

Essay

Low-Resource Materials: Rethinking Resource Sustainability in the Construction Sector

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Abstract

In the European context of the ecological transition, the construction sector urgently requires a shift from resource depletion to preservation. This study addresses the heterogeneity of the definition of natural, artificial, renewable, and non-renewable resources in the literature, establishing a coherent framework. Based on the analysis of these definitions, the study delineates the concept of *Low-Resource Materials* (LRMs) as a dynamic repertoire characterised by renewable, restorable, reused, and recycled components aimed at safeguarding material assets. Three core criteria and two indirect criteria for identifying *Low-Resource Materials* have been specified: these are designed to minimise virgin raw material consumption and reduce ecosystem pressure. The *Low-Resource Materials* conceptual framework supports designers in selecting materials and construction systems for the development of sustainable architectures with high material efficiency. Future research should refine this repertoire by evaluating various technical and regulatory thresholds, for the defined LRMs, and assess the acceptable limits of composite elements, to guarantee sustainable options at their end-of-life.

Keywords: bio-based materials; circular economy; Low-Resource Materials; resource consumption; recycling; renewing; reuse; and restorability; sustainable construction

1. Introduction

1.1. The Issue of Material Resource Consumption

The issue of resource management represents one of the foundational principles of contemporary sustainability. Specifically, optimising the management of energy resources fosters a systemic improvement in environmental conditions, particularly concerning air quality and climate change mitigation. However, the ecological sphere includes multiple assets not directly attributable to the energy sector, including material resources. An example is the 2024 report on special waste in Italy, drawn up by the Institute for Environmental Protection and Research (ISPRA) in collaboration with the National System for Environmental Protection (SNPA): 161.4 million tonnes of special waste were generated in 2022 in Italy; of this total, 50 per cent—amounting to 80.8 million tonnes—came from construction and demolition works [1]. Within the current theoretical horizon of “post-sustainability” [2], it is necessary to understand the resource management process in an integrated manner. In light of the concept of sustainability, it becomes fundamental to adopt broader prevention strategies, evaluating how to redefine current priorities instead of focusing almost exclusively on energy consumption.



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In this scenario, European Union policies and initiatives are already geared toward making Europe the first climate-neutral continent, targeting a 55% reduction in greenhouse gas emissions by 2030 and full climate neutrality by 2050 [3]. The Institute for Sustainable Futures at the University of Technology Sydney conducted a study entitled “Fossil Fuel Exit Strategy”, aiming to analyse the feasibility of the gradual fossil fuel phase-out required to keep global warming below 1.5 °C, comparing it with a viable scaling pathway for renewable energy resources. The study reveals that to limit the climate change already underway, it is necessary to halt both the extraction and the expansion of fossil fuel production [4]. Through a series of realistic global predictive modelling scenarios, which account for land resource availability and associated constraints, the study demonstrates that it is possible to rapidly phase out fossil fuels in favour of increased energy production from renewable sources. The results of the investigation show that the global potential for energy production from renewable sources is greater than what is actually required to meet the energy needs of every person in the world [4]. Currently, the production of fossil fuels exceeds demand: the planet has more than sufficient renewable energy resources, and it is possible to expand the infrastructure rapidly enough to meet global energy demand without any overall deficit [4].

If one were to consider the land area required, for instance, by a solar farm to provide the total global energy demand, it would amount to approximately 450,000 km²—corresponding to about 0.3% of the Earth’s land surface. This area is smaller than that currently required for extraction sites, mines, and fossil fuel transport infrastructure, which in the United States alone occupy 126,000 km²—equivalent to 1.3% of the national territory. Furthermore, the fossil fuel industry cannot compete with the technological learning curves of renewable energy; therefore, demand is inevitably bound to decline with the continuous growth of solar and wind energy. At the current overall annual growth rate of 15–20% for solar and wind technologies, fossil fuels will be phased out from the electricity generation and distribution sector by 2035 and from the total energy supply by 2050 [5]. These findings further reinforce data from the think tank Ember—a UK-based independent global organisation that promotes the transition to clean energy through data and policy—which states that in 2025, renewables overtook coal as the primary source of electricity generation globally. Overall, wind and solar accounted for a record 30% share of EU electricity generation, outperforming fossil-derived energy for the first time [6].

A complementary perspective is provided by the International Renewable Energy Agency (IRENA) in its 2026 report. IRENA identifies the transition away from fossil fuels as a systemic transformation centred on the combined development of renewable energy, electrification and energy efficiency. Under its revised 1.5 °C Scenario, the share of renewables in electricity generation is projected to reach approximately 92% by 2050, while the share of fossil fuels in total final energy consumption decreases from 81% in 2023 to around 15% in 2050 [7].

In summary, the considerations outlined thus far present a comprehensive framework confirming that renewable sources can, prospectively, ensure an energy supply sufficient to meet global demand [7].

In such a scenario, where energy sufficiency targets can be easily achieved in the near future, the resource management paradigm will undergo a necessary shift in priorities, moving the axis from energy optimisation to the containment of material resource extraction. Hence, a relevant issue emerges, which is essential for advancing towards a sustainable approach to resource management: the limited availability of material resources. Having established that energy supply will not pose a critical challenge in the future, the other issue that arises is the impending scarcity of raw materials. This topic should be understood not only with reference to critical raw materials, but also—and above all—to materials

currently widely available, such as sand, gravel, clay, and limestone, which could face progressive depletion within a few decades.

The importance of focusing on material use and consumption within industrial processes was highlighted during the presentation of the New Circular Economy Action Plan (CEAP) in March 2020. On this occasion, the Executive Vice-President of the European Commission for the European Green Deal, Frans Timmermans, stated that secondary materials accounted for only 12% of total material use in the economy system—a figure that stands in stark contrast to European policies already initiated to reduce resource consumption. For this reason, the new CEAP aims to ensure that used resources are maintained within the economy for as long as possible, with the objective of converting the traditionally linear European model into a circular one. This is imperative because resource extraction and processing are responsible for half of global greenhouse gas emissions and over 90% of biodiversity loss and water stress [8]. Furthermore, general economic growth, and the subsequent stimulus to the construction sector, drives the global consumption of a larger quantity of raw materials; the use of biomass, fossil fuels, and minerals is projected to double, rising from 89 gigatonnes (Gt) in 2017 to 167 Gt by 2060 [9]. The *Domestic Material Consumption* (DMC), measuring the internal volume of raw materials consumed within the European Union, comprises 55% non-metallic minerals, other products, and waste for final treatment and disposal, 23% biomass, 17% fossil fuels, and 5% metallic minerals [10].

In the Anthropocene, estimates indicate that, for example, in 2026 population demand for natural resources exceeded the regenerative capacity of Earth's ecosystems by approximately 1.7 Earths, representing at least 76% [11]. Consequently, in recent years, Earth Overshoot Day [12] has occurred progressively earlier, a phenomenon driving growing global concerns regarding the sustainability of current production and consumption models. This metric highlights that natural resources are subject to depletion at a rate surpassing the planet's regenerative capacity. Increased overexploitation has accelerated raw material depletion, causing biodiversity loss, climate change, resource destruction, and water scarcity—effects that are most pronounced in the territories hosting the supply sources [11]. Available raw materials are finite, and without a shift in utilisation patterns, they are bound to face progressive exhaustion. Therefore, adopting circular production models is essential to conserve resources over time, preventing extracted and processed materials from being sent to landfills at the end of their life cycle [13]. Any resource can be considered depletable; even those commonly defined as renewable are not infinite, as intensive and unregulated use can compromise natural regenerative cycles, progressively reducing availability and potentially leading to their disappearance. This dynamic underscores that resource sustainability depends not only on their intrinsic nature but also on the capacity of economic systems to adopt responsible management practices that balance consumption rates with renewal timescales.

Considering the construction sector at the European level, it consumes a high quantity of raw materials, as reported by the *Domestic Extraction* (DE) indicator. Defined for the first time in 2018 by Eurostat, this indicator shows the amount of raw materials extracted and employed within the economic process, aiming to describe the environmental pressures exerted on territories both in terms of land degradation and material depletion [14].

A case in point is resources such as sand, clay, and gravel. These are potentially depletable due to their extensive regeneration times; for instance, the natural formation of sand occurs through gradual geological erosion processes: its timescale spans hundreds of thousands of years [15].

The mining industry is the sector responsible for the largest volume of waste globally. For example, producing one tonne of copper generates approximately 110 tonnes of tailings

and requires the removal of 200 tonnes of overburden or topsoil. Within the European Union, mineral waste constitutes the second largest waste stream, representing around 25–30% of all generated waste—a figure projected to rise if mining activities continue to expand [16].

Taking sand as an example, it is a material widely utilised across various domains. Despite being widely distributed and abundant in many territories, it is available in limited quantities for the construction sector, where it serves as a key element for producing two heavily used materials: concrete and glass. Over the past 150 years, the use of concrete has driven an increase in construction productivity and subsequent urban expansion, becoming the predominant building material due to its low cost, high strength, and ease of use: consequently, sand exploitation has increased. To quantify consumption related to reinforced concrete structures, it can be noted that building a standard residential structure requires approximately 200 tonnes of sand, whereas a hospital requires 3000 tonnes. Each kilometre of motorway necessitates 30,000 tonnes, and constructing a nuclear power plant is estimated to require around 12 million tonnes [17]. The global population increased from approximately 3 billion in 1960 to 8.2 billion in 2025. Over the same period, the expansion of built-up areas consistently outpaced population growth, reflecting increasingly material-intensive patterns of development. As the largest component of global material use, sand extraction increased more than fivefold between 1970 and 2020, rising from 9.6 billion tonnes to approximately 50 billion tonnes, corresponding to an average annual growth rate of 3.2% [15]. Given the significant consumption volumes of this material and its relative availability, it is valuable to evaluate its provenance. While vast desert areas potentially exist from which to source the material, desert sand is unsuitable for construction applications; because it is continuously shifted by the wind, it erodes, typically forming rounded grains that fail to bind effectively. Conversely, marine or river sand does not undergo this surface-smoothing process and consists of more angular grains with rough edges, which inherently allow for greater material compaction [17]. The city of Dubai is an emblematic case of this phenomenon; despite being located in the Arabian Desert, it has imported vast quantities of sand from other countries, such as Australia, to construct artificial islands as Palm Jumeirah and Palm Jebel Ali. Furthermore, it is important to note that sand, in its baseline natural state, plays a crucial role within the ecosystem services provided to humanity, preserving biodiversity and supporting economic development [18]. Despite its significance, its extraction, use, and management remain unregulated in many parts of the world, leading to adverse social and environmental consequences. Sourcing sand from marine ecosystems and rivers causes seabed erosion, progressive delta reduction, land-use change, dust-induced air pollution, and threats to biodiversity and fisheries [18].

Another mineral resource requiring closer examination is gravel, the demand for which is projected to grow significantly in the coming decades. According to a 2019 UNEP study, sand, gravel, clay and other aggregates are the second most extracted category of natural resources in the world, after water [15]. From 1970 to 2020, the share of non-metallic minerals, in total global material extraction, increased from 31% to nearly 50% [15]. Despite their extensive use, natural aggregates are becoming increasingly difficult to source, and their production entails significant environmental impacts. Coarse aggregates, generally obtained from crushing bedrock or large boulders, require an intricate process involving drilling, blasting, excavation, crushing, screening, stockpiling, and transport [19]. Environmental impacts manifest as early as the quarry preparation phase through the removal of topsoil and continue throughout all subsequent production, utilisation, and end-of-life phases of the aggregates. During these activities, the operation of vehicles, heavy machinery, and crushing plants drives energy consumption and the subsequent release

of greenhouse gases [20]. These effects are compounded by landscape degradation and instability, water resource contamination, and particulate matter air pollution. Furthermore, extractive activities entail additional environmental impacts, including morphological alterations of the landscape, noise and dust emissions, vibrations from blasting, and the degradation of surface and groundwater [21]. From an ecological footprint perspective, coarse aggregates contribute significantly to terrestrial acidification and eutrophication phenomena associated with concrete production. Indeed, the production of natural aggregates requires a series of initial activities including deforestation, drilling, explosive blasting, and pressure crushing [22]. These processes are exacerbated by open-cast mining activities, which encourage soil erosion, morphological alteration of the terrain, and the degradation of natural ecosystems. In this context, the use of recycled aggregates obtained from recovered waste concrete represents a sustainable and strategic alternative [21]. Compared to natural aggregates, they exhibit a significantly lower environmental impact, with distinct advantages in reducing acidification, aquatic ecotoxicity, ionising radiation, and global warming contributions. The high impacts of natural aggregates stem largely from intensive and invasive extraction methods, which is why their partial or total substitution with recycled aggregates constitutes an effective solution to mitigate environmental damage associated with the construction sector [21].

1.2. Current Pathways to Mitigating Material Resource Consumption

To date, several approaches aimed at material resource conservation and efficiency are available and can be considered best practices. The most prominent methods are *urban mining* and *waste mining*. These strategies partially alleviate the vulnerabilities of the current resource supply chain without altering its underlying logic. Developed in response to resource scarcity and the environmental impacts of extraction, these practices exploit the existing built environment as an “open-cast mine”. Complementary approaches operate at the product and design level, where tools such as the Material Circularity Indicator (MCI) can be used to assess and compare product circularity and to inform design and procurement decisions [23]. Similarly, the Cradle-to-Cradle Certified Circularity framework establishes measurable objectives for circular product development, encouraging products to be designed for subsequent use cycles through reuse and recycling pathways [24]. While the problem is mitigated, the core issue remains unresolved. Within a closed system, raw materials do not disappear but instead end up in forms that are no longer immediately usable, such as virtually unrecoverable residues. Therefore, the “loss” of raw materials implies that they are no longer available in a form useful to our production processes [13].

Conversely, in both new construction projects and the retrofitting or renovation of the existing building stock, material conservation can be addressed through a conscious design approach based on a careful evaluation of the resources used and the methods by which they are transformed and assembled. In this context, the principles of Design for Disassembly and Adaptability (DfD/A) can be incorporated from the early stages of the design process to facilitate the future disassembly, modification, and repurposing of building components, thereby reducing unnecessary removal and new construction while improving resource efficiency [25]. From this perspective, design plays a pivotal role in reducing material consumption, not only through quantitative reductions in material use but also via the meticulous selection of building components based on their origin, durability, reuse potential, recyclability, and life cycle environmental impact. Design oriented towards material efficiency limits the use of non-renewable resources by favouring renewable materials and reversible construction systems. This approach extends the service life of buildings, reduces waste generation, and curtails the extractive and manufacturing processes associated with

the construction sector, thereby contributing to the transition towards more sustainable and circular building models. However, while these approaches contribute to reducing raw material consumption and appropriately emphasise the design phase—shifting responsibility from industrial production to client and designer decision-making—they focus primarily on structural and product reversibility rather than encouraging considerations of the different material categories to be adopted.

A further strategy applied in recent years to both new constructions and renovation interventions through material-efficient design is the use of bio-based materials. Interest in bio-based products stems from the need to reduce the consumption of non-renewable virgin resources and limit the environmental impacts associated with fossil-derived materials [26]. In this context, Mousavi-Avval et al. [26] highlight how growing concerns regarding climate change, fossil resource depletion, and greenhouse gas emissions have intensified global efforts toward a transition from fossil-based to bio-based products. Numerous scientific studies underscore that utilising biologically sourced materials can significantly reduce the environmental footprint of the construction sector while promoting resource efficiency [26–32]. In this scenario, the construction sector is progressively adopting strategies aligned with the circular economy and the bioeconomy. Transforming the built environment from a linear to a circular economic model represents one of the primary strategies to mitigate raw material consumption and life cycle emissions of buildings. Many countries are promoting the development of a bioeconomy specifically to mitigate climate change and reduce reliance on fossil resources [30]. Concurrently, the bioeconomy offers the opportunity to replace conventional materials with renewables characterised by low greenhouse gas emissions [29]. Within the building sector, the development and utilisation of bio-based materials can help counter climate change and other environmental impacts. At the same time, the circular bio-based economy is characterised by reuse, regeneration, recycling, the cascading use of bio-based products and their residues, and the exploitation of organic waste streams. The increasing deployment of bio-based products reduces petroleum consumption by substituting petrochemical derivatives, thereby decreasing dependence on non-renewable fossil resources and enabling more sustainable resource use [26–30]. According to several authors, their application could drastically reduce landfill waste and offer opportunities to significantly lower CO₂ emissions and fossil fuel consumption [29–31]. However, due to their intrinsic characteristics, many of these materials—with the exception of individual cases such as wood—cannot withstand excessive loads and are consequently unsuitable for structural functions. Indeed, natural fibres and materials present disadvantages regarding load-bearing capacity: they are anisotropic, which complicates the interpretation of their mechanical behaviour, and they are generally not robust enough to support heavy structures [33]. These materials display non-uniform mechanical properties, including variations in strength, stiffness, and durability, necessitating careful evaluation during the design phase. Furthermore, issues related to moisture absorption, fire resistance, and long-term performance must be addressed to ensure the structural integrity and long-term performance of bio-based composite structures [34].

As demonstrated, while bio-based materials or materials derived from urban or waste mining represent a priority strategy across multiple technological applications, they cannot independently satisfy all the requirements demanded in a new construction or renovation intervention. Consequently, it is indispensable to integrate this approach with the use of complementary materials.

1.3. Aim of the Research

In light of the considerations outlined above, the research presented herein aims to define a conceptual framework to support the selection of building materials and compo-

nents for the construction sector, capable of reducing raw material consumption in both new construction and building renovation and retrofitting.

In recent years, research into sustainable building materials has produced plenty of definitions and developed numerous classifications aimed at finding ways to mitigate the environmental impacts of the construction sector. These include, for example, low-impact materials, low-carbon materials, regenerative materials, resource-efficient materials and circular materials; each address specific characteristics of material sustainability and priorities, respectively: the reduction in life cycle environmental impacts; the reduction in embodied greenhouse gas emissions; the contribution to the restoration of natural systems and the generation of positive environmental and social outcomes; the efficient use of resources and the preservation of material value throughout the life cycle; and the reduction in material flows to minimise resource consumption and waste generation. Their definitions are set out below to provide a better understanding of the overall context.

According to the *Sustainable Directory*, a *low-impact material* can be defined as “[...] a resource whose entire life cycle, from extraction and processing to use and disposal, has been optimised to minimise its negative environmental, social, and economic consequences” [35]. Analysing the etymology of the expression, the term “low” denotes a reduction in negative environmental impacts, while “impact” refers to ecological and social effects. The term “material” indicates the fundamental components of products and infrastructure. A low-impact material is therefore a resource selected for its minimal negative effect on the environment throughout its life cycle, the optimisation of which is quantified through Life Cycle Assessment (LCA). Although the concept of low-impact materials represents an approach for evaluating environmental impacts throughout the material life cycle, it focuses predominantly on measuring the environmental consequences associated with production and utilisation processes. In particular, the concept centres on carbon reduction with reference to the 2030 and 2050 targets set by the European Union, thus limiting its scope.

Another classification involves *low-carbon materials*—also known as low-embodied-carbon materials—whose specific aim is to reduce the greenhouse gas (GHG) emissions embodied in the material: “Low embodied carbon (LEC) materials (commonly referred to as low carbon transportation materials or low carbon materials) have low climate impacts throughout their life cycle, specifically in terms of the embodied greenhouse gas emissions (GHG) associated with extraction, processing, transport of material to final manufacture, and manufacturing. The term generally refers to materials with lower GHG emissions as compared to similar materials” [36]. In many cases, the carbon footprint is assessed through the concept of embodied carbon, which accounts for the emissions associated with the various stages preceding and accompanying the use of a material. Depending on the system boundaries adopted, these may include the extraction of raw materials, their processing, transportation, and manufacturing. Accordingly, the category of low-carbon materials primarily focuses on reducing carbon emissions in line with the sustainability targets established by the European Union. A material may therefore be considered low carbon in comparison with an equivalent alternative without necessarily implying lower resource consumption, a high proportion of recycled content, or the potential for material recovery at the end of its service life.

A further perspective is represented by *regenerative materials*, a concept that forms part of the broader paradigm of regenerative design. These materials are defined as “[...] building materials and technologies that can support a positive sustainable development, thanks to their low (or negative) impacts on environment and well-being, and instead contributing to the local economy, supporting environmental remediation and providing

for safe and comfortable solutions for the users and workers” [37]. Examples of regenerative materials include bio-based materials such as bamboo, straw, and hemp-based technologies, as well as wood- and earth-based solutions. Furthermore, the application of a regenerative approach to the construction sector encompasses the use of recycled and upcycled building components, construction waste, and residues from other processes, such as plastics and demolition waste, through a range of strategies aimed at enabling their transformation and reuse [37].

Another concept that has been developed is *resource-efficient material*, which differs significantly from the previous ones since it does not identify specific materials but rather a principle of resource management. According to the OECD, resource efficiency is “[...] materials are used efficiently at all stages of their life cycle (extraction, transport, manufacturing, consumption, recovery and disposal) and throughout the supply chain. Moving towards a resource-efficient and circular economy is critical from both supply security and environmental perspectives and provides the basis for a sustainable and competitive economy” [38]. Resource efficiency thus refers to the ability to achieve a given function by using fewer resources or by preserving the value of materials for a longer period. Trade policies can promote greater resource efficiency by fostering economies based on recycling processes, ensuring regulatory consistency across different waste management frameworks, and addressing issues relating to exports to countries with inadequate recycling facilities [38].

Closely linked to resource management based on resource efficiency is the concept of circular economy. The circular economy is defined as a principle which “aims to maximise the value added of products and services in the economic value chain, both to minimise residual waste and to ensure that resources remain in use for longer” [38]. The definition allows for optimised resource management; therefore, when materials reflect the principles of the circular economy, we can talk about *circular materials*. In the construction sector, circularity can be pursued through a range of strategies. The OECD identifies three main mechanisms for reducing demand for natural resources: (i) creating material loops by replacing virgin raw materials with secondary materials and recovered, repaired, or remanufactured products; (ii) slowing material flows by extending the lifespan of products and keeping them in use for longer periods; and (iii) narrowing material flows through more efficient resource use, technological innovation, and changes in consumption patterns [38].

Linked to it, the European Environment Agency highlights that a range of technologies and tools can be relevant to a sustainable building system. Among various examples, sustainable products can be cited, for which there is an increase in research and development activities related to the use of recycled, *low-impact*, and sustainable construction materials capable of reducing a building’s environmental footprint [39].

In addition to the aforementioned categories of materials, the construction sector can rely on several strategies, certification protocols, and indices that aim to verify or certify the sustainability of a building or construction process. Examples include the LEED and Level(s) frameworks, the Ellen MacArthur Foundation’s Material Circularity Indicator, and the implementation of material passports to track construction products. Although these tools undoubtedly foster more sustainable building design and management, they do not fully address the gap identified in this research. Despite their diversity, they focus primarily on evaluating environmental indicators of specific materials; however, they offer no guidance on how these materials can be effectively combined throughout the entire construction sequence—from foundations to finishes. All things considered, existing tools and policies serve as valuable instruments for ex-post sustainability assessments or for guiding targeted material selections. Yet, they lack a comprehensive perspective on

selecting and combining resources and materials to maximise raw material savings, failing to account for both the intrinsic properties of individual materials and their synergistic potential to minimise overall material consumption.

The present research aims to address the gaps identified above. To this end, a repertoire of materials sharing common characteristics has been identified, termed *Low-Resource Materials* (LRMs). In particular, attention has been paid to the capacity to limit the use of non-renewable resources by using materials that implement renewability, recycling, reuse, and restorability, and which simultaneously support the implementation of new supply chains. For this reason, the proposed approach combines bio-based materials with others that, despite being artificial and/or non-renewable, can minimise the overall consumption of finite resources in a building's construction.

This new category aims to introduce a more realistic and operational approach to resource management, one that does not exclude non-renewable materials but instead aligns their use with reduction, optimisation, and circularity strategies, whilst promoting the maximum possible utilisation of renewable resources. The concept of *Low-Resource Materials*—which is based on the assumption that in the near future a large share of energy will be generated from renewable and non-polluting sources—does not rely on reducing energy consumption or emission impacts, which are extensively covered by other approaches, but instead explores the relationship between architecture, construction materials, and raw material wastage. However, it must be noted that this relies on the assumption that most energy used in industrial and construction processes will originate from renewable sources; such a shift will not only reduce the embodied energy of materials, but also lower the embodied carbon and environmental impacts associated with conventional fossil fuels.

The objective of this research was therefore twofold: (i) to elaborate on the concept of the *Low-Resource Material* (LRM) and formulate its definition; and (ii) to define the criteria needed to structure an initial inventory of materials—which can be subsequently expanded—that qualify due to their characteristics. Therefore, the concept and framework of *Low-Resource Materials* will be outlined, and a preliminary repertoire of materials falling within this category will be presented.

2. Materials and Methods

To achieve the research objectives, semantically based clusters were defined to subdivide and classify the range of materials commonly used in construction. This clustering process was conducted starting from four core concepts related to material resources: natural, artificial, renewable, and non-renewable. A selection of definitions for the four criteria was therefore examined and identified based on their relevance within the scientific and institutional debate, drawing from both the academic literature and regulatory documents of international bodies or organisations.

The adopted approach enabled the development of progressively more detailed clusters, thereby identifying specific categories of materials that—thanks to their ability to preserve natural resources or limit their consumption—could be classified as *Low-Resource Materials*.

2.1. Natural and Artificial Resources

The analysis initiated by examining the concept of a natural resource. The definitions proposed in the literature, as reported in Table 1, show considerable heterogeneity, which can be attributed to the use of the term across different disciplines: economics, ecology, geography, and socio-politics. Among the various definitions identified and analysed, it

is possible to recognise certain common and recurring conceptual cores, which allow the contributions to be organised into coherent interpretative groups.

Table 1. Definitions of natural resources present in the literature and analysed in this document.

Year	Definition	Reference
n.d.	“Factors of production provided by nature. This includes land suitable for agriculture, mineral deposits, and water resources useful for power generation, transport, and irrigation. It also includes sea resources, such as fish and offshore mineral deposits”	[40]
2009	“From the perspective of economics, resources are considered factors of production. Resources can be mined, extracted, or harvested as raw materials that go into sustaining our economy. Such natural resources are distinguished from other forms of human resource (like labor or technology)”	[41]
2008	“natural assets (raw materials) occurring in nature that can be used for economic production or consumption”	[42]
n.d.	“all food, mineral, water and energy resources on Earth that are immediately available to humankind and of use to it” ¹	[43]
2025	“The natural resources, which includes the nonliving or “abiotic” portion of nature, comprise the air, water, soil, minerals, climate, solar energy and the “biotic” or “living” components of nature which are made up of microbes in addition to plants and animals”	[44]
2020	“The term natural resources include soil (all minerals and fossil fuels), water, air and biological diversity [. . .]”	[45]
2023	“materials and substances that occur in nature and are valuable to humans for various purposes [. . .]”	[46]
n.d.	“any biological, mineral, or aesthetic asset afforded by nature without human intervention that can be used for some form of benefit, whether material (economic) or immaterial”	[47]
2002	“Natural resources are materials, energy, and their attributes [. . .] including solar and biological resources, as well as their attributes (for example, some societies value an aesthetically pleasing landscape view as a natural resource)”	[48]
2006	“Management of natural resources has become a contentious and divisive issue throughout the world. The natural environment is the basis of all economic activity and provides humans with food and water, raw materials needed for the production of consumer goods and services, and ecosystem goods and services [. . .]. Ecosystem services include air and water purification, mitigation of floods and drought, detoxification and decomposition of wastes, generation and renewal of soil, biodiversity, partial stabilization of climate, nutrient cycling and pollination, and others”	[49]
2009	“The term ‘natural resources’ refers to the functional utility that social groups derive from the environment and is widely used in human geography. Natural resources is also a deeply problematic term, because the attribution of utility and value to the nonhuman world is one of the primary means by which dominant social groups impose order and control upon the world”	[50]

To complete the conceptual framework, it is necessary to define artificial resources (Table 2), which configure themselves as complementary elements to natural resources.

Table 2. Definition of artificial resources present in the literature and analysed in this document.

Year	Definition	Reference
2025	“[. . .] created through chemical reactions, e.g., plastics (e.g., polyethylene, polypropylene, PVC), synthetic fibers (e.g., nylon, polyester)”	[51]

2.2. Renewable and Non-Renewable Resources

Following the distinction between natural and artificial resources, a further analysis is required to classify the different materials belonging to the construction sector. Indeed, it is possible to distinguish natural resources according to their capacity to regenerate in the short or long term, differentiating between what can be considered renewable and what cannot. To this end, a literature search was conducted to select definitions of renewable resources, displayed in Table 3, which collectively contribute to outlining the conceptual framework.

Table 3. Definitions of renewable resources present in the literature and analysed in this document.

Year	Definition	Reference
2002	“Renewable resources are those that are continually available, like solar energy and wind power, or that can be replaced within the lifespan of humans such as wood, plants, and animals”	[48]
2019	“Resource that is grown, naturally replenished or naturally cleansed, on a human time scale”	[52]
1976	“A material may be defined as “renewable” if the supply can be restored or replenished when the initial stock has been exhausted. In this sense, geological materials deriving as they do from a relatively static condition are commonly thought of as nonrenewable. Biological materials derived from dynamic growth processes are thought of as renewable”	[53]
2008	“Renewable natural resources are natural resources that, after exploitation, can return to their previous stock levels by natural processes of growth or replenishment. Conditionally renewable resources are those whose exploitation eventually reaches a level beyond which regeneration will become impossible. Such is the case with the clear-cutting of tropical forests”	[42]
2014	“Material that is composed of biomass and that can be continually replenished”	[54]

To complete the conceptual framework, reference can be made to the OECD, which provides a definition of non-renewable resources: “Non-renewable natural resources are exhaustible natural resources such as mineral resources that cannot be regenerated after exploitation” [42] (p. 365). This latter definition definitively and with certainty excludes from the sphere of renewable resources those natural elements characterised by extremely long regeneration periods.

3. Results

3.1. Analysis of the Definitions of Natural and Artificial Resources

With reference to the definitions reported in Section 2.1, a notable heterogeneity can be highlighted regarding the concept of a natural resource. This variability is attributable to the different disciplines—namely economics, ecology, geography, and socio-politics—that generated them. It is possible to identify certain common and recurring conceptual cores that allow these contributions to be organised into coherent interpretative groups.

A first group interprets natural resources from an economic-productive perspective, considering them as factors of production or fundamental inputs derived from nature for the functioning of economic systems. From this perspective, Oxford Reference [40], Neo [41], and the OECD [42] interpret the concept of natural resources as material assets provided by nature that can be utilised in production processes following extraction or cultivation. According to these authors, they acquire value as production factors and are primarily considered in terms of availability, accessibility, and their capacity to generate

economic outputs, rather than solely for human well-being. The definitions highlight their role in production and consumption processes, conceiving them as assets originating from nature that are available to be extracted, harvested, or cultivated, and subsequently transformed to sustain economic activities.

A second group of definitions, proposed by the Enciclopedia Treccani [43], Jain et al. [44], and Sala Lizarraga et al. [45], focuses primarily on the typology of resources. These confirm a complex and systemic view of natural elements. In particular, Jain et al. [44] propose a division of resources into abiotic (air, water, energy, and soil) and biotic (biomass, microorganisms, and animals).

A third group, identifiable through the definitions proposed by Ali et al. [46], Encyclopaedia Britannica [47], and Arocena et al. [48], suggests an interpretation that considers the relationship between resources and humans, focusing on the value and utility of resources for human beings. Notably, Arocena et al. [48] introduce a relevant element by identifying a cultural value dimension of natural resources.

In addition to these three identified groups, there are other explications of the natural resource concept in the literature, including two that diverge from the previous ones. The first, defined by Prato [49], positions itself within an ecological perspective, highlighting that natural resources play an important role within environmental systems and ecosystem services. This vision significantly expands the concept of a resource, including not only tangible elements but also ecological functions essential for maintaining life and socio-economic systems. Indeed, by ecosystem goods, the authors mean products such as timber, biomass fuels (coal, crude oil, and natural gas), and natural fibres (cotton and wool) used for the production of intermediate goods (such as construction timber, aluminium, and inorganic fertilisers) and/or consumer goods and services (such as housing, automobiles, clothing, and healthcare). The second definition, articulated by Bridge, adopts a critical and socio-political perspective, emphasising how the attribution of value to nature represents a process through which dominant social groups exercise control over natural elements. This highlights the issue that the concept can have a relational character, as it is tied to dynamics of power and culture, as well as economics.

Overall, this collection of definitions highlights that the concept of a natural resource is based on a dual structure. On one hand, phrases such as “provided by nature”, “immediately available on Earth”, “occur in nature”, “derive from the earth”, “afforded by nature”, “derived from the environment”, and “occurring in nature” all refer to the provenance and formation of resources. They underscore that natural resources exist independently of human action and are generated by a succession of natural processes. On the other hand, expressions like “for humans and useful to them”, “improving the quality of human life”, “used for benefit”, “functional utility”, “widely used in human geography”, and “for economic production or consumption” refer to the functional dimension—namely, the purpose and utility that resources have for human society. In this case, the focus shifts to their role in satisfying needs, economic production, and human well-being. These two groups of expressions define natural resources as the result of the intersection between an origin in nature and the attribution of value for humans. A natural resource is not such simply because it exists in nature; rather, it acquires this status the moment it is recognised and used by humans for a specific purpose, thereby becoming a “resource”. The concept of a resource implies a relationship between the natural element and the social system that attributes value and utility to it. Over time, advancements in knowledge and the implementation of technologies allow natural elements that previously had no utility to become resources. They are therefore a dynamic concept that evolves over time, reflecting how humans use the environment to satisfy various needs. As definitions of natural resources,

they contribute to outlining the assembly of natural “things” that possess function and utility for humans.

From this perspective, the analysis has been extended to the concept of an artificial resource, which constitutes the second major set of elements employed by humans to satisfy their needs by transforming natural elements themselves. In the definition proposed by Pacana and Siwec, an artificial resource is characterised by an anthropogenic origin; in fact, they are obtained through man-made transformation processes that alter the structure of the raw material to produce materials with specific properties. Unlike natural resources, whose availability and composition depend on environmental processes, artificial resources are the result of production processes controlled by humans. In the construction sector, this category includes numerous polymeric and synthetic materials, such as plastics and man-made fibres, which are used for their functional performance and their adaptability to design requirements.

Taking these considerations into account, it is appropriate to make a specific clarification regarding the relationship between natural and artificial resources, as the transformations a resource undergoes can vary significantly. Some processes involve predominantly physical–mechanical modifications that do not substantially alter the original structure of the material, whereas others involve deeper chemical transformations that irreversibly modify its characteristics. In the latter cases, the resource loses its original configuration and can no longer be traced back to its initial natural state. Based on this distinction, the concept of a transformation limit is proposed, understood as the threshold beyond which human intervention substantially modifies the original nature of the resource, transforming it into an artificial material. This limit can be identified both in the presence of chemical alterations or when processing methods or modes of use render the resource officially irreversible, meaning it is no longer recoverable or usable in its original state. It should be noted that within the scope of the proposed definition, despite the most commonly used meaning of “artificial materials”, even products exclusively made with natural elements, which undertook man-made processes that modified their reversibility option, can be considered artificial materials.

In the case of wood, for example, operations such as cutting, drying, shaping, or glueing represent interventions that, while altering the shape and performance of the material, do not substantially modify its underlying chemical composition. Unlike fully synthetic composites, wood retains much of its hierarchical structure after mechanical processing, preserving a direct connection to the biological resource. Even in engineered wood products such as glulam, CLT and LVL—where chemical adhesive bonding is irreversible—structural elements such as beams, columns, and panels can be reclaimed. Provided that the overall assembly features detachable connections, these components remain reusable either directly or through secondary processing and resizing. Biological processes that alter its composition—such as growth or ageing—occur autonomously, without direct human intervention. On the other hand, OSB, particleboard and MDF panels are considered artificial, as the manufacturing process substantially alters the material, which behaves like a composite rather than in accordance with the mechanical strength properties typical of timber. Furthermore, other examples are hemp or rice blocks, which use cement or lime in their composition, and cannot be reversed; thus, they fill in the artificial materials definition.

The case of the cement manufacturing process is different: here, raw materials such as marl or limestone would maintain their composition if left in their natural state; however, through high-temperature industrial processes, they are transformed into a binder with profoundly different chemical and physical characteristics, resulting in an artificial material. An analogous consideration can be made for lime, whose production (quicklime) derives

from an anthropogenic thermochemical transformation. Following its application, the material undergoes a natural carbonation process that alters its crystalline structure, and any subsequent regeneration processes require a further industrial treatment that once again alters its composition.

As for concrete, it incorporates other natural raw materials, specifically coarse and fine aggregates such as gravel and sand. Their combination forms a composite material with mechanical and physical properties fundamentally distinct from those of its individual constituents. Once bound, these natural aggregates cannot be fully isolated from the cementitious matrix or restored to their primary state for reuse in their original capacity across other applications. The hydration and hardening reactions of concrete induce irreversible physical–chemical transformations across the matrix, classifying concrete as a synthetic composite material. Although end-of-life concrete can be processed into recycled concrete aggregate (RCA), the resulting material exhibits fundamentally different physical properties compared to virgin aggregates. This distinction is particularly critical in the fine fraction (recycled sand), where performance is severely constrained by a high content of residual attached mortar, leading to increased water absorption and reduced mechanical performance.

Finally, the case of steel represents a particularly significant example of an artificial material obtained from a natural resource. Iron, present in nature in the form of mineral oxides, undergoes a series of complex industrial transformations that profoundly modify its structure. Through high-temperature smelting processes, the ore is separated from impurities and subsequently refined and alloyed with other elements to obtain various steels. In this case, the transformation is not only physical; indeed, a modification of the chemical composition and microstructure of the material occurs, determining completely new mechanical and performance characteristics compared to the original raw material.

The processing limit that distinguishes a natural material from an artificial one can therefore be identified by the presence of an irreversible physical or chemical transformation performed by humans. In this sense, artificial materials can be defined as products that, despite originating from resources within the biosphere, are profoundly modified by human intervention at a chemical level, to the point of partially or totally losing their original characteristics.

3.2. Analysis of the Definitions of Renewable and Non-Renewable Resources

Regarding the concept of a renewable resource, its definitions were identified and reported in Section 2.2. The formulation by Arocena et al. [48], like others, brings together two fundamental elements: (i) continuous availability and (ii) regeneration through natural processes within a timeframe compatible with human activity. The temporal criterion associated with the concept of renewability is also explicitly indicated by the British Standards Institution. In the contribution provided by the National Resource Council [53], a distinction emerges between resources generated by dynamic growth processes, such as biological resources, and those formed under substantially static conditions, such as geological resources; this contribution defines a distinction between what is renewable and what is not. The OECD [42] introduces the concept of “conditionally renewable” resources, emphasising that renewability cannot be considered unlimited, as it depends on the level of human exploitation. Similarly, the European Environment Agency addresses the balance between consumption and regeneration, clarifying how renewability is conditional upon use not exceeding the net rate of regeneration, thereby integrating the principle of sustainability into the concept itself, as done by the OECD. Finally, the definition by the European Committee for Standardisation [54] narrows the scope of appli-

cation to that which is derived from biomass, providing a regulatory basis for identifying bio-based materials.

From a comparative analysis of these definitions, it emerges that the concept of renewable resources is based on three main criteria: (i) the capacity of natural regeneration, (ii) the compatibility of regeneration with the human timescale and (iii) the balance between the rate of use and the rate of renewal. In general, a direct correlation emerges between natural resources and the concept of renewability. Renewability cannot, therefore, be considered an absolute property, but rather a dynamic condition that depends on management methods and levels of exploitation.

Based on this analysis, within the present study, only those resources that jointly satisfy the criteria of natural regeneration and temporal compatibility with human activity are considered renewable. Materials whose formation requires geological timescales of development—as suggested by the OECD [42]—or that are unable to regenerate their reserves through biological processes are therefore excluded. Furthermore, the issue of the rate of use is set aside, implicitly assuming that resources are employed responsibly, avoiding overexploitation.

3.3. Definition of the Concept of Low-Resource Material

Based on the definitions analysed, the conditions specifying the concepts of natural or artificial and renewable or non-renewable resources have been formulated.

Regarding the first concept, the characteristics that define a natural resource (NR) can be outlined as follows:

- Materials and substances originating directly from nature;
- Materials and substances extracted or cultivated as raw materials;
- Assets that acquire value by being useful to humans and contributing to economic production.

Consequently, artificial resources (ARs) can be characterised as follows:

- Derived from materials present in nature;
- Elements that modify natural raw materials through physical and/or chemical transformation processes;
- Obtained through techniques and technologies developed by humans.

Regarding the second group of resources, renewable resources (RRs) can be defined as follows:

- Of biological origin;
- Generated by dynamic growth processes;
- Characterised by continuous availability;
- Elements whose regeneration occurs through natural processes compatible with the human lifespan;
- Resources whose exploitation must not exceed the net rate of regeneration.

Therefore, non-renewable resources (NRRs) are

- Depletable;
- Unable to regenerate after exploitation.

Based on these characteristics, the boundaries of the main clusters were defined, and, at the same time, categories of construction materials were placed within these boundaries (Figure 1): these latter are examples of the main ones but can be further integrated based on the description and characterisation of each material. It should be borne in mind that, since the research objective focuses on resources for the construction sector, energy resources can be identified as natural and renewable resources but have not been included in this analysis.

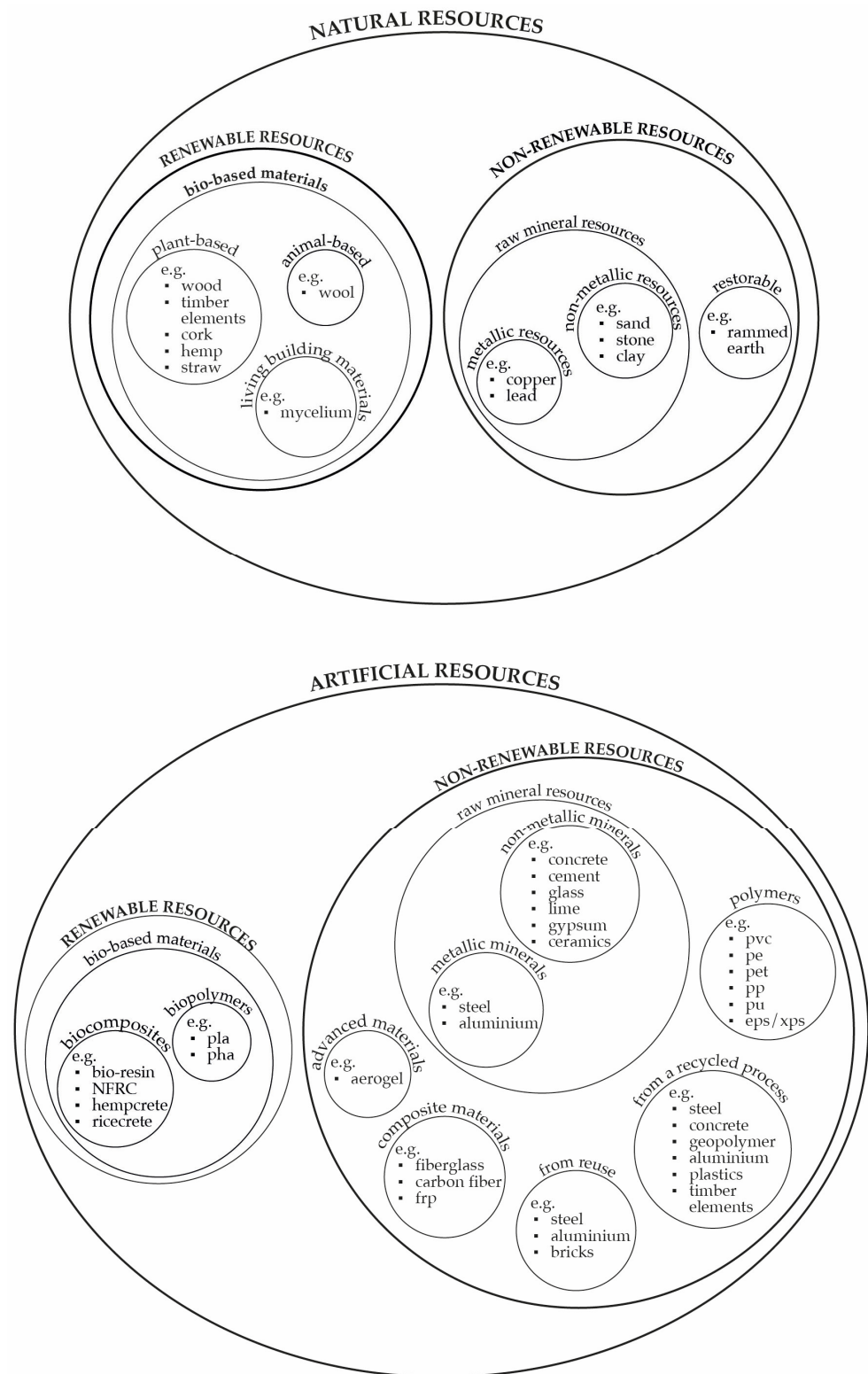


Figure 1. Graphical representation of the semantic clusters deduced from the resource classification criteria.

The diagram in Figure 1 is the graphical representation of the semantic clusters deduced from the criteria outlined above. This is an interpretive model, to be used for identifying those materials that do not—or only partially—deplete material resources despite belonging to a cluster where non-renewable resources tend to reside. The uniqueness and originality of this interpretive model lie precisely in the fact that the usual distinctions between renewable and non-renewable and between natural and artificial materials—which

traditionally influence the classification of so-called “sustainable” materials—do not constitute fixed boundaries. Instead, they form permeable clusters within which to identify materials that are useful, if not essential, for the realisation of sustainable architectures. In Figure 1, both construction and building materials can be found in the presented clusters, as both can be used as construction products.

From this conceptual synthesis, the definition of LRMs is formulated as follows:

“Low-Resource Materials are construction and building materials of natural or artificial origin that prioritise the use of renewable resources and recycled content, minimise the use of non-renewable virgin raw materials, and avoid highly invasive extractive processes. Consequently, they also generate lower emissions of CO₂ and other pollutants during the production phase and contribute to waste reduction throughout the entire life cycle, while ensuring adequate technical performance”.

Based on this conceptual definition, the identification of materials attributable to the LRMs category relies on fulfilling the following three core criteria:

1. Reduced use of virgin raw materials and preference for renewable resources;
2. Limitation of highly invasive extractive processes;
3. Maximum percentage of recycled content for non-renewable materials.

The three criteria outlined above identify a range of construction and building materials and products that, in addition to reducing raw material consumption, contribute, indirectly, to minimising waste generation and reducing emissions of CO₂ and other pollutants. However, because they do not all contribute in equal measure to waste and pollutants reduction, two secondary criteria have been established to refine the selection when narrowing down a set of previously identified LRMs. These additional criteria are

4. Reduction in waste throughout the entire life cycle;
5. Reduced emissions of CO₂ and other pollutants.

These five criteria reflect the need for materials to significantly limit the use of virgin raw materials, favouring renewable resources or those originating from secondary streams. Furthermore, extractive processes that entail significant impacts on ecosystems—such as irreversible soil alterations, destruction of natural habitats, or landscape degradation—must be avoided. In addition, they must consist of a significant proportion of recycled material from post-consumer or production waste, thereby contributing to closing production loops and reducing the demand for primary resources. This material recycling objective should be defined differently depending on the technical characteristics of the various elements as well as the availability of secondary raw materials and recyclable waste, and it should be based on both technical limits and national regulations. For instance, for structural applications, steel products are required to contain a minimum proportion of recovered or recycled material and by-products. The minimum content is 75% for non-alloyed electric-furnace steel, 60% for alloyed electric-furnace steel, and 12% for steel produced through the integrated cycle [55]. As another example, for concrete, as set out in the Italian Technical Standards for Construction updated in March 2023, the maximum proportion of recycled aggregates that may be used depends on the concrete’s exposure and strength classes, as well as on the origin and composition of the recycled material. The regulations permit the incorporation of up to 30% recycled aggregates consisting exclusively of concrete in structural use with a strength class of C30/37. This proportion increases to 60% for concrete with a maximum strength class of C20/25, while, for non-structural applications, the proportion of mixed recycled aggregates may reach 100% [56]. This implies favouring solutions that allow for reuse, disassembly, recycling, or recovery, promoting the continuity of material cycles.

Materials must also contribute to minimising waste generation during the manufacturing phase, throughout the construction of the building, and at the time of decommissioning. Finally, the reduction in CO₂ emissions is one of the key parameters currently considered in sustainability protocols. For this reason, this fifth criterion has been included, although the research is based on the assumption that low-carbon energy sources are widely used, and the materials used are expected to exhibit low greenhouse gas emissions and other atmospheric pollutants throughout their entire life cycle, including the extraction, production, end-of-life, and transport phases, weighing both the distance and weight of the materials.

As abovementioned, from a procedural standpoint, criteria 4 and 5 serve as additional parameters for identifying the most suitable material from options selected using the three core criteria.

3.4. Categories of Low-Resource Materials

To correlate the types of resources described in Section 3.3 with the concept of LRMs, Table 4 outlines their inherent characteristics, highlighting those that align with the LRM framework. It should be noted that LRMs, as other classifications, are not expected to meet all the characteristics listed to be classified as such; the table thus shows that the category of *Low-Resource Materials* can include a range of construction and building materials with different characteristics.

Table 4. Relationship between the defining characteristics of natural resources (NRs), artificial resources (ARs), renewable resources (RRs), non-renewable resources (NRRs), and the characteristics encompassed by the *Low-Resource Materials* (LRM) concept.

Characteristics	NR	AR	RR	NRR	LRM
Derived from nature	x		x		x
Extracted or cultivated as raw materials	x				x
Economic value and utility	x				x
Physical and/or chemical transformation		x			x
Human-made production processes		x			x
Biological origin	x		x		x
Dynamic regeneration			x		x
Continuous availability			x		x
Regeneration within human timescale			x		x
Sustainable harvesting below regeneration rate			x		x
Depletable				x	x *
Do not regenerate after exploitation				x	x *

* The definition of LRMs may also include certain non-renewable materials, but only if they have already been extracted and can be recovered through a recycling process.

Similarly, Table 5 is provided to correlate other classifications of materials explained in Section 1.3 with the concept of LRMs.

Based on this approach, Figure 2 represents a first application of the interpretive model to identify a repository of LRMs. It illustrates the categories of construction and building materials that belong to the LRMs, which highlights first and foremost the two main clusters consisting of natural resources and artificial resources, subsequently broken down into the subcategories of renewable and non-renewable. Within these macro-categories, examples of construction and building materials belonging to the construction sector have been placed to highlight their origin, degree of transformation, and resource utilisation methods. It should be noted that, as already stated, the presented figures are not all-encompassing of all possible resources and materials within each category. Instead, a selection of representative

examples has been provided, focusing on those that are currently the most widely available on the market.

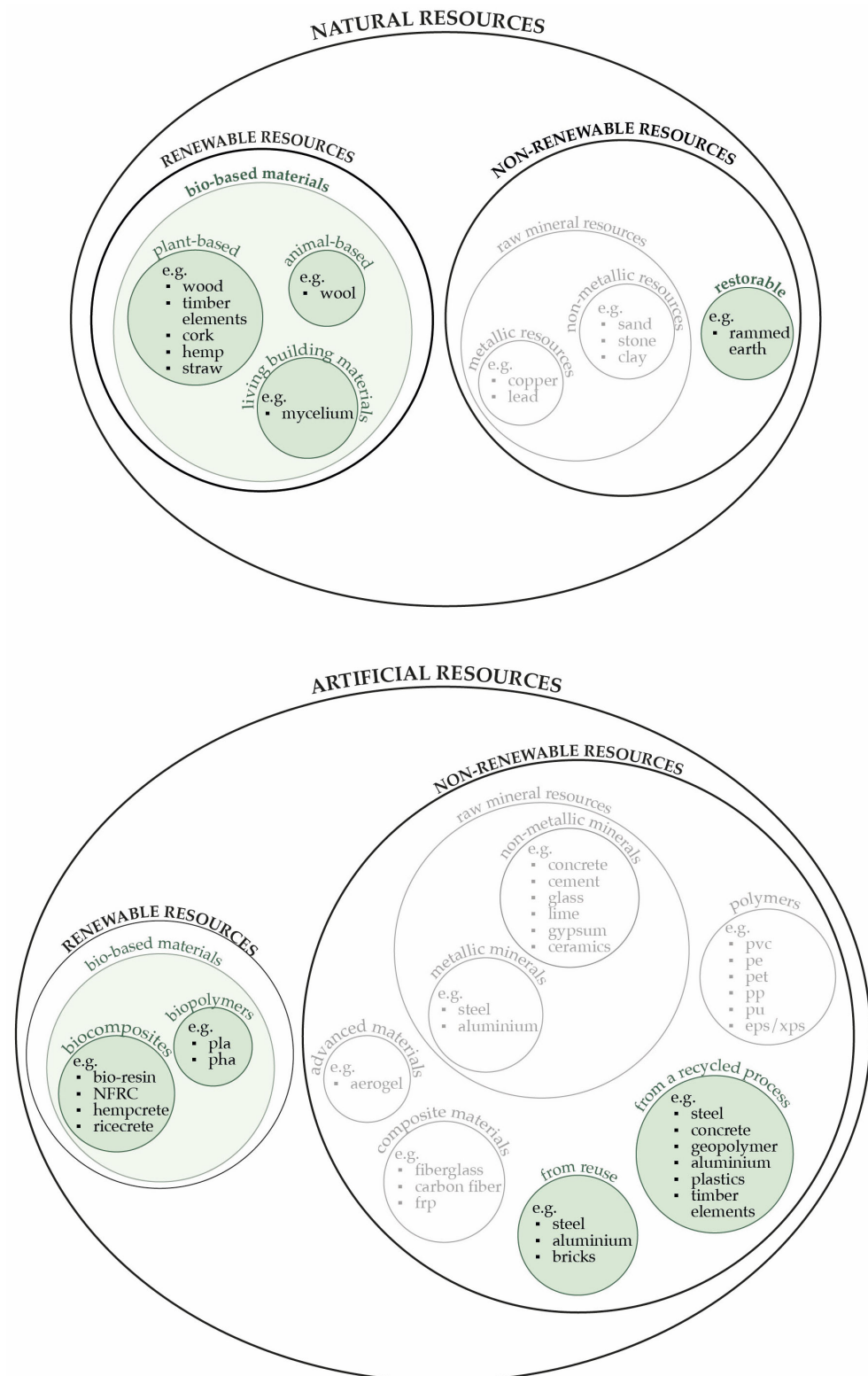


Figure 2. Identification of *Low-Resource Materials* (in green) within the semantic clusters deduced from the resource classification criteria.

Table 5. Relationship between the distinctive features of *low-impact materials* (LIMs), *low-carbon materials* (LCMs), *regenerative materials* (RMs), *resource-efficient materials* (REMs), *circular materials* (CMs), and the concept of *Low-Resource Materials* (LRMs).

Characteristics	LIM	LCM	RM	REM	CM	LRM
Reducing environmental impacts	x	x	x	x		x
Reducing social impacts	x					
Reducing economic impacts	x					
Low CO ₂ emissions		x				
Low energy consumption						
Use of renewable resources						x
Use of recycled/recovered materials						x
Reduction in the consumption of virgin raw materials						x
Contribution to the local economy			x	x		
Contribution to environmental regeneration			x			
Efficient use of resources				x	x	x
Reduction in waste generation					x	x
Preservation of the value of resources over time					x	x
Economic optimisation of products					x	

The first category of LRMs, which falls within the cluster of natural resources, relates to *bio-based materials*. These can be further subdivided into the following: *plant-based*, which includes all vegetable-based materials such as, for example, wood, cork, and hemp, made from plant-based raw materials or with the addition of binders that help to reverse the mixture; *animal-based* which includes materials derived from animal organisms, such as wool; and *living building materials*, namely materials capable of growing or self-repairing, thus characterised by self-sustainability, self-healing, self-replication, and responsiveness to biological signals, such as mycelium [33]. In addition to these, artificial bio-based materials can be identified. These are produced from natural components through chemical processes that yield *biopolymers* or *biocomposites*, or that permanently alter the original natural resource, preventing its reversal to its initial state. One example are plant-based natural fibre reinforced composites (NFRCS), in which the most used natural fibres are cotton, sisal, jute, flax, hemp, bamboo, banana, coconut fibre and sugar cane. These fibres are combined with polymer matrices of various origins [57]. Analysing their composition, however, reveals the presence of a percentage of non-renewable materials within many bio-based products [58]. The production of 100% environmentally friendly biocomposites—in which both the polymer matrix and the reinforcing material are derived from natural and renewable sources—remains a challenge [57]. Nonetheless, the fact that these are blended with mineral or synthetic additives does not negate their positive contribution in terms of an overall reduction in the consumption of fossil or mineral resources. Indeed, even when “contaminated” by components of mineral or synthetic origin, such products still allow for a decrease in the use of non-renewable raw materials compared to conventional solutions. It is therefore appropriate to accept a certain percentage of non-renewable elements within bio-based materials, while remaining aware that this may compromise the total recyclability of the product. This awareness must not translate into abandoning the general objective of the research, as bio-based materials remain a strategic choice, constituting a set of materials capable of limiting the consumption of non-renewable resources, and contributing to the construction of coherent criteria for more sustainable building practices. Furthermore, corporate research continuously aims to improve formulations to make these products as sustainable as possible. A more problematic aspect concerns the end-of-life scenario: the intermixing of different materials in a product’s composition can indeed present a critical challenge. In this regard, it is important to emphasise a fundamental distinction: while for non-renewable resources it becomes central to reduce extraction through recycling and

reuse strategies, in the case of renewable materials, recycling plays a secondary role. Being generated by natural processes of continuous growth and regeneration, these materials renew themselves over medium-to-short cycles over time. Consequently, the primary interest is not so much their recycling, but rather the sustainable management of the resource, the maintenance of the biological cycles that guarantee their long-term availability, and the reduction in environmental impacts associated with the disposal phase. It is important to note that, for materials consisting mainly of renewable resources, such as NFRs or fully plant-based bio-based materials, the question of their end-of-life does not represent a problem from the perspective of material consumption. Due to their renewable nature, they can be reused in different applications, shredded to make new products, or used for composting.

Another category, always within natural resources, consists of natural materials defined as *restorable*, meaning those materials that, even after being used in the building sector, can be returned to their original state without significant loss of their initial chemical–physical properties and performance. These are materials that do not undergo irreversible chemical transformations, enabling a process of reuse or restoration to their initial condition. An emblematic case is rammed earth (unfired earth), which, despite being a non-renewable resource due to long regeneration times, exhibits a high degree of restorability; indeed, when used to produce building elements—such as blocks or panels obtained through compaction or cold-pressing—it does not undergo permanent chemical alterations. Consequently, at the end of its useful cycle, it can be easily broken down and returned to its original condition, even when natural fibres are added to the mixture, which can then be left for composting. This characteristic clearly distinguishes it from materials such as clay, which undergoes irreversible chemical–physical transformations due to high-temperature firing processes that permanently alter its structure. In this case, the material can no longer be returned to its initial state.

Within the cluster of artificial materials, a category falling under *Low-Resource Materials* is represented by products derived from *recycling processes*. In this case, the material stems from a process of transforming waste or scraps from previous usage cycles, which are reintroduced into the production system as new secondary raw materials. Recycling can significantly reduce the extraction of virgin resources, which is a crucial aspect especially regarding non-renewable resources. A relevant example is recycled steel, which can be produced from scrap with percentages up to 100%, while maintaining performance properties comparable to those of virgin steel, and remaining recyclable again at the end of its life. Similarly, concrete containing recycled aggregates allows for the partial replacement of natural aggregates, reducing the impact associated with extraction. In both cases, the consumption of new virgin resources is considerably reduced. In the case of wood-based elements, products such as OSB, particleboard and MDF panels are made mainly from recycled wood sources; for example, they can be produced from sawmill offcuts, small-diameter rounds or oversized timber that is less suitable for other uses, and this waste wood is reduced to flakes or chips, and adhesives are added to form new elements. Nevertheless, the mere presence of recycled content is not sufficient to classify a material as a *Low-Resource Material*. While all recycling processes inherently reduce raw material consumption to varying degrees, evaluating how these materials perform across multiple recycling loops is crucial. For example, whereas steel can theoretically be recycled indefinitely, other materials cannot; furthermore, although materials such as concrete experience downcycling, they can still be repurposed rather than classified as waste—serving, for instance, as road subbases or mixed aggregate (*tout-venant*). Conversely, materials like fibre-reinforced polymers (FRPs) reach an end-of-life state after just a few recycling cycles and must subsequently be managed as standard waste. Indeed, although reducing waste generation is not the

primary objective of LRMs, this aspect has been identified as an enabling criterion when needing to choose between two LRMs.

Finally, the last category consists of *reused materials*, which differ from the previous ones due to the absence of significant transformation processes. Reuse involves the direct re-employment of elements originating from existing buildings or structures, keeping their physical and chemical characteristics virtually unaltered. Operations such as sorting, dismantling, and dimensional adaptation do not modify the nature of the material but extend its life cycle. Typical examples include reclaimed bricks or reused steel elements, which can be reintegrated into new construction contexts without undergoing industrial processes. Reuse therefore represents a particularly effective strategy in terms of reducing resource and energy consumption.

4. Discussion

The analysis of the definitions of natural, artificial, renewable, and non-renewable resources has enabled the construction of an interpretative framework useful for classifying the origin and transformation methods of materials employed in the construction sector. A key initial implication emerges from this analysis: although natural materials are traditionally associated with lower environmental pressure, this condition does not automatically guarantee a reduction in life cycle impacts. Conversely, certain artificial materials can substantially lower non-renewable resource consumption through recycling, reuse, and recovery strategies. Ultimately, a material's sustainability should not be judged by its natural or artificial origin alone.

The main reason behind the introduction of *Low-Resource Materials* lies in the need for a theoretical framework that is sufficiently broad and practical to guide the selection of materials required to complete a building. The classifications currently found in the literature—including *low-impact materials*, *low-carbon materials*, *regenerative materials*, *resource-efficient materials*, and *circular materials*—each focus on a specific sustainability attribute and are unable to encompass the full range of building and construction materials required to construct a building. Typically, employing one of these material categories will compel the use of other materials from outside that specific group; often, this involves resorting to high-impact materials, thereby undermining the original intent.

The concept of *Low-Resource Materials* aims to bridge this gap by adopting a cross-cutting perspective, which integrates characteristics drawn from the existing approaches, and it prioritises the ability of materials to reduce the consumption of non-renewable resources. In this sense, LRMs shift the focus from reducing environmental impacts, or climate-changing emissions, towards the issue of the availability of material resources, considered one of the main challenges the construction sector will face in the long term. The novelty of the concept therefore lies in adopting an integrated perspective establishing material conservation and the minimisation of virgin non-renewable resource consumption throughout the material life cycle as its priority objective.

Furthermore, the proposed classification should not be interpreted as closed and definitive, but rather as an open and dynamic framework. Advances in technology, production processes and innovations in the field of materials may allow for the inclusion of new solutions which, whilst not currently falling within the category of *Low-Resource Materials*, will in future be able to meet its classification criteria.

From an application standpoint, the developed *Low-Resource Materials conceptual framework* can represent a useful theoretical foundation for guiding future design phase strategies and material selection criteria in the construction sector. In particular, it can support designers in the identification of materials and building elements consistent with resource reduction goals. It is appropriate to point out that the framework does not replace consol-

idated quantitative evaluation methodologies, such as Life Cycle Assessment (LCA), or environmental protocols and certification systems.

Indeed, LRMs operate at the material category level by offering designers a prospective repertoire of materials suited to specific applications; however, the specific and comparative selection among alternative options must still be supported by an assessment conceptual framework based on the quantitative measurement of functional performance.

Given the current state of theoretical development of the concept of LRMs, a future practical application of their framework will enable addressing and resolving certain shortcomings currently observed. First is the definition of minimum thresholds for recycled content in non-renewable materials. Indeed, the results highlight that it is not possible to identify a single valid value across all material categories, as recycling percentages depend on the technical, performance, and regulatory characteristics of individual materials. For example, materials such as steel allow for extremely high recycling percentages without significant loss of performance, whereas other materials, such as concrete, present more restrictive technical limits related to the quality of recycled aggregates and permitted structural uses. A second aspect to better investigate concerns the presence of non-renewable components within many bio-based materials. Although these materials still contribute to reducing the overall consumption of synthetic or mineral resources compared to conventional products, the presence of additives of such derivation can compromise aspects such as the material's recyclability, biodegradability, or restorability. It is therefore necessary to further investigate whether an acceptable threshold for non-renewable components within bio-based materials should be defined, and according to which criteria such a limit could be established.

5. Conclusions

In the context of the ecological transition, the issue of material resource availability assumes an increasingly central role. While, on the one hand, the progressive spread of renewable energy suggests the possibility of reducing dependence on fossil fuels, on the other, the need to limit raw material consumption and the impacts associated with extractive processes emerges with increasing clarity. From this perspective, the concept of *Low-Resource Materials* can represent a valuable conceptual framework for guiding initial design choices towards solutions capable of reducing pressure on natural resources, favouring renewable, reversible materials originating from recycling or reuse processes.

From an operational standpoint, there is no intention to replace well-established tools for environmental assessment; rather, the objective is to integrate them. The concept of *Low-Resource Materials* can indeed provide preliminary support during the design phase, guiding professionals in selecting materials based on their relationship with resource consumption, which can subsequently be explored in depth through standard performance, energy, and environmental evaluations.

As highlighted, there are some aspects that require further investigation. Firstly, the preliminary list of materials should not be regarded as exhaustive, but rather as an initial basis for classification that is subject to updates in line with technological developments, the availability of new materials and advances in scientific knowledge. Secondly, it is necessary to evaluate whether it is useful to establish minimum thresholds for recycled content in non-renewable materials, taking into account the differing characteristics of each and a continuously evolving regulatory framework. At the same time, the role of non-renewable components within bio-based materials needs to be examined more closely, assessing to what extent these elements may influence their recyclability, biodegradability, and restorability. Lastly, the analysis relates to an illustrative Italian national context, and

further research to extend the scope of the analysis based on the legislation of other EU Member States is needed. Although the *Low-Resource Materials* concept is already applicable based on the three established core criteria and two additional ones, future research should focus on these critical challenges, allowing for a further in-depth characterisation of LRMs within the current context.

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Abbreviations

The following abbreviations are used in this manuscript:

ARs	Artificial Resources
CMs	Circular Materials
DE	Domestic Extraction
DfD/A	Design for Disassembly and Adaptability
DMC	Domestic Material Consumption
LCA	Life Cycle Assessment
LCMs	Low-Carbon Materials
LIMs	Low-Impact Materials
LRMs	Low-Resource Materials
NRs	Natural Resources
NRRs	Non-Renewable Resources
REMs	Resource-Efficient Materials
RMs	Regenerative Materials
RRs	Renewable Resources

Notes

- ¹ The original Italian version of the definition is: “tutte le fonti alimentari, minerarie, idriche ed energetiche immediatamente disponibili sulla Terra per l’uomo e a lui utili”

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