactured components and alternative uses. The building stock must be perceived as a resource and a possibility to have stocks for the future.

Renewable
Exploiting energy and materials from renewable sources as much as possible in sustainable design. The use of clean energy in the construction and life of the building is crucial for a lower impact. It is also relevant that, for the same performance, materials from renewable rather than non-renewable sources are preferred.

Implementing sustainability can enhance the quality of our lives by improving the way we live and our relationship with the environment. Sustainable architecture must meet human needs without destroying the existing environment and resources. It becomes crucial to design by trying to involve the surrounding environment: not only from a cultural and social point of view, designing buildings in harmony with the context; but also using local energy, materials and labor (Allione 2012). Sustainable buildings become an asset for people and the environment, preserve human and ecosystem health, can last longer and have a reduced cost. The appropriate use of materials in architecture makes it possible to achieve this goal and to ensure the well-being of all for a long time.

Materials & future

The evolution process of materials and technology has permitted to slowly define a materials palette that has been engineered and improved until the basic creation of a traditional construction method: wood, stone, ceramics, metals, concrete, glass and recently plastic and composites (Bechthold & Weaver 2017). In the 20th century, the increased offer and the problem of *iperscelta* involved the architecture field too (Manzini 1989; Papile et al. 2021). However, designers have continued to use the limited materials palette because of the established know-how and the request for normsv and standards.

In the early 2000s, a rapid development in materials, technology and digitization began. Through the fast exchange of information, knowledge from different sectors has been shared, promoting technology transfer. This phenomenon has led to an increasing number of new possibilities. The role of material scientists has changed, becoming the center of innovation and making materials the catalyst for novel design expressions. Driven by their curiosity and enthusiasm to test themselves, designers and architects have begun to explore new materials and new possibilities, in some cases becoming "designer makers" (Camere & Karana 2018). Designer makers have explored the possibilities of new materials from renewable resources, recycled resources and revived materials from discarded resources of industrial streams of production, becoming active actors in the creation of materials: this practice takes the name of DIY materials.

Thanks to this phenomenon, there has been a development of research topics on materials for interior design and architecture in general. Although it is improbable that there will be a reduction or significant move away from conventional materials, it is possible to identify some alternatives for the future (Papile et al., 2022). Researching through online databases, books and literature, six different material trends can be identified:

Functionals
Materials that respond to an input with an output

Bioxxx
Biobased and/or biodegradable materials, material classes characterised by the "bio" prefix (plus compostable materials)

Re-discovered
Materials that are recycled, reinterpreted, redesigned to avoid waste

Biomimetic
Materials that get inspiration and seek connections with nature

Alive
Materials that change, move, grow over time

Foodology
Materials and/from/being food

Functionals

Functional materials, also known as smart materials, have peculiar characteristics by their very nature (Lefebvre et al. 2014). In this trend, we can find some examples of materials for architecture and interior design.

Two case studies by the MIT are experimental and can be inspirational for architects and interior designers. The first is Aeromorph, an origami that turns an ordinary sheet of paper into a three-dimensional shape. The project structures are designed through a simulation software and then created using a three-axis CNC prototyping machine. Once Aeromorph is ready, researchers can inflate it to create the designed three-dimensional shape.

The second project is Programmable materials, a collection of dynamic artifacts made of self-transforming carbon fiber, printed wood grain, custom textile composites and other plastics. The project aims to exploit the properties of functional materials and composites to create highly programmable materials for product design, the fashion industry and architecture: robots without robots. During the last Fuorisalone (2021) at Bulgari's exhibition, the Studio Roosegaarde showed Lotus Oculus. The installation consists of an active wall that unfolds itself and creates a play of light and movement.

In the same trend, we can find all the traditional functional materials. Those comprehend self-cleaning surfaces like the TiO2 cement or paintings, materials optimizing the energy exchange like fluorescent and phosphorescence materials.

A practical example of the application of functional materials is the Smart glass that reacts to the external stimulus by modifying the amount of light that passes through it (Mohamed 2017). Smart glasses can be passive, without electricity, or active so that their properties are controlled and changed when a specific voltage is applied.

Bioxxx

The desire to reduce the environmental impact of materials has led to finding alternatives to traditional materials in the bio-based materials field. The use of renewable resources has had a lower impact, reducing carbon and energy emissions. Bio-based materials also enhance social and living well-being, ensuring a more harmonious environment for human life. However, it should be noted that the use of bio-based materials is not always the most sustainable choice, if, for example, it does not guarantee the same long-term efficiency as traditional materials. To compare and combine bio-based and sustainability words is necessary to take stock of the actual efficiency of these materials. Methods of measuring environmental impact, such as LCA (Life Cycle Assessment), can be used to overcome this problem. The fact remains that materials from renewable resources have less impact on the environment in terms of origin and can be more easily incorporated into a circular economy system.

In this regard, designers and architects have rediscovered some traditional materials as new opportunities for architecture, such as wood, hempcrete, straw and cane (Yadav & Agarwal 2021).

Wood is one of the resources that has always been used in architecture because it is easy to work with and suitable for various uses, both structural and for furniture. Although it has been associated with low-level buildings, wood has gained much more interest in recent years. Furthermore, materials scientists are showing interest in the hygroscopic and orthotropic nature of wood, and its mechanical behavior is becoming a topic of interest to fully exploit its properties (i.e. material properties differ along three mutually orthogonal axes) (Bechthold & Weaver 2017). Moreover, although scientifically speaking bamboo is a grass, it is increasingly valued as a construction material. Its rapid growth and wood-like properties make it a readily available and regenerable alternative to traditional solid wood. Bambuflex, on the other hand, is the first flexible bio-agglomerate of bamboo constituting panels. This material is biodegradable and has thermal and acoustic insulation properties. The raw materials used are 100% of vegetable origin, and the production process has a near or zero impact.

Hempcrete is another emerging material. Hemp is a fast-growing plant that is resistant to flake and mould. The properties of its fibers make it suitable for architecture, both for the insulation panels construction and hempcrete. Hempcrete is a mixture of hemp, water and lime. The low weight of this material compared to traditional cement means that hempcrete can also reduce the amount of energy that a building needs to generate by reducing the emissions associated with moving significant materials (Yadav & Agarwal 2021).

Straw and reed have been widely used materials since ancient times. Some studies have shown that straw, if protected from humidity, is a durable, load-bearing, long-lasting and insulating material. While reed, traditionally used as straw for roofing, can last even more than 50 years if of good quality.

Another significant bio-based material for architecture is rice husk. The Piedmontese company Ricehouse focuses on using waste products from rice cultivation to make building products. The company offers materials based on rice husk and rice chaff. Rice husk, the outermost husk of paddy rice, combined with lime or clay, replaces sand to create an insulating plaster. The dried husk, the middle layer covering the rice, can be incorporated into plaster or paint, making them more elastic, breathable and antibacterial.

Re-discovered

In this category, there are materials from waste and byproducts (Sauerwein et al. 2017). The increasing focus on more sustainable materials has led to attempts to produce traditional materials from recycled sources. Therefore, it is possible to obtain products with similar characteristics to traditional ones but with new aesthetics. Recycling takes place not only for plastic materials but also for metals, ceramics and glass, wood, etc.

An example is Silicastone, a ceramic material made of 98% waste material (recycled glass and porcelain). Its production method respects the environment: all internal waste is recovered, and the material is joined with no binders but heated at a considerably lower temperature than conventional ceramic. The material is available in tile and board form for indoor and outdoor use. By its nature, each piece of Silicastone is unique, and no two surfaces are ever the same.

Another example is the Italian company Stonethica which recycles waste from marble and natural stone processing and assembles them into slabs using a non-toxic two-component resin.

Thanks to the patented process, an average of 80% of the starting material is recovered, resulting in products made up of between 98.6% and 99.4% stone waste. The use of Stonethica contributes to meeting the parameters for assessing the environmental performance of buildings. The final product is a homogeneous material characterized by layered textures due to the overlapping of marble strips that prevent the areas of intersection between the assembled scraps from being perceived.

Finally, PaperStone panels are made from recycled paper and cardboard. After obtaining superimposed layers of paper, these are subsequently impregnated with a resin called PetroFree, coming from cashews. PaperStone uses natural pigments for coloring instead of traditional ones, ensuring greater UV resistance, stable colors and even better color distribution. PaperStone can be easily repaired, cleaned and maintained thanks to a treatment with natural oils, as if it were wood.

Biomimetic

The trend takes its basis from biomimicry. Biomimicry is the study of the biological and biomechanical processes of nature (Benyus 1997; Rossin 2010). From a circular economy perspective, it is very relevant to understand the mechanisms of nature to create systems that regenerate each other.

The designer Lindey Cafsia develops Plyskin, an insulation material that imitates the skin and fur of a polar bear. Plyskin consists of three layers: the outer layer is a white fur made of recyclable polyamide; the second layer has a honeycomb structure, which makes the panel rigid; the third is a black, hollow layer filled with heat-absorbing material.

Another significant project is Responsive Surface Structure by the Department of Form Generation and Materialisation of the HFG Offenbach University of Art and Design. The research project tries to exploit the dimensional changes of wood caused by variations in environmental humidity. The surface structure adapts its skin porosity, and related cross-ventilation, in response to humidity without mechanical control devices. As they report, the response is triggered by the changes in moisture content of the material and actuated through related shape changes in a material element, which affects the structure's degree of porosity.

Water Reaction was conceived by the designer Chen Chao as his end-of-year project at the Royal College of Arts (London). He drew inspiration from the pine cone and its behavior: opening and closing, it releases and protects the seeds. Water Reaction modifies its shape without mechanical structures or electrical elements but only by detecting humidity. The material has already been applied to various products used in water-related contexts, such as outdoor architecture and crops.

Alive

The interaction between materials and the surrounding environment is getting deeper, creating a new dimension of the relation between material and designer. From the metabolic waste of living organisms such as bacteria, fungi and yeasts, new materials have been created that are still being explored. One of the main processes used is biofabrication: producing through the growth of living organisms and cells, using renewable resources as feeding elements for the living organisms, as reported by Camere and Karana (Camere & Karana 2018).

The designer maker works with biofabricated alive materials and experiments with new production methods for tangible solutions applicable to artifacts of the near future.

Mycelium is an example of biofabrication. Developed over the last ten years, this type of natural composite has now found its place in some market sectors. Mycelium is the root and digestive system of mushrooms. It is constituted by uncountable groups of hyphae, which form the vegetative part of the growth of fungi. The mycelium can develop in a few minutes: it is sufficient that the right conditions exist in soil for it to spread rapidly (Yadav & Agarwal 2021). After an initial experimental phase, some companies have started to industrialize this process and exploit the material's low density, acoustic and thermal insulation properties. Today, it is possible to find ready-made solutions such as sound-absorbing panels and floors by Mogu, or packaging solutions, for fashion and food experiments by Ecovative.

Other resources for alive materials are bacteria. Bacterial cultures can give rise to composites used for leather-like or paper-like materials production. These processes require a lot of attention, especially to avoid contamination.

An example is kombucha leather, a cellulosic material deriving from the fermentation of tea. To date, these remain almost experiments, but designers are looking for possible applications in the world of fashion, products and interiors, trying to industrialize the process as best as possible (D'Itria et al. 2021; Papile et al., *in press*).

Materials produced from algae are other alive materials. The algae came mainly from the beaches, preferring harvesting to cultivation. Cultivation would involve a significant use of water and energy. The collected algae are then cleaned to be processed. There are several projects by designers who use this resource. They can use algae as a source of proteins to create bioplastic, like Ari Jónsson did with the bottle he designed. The designer started from agar, and by mixing its powder with water, he obtained a gelatinous membrane with which he made the container. The bottle decomposed immediately after being emptied.

Designer Shneel M. Bhayana has developed another active use of algae with the Bio-ID Lab. The Indus project consists of a modular system of clay tiles inspired by leaves. These clean the water thanks to algae and seaweed-based hydrogel. The project focuses on the rural community of artisans in India, enabling them to regenerate water for reuse within their manufacturing processes. Indus has won several awards, including LafargeHolcim Awards and the Art Foundation Futures Award.

Foodology

In this category, we find materials from food waste. Starting from different waste streams, such as fruit, mushrooms, and proteins of different nature, we get to create yarns, fabrics and bioplastics. These materials constitute a trend that combines the concepts of bio-based and re-discovered. Foodology materials, based on their nature, have anti-bacterial, anti-humidity and thermo-regulating properties.

Totomoxtle is a project by Fernando Laposse in collaboration with the Ejido Tonahuixtla community. The decorative panel is created from a composite material from the colored bracts of native corn. The waste from the corn processing is used to obtain very different products and surfaces. The idea is not only a starting point and an invitation to develop a circular economy but also a warning about the risk of extinction of the diversity of native maize in favour of genetically modified maize.

Another project is Cooking New Materials. At the Fuorisalone 2019, the designer Youyang Song presented her new materials created through a process developed by herself. She has combined banana and orange peel or soymilk pomace with a natural binder as a matrix. The result is a 100% biodegradable, flexible, leather-like material with different finishes and textures that can be easily reused through annealing.

A product already partially industrialized and present on the market is Piñatex. Born from the company Ananas Anam as a plant-based alternative to leather, Piñatex is made from pineapple waste in the form of thin cellulose fibres extracted from its leaves. The latter is generally considered an agricultural by-product often burned or left to rot.

The company, therefore, took the waste from the pineapple plantations in the Philippines from which local factories pic the threads and, through a decortication process, felted them together into a non-woven fabric used for clothing, footwear or furniture.

Meanwhile, the designer Thomas Vailly has explored how to turn sunflower crop waste into bio-materials. Sunflower cultivation traditionally produces oil, seeds, bio-fuel and agricultural waste. The designer exploits the leftover from the harvest to create material with a non-synthetic binder and a non-toxic varnish. As he said: “The rules were simple, we can only use sunflower by-products, no added ingredients [...]” (Hitti 2019). The resulting material is an acoustic insulation panel constituted by the marrow combined with the water-based glue made from the sunflower seeds to form a light and foamy composite material that acts as a natural alternative to polystyrene.

Materials and architecture have a mutually dependent relationship. Materials allow architecture to exist, and architecture enables advances in materials development.

Over the years, we will encounter an intensification of the complexities of the materials world due to the deepening of different research themes. Complexity will concern the technological dimension but, above all, the relationship between man and the environment. Therefore, it will be crucial to look at nature as a source of inspiration but also as a precious gift. Experimentation becomes a fundamental point for creating new functions and aesthetics that offer innovative design ideas for architecture and interior design.

The new materials explored are examples of how different approaches can achieve sustainability.

Designers and architects can take inspiration from nature to create new buildings that ensure human well-being and, at the same time, have a reduced environmental impact.

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CASE STUDIES

Aeromorph
https://tangible.media.mit.edu/project/aeromorph/
Programmable materials
https://selfassemblylab.mit.edu/programmable-materials
Lotus Oculus
https://www.studioroosegaarde.net/project/lotus
Bambuflex
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Ricehouse
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Silicastone
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Sunflower Entreprise
http://studiothomasvailly.com/project/sunflower-entreprise-i/