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Rossella Corrao · Tiziana Campisi · Simona Colajanni · Manfredi Saeli · Calogero Vinci *Editors*

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Contents

Valorisation and Reuse of Cereal Wastes for Construction Applications in a Circular Economy Perspective: A Review of the State of the Art

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Abstract. Nowadays it is well-known, also by the general public, that the uncontrolled use of non-renewable natural resources, the energy demand increase, and the pollutants emission into the atmosphere have a devastating impact on the environment, on human health, and the society in general. In this scenario, construction is a high concerning sector; hence, there is an urgent need to employ materials with low environmental impact for all those activities connected to the sector, such as construction or redevelopment of buildings, structures and infrastructures according to the required high-performance standards. Moreover, another problem is the generation of enormous quantities of wastes and by-products whose disposal often poses many difficulties, not considering that the usual landfilling causes an additional environmental burden. This study is a part of a doctoral research supported by a PNRR project aimed at the R&D of materials, products and systems for buildings energy improvement, through the valorisation and reuse of secondary raw materials. In particular, this work presents the state of the studies on wastes deriving from the cereal sector, analyzing how they can be reused for the production of more sustainable building materials intended for energy performance improvement as demanded by the current European and national regulations. Cereal wastes reuse, like most of those resulting from the agricultural sector, represents a valid opportunity for a greener construction, also promoting a sustainable approach from the circular economy perspective and in line with the Minimum Environmental Criteria. Therefore, valorisation and reuse of recycled materials in construction would not only reduce their environmental impact, but would also contribute to increase sustainability in construction, a sector that still presents many critical issues connected not only to the actual construction practices, but also to all those activities of production and management that characterize buildings.

Keywords: Bio-waste Reuse · Buildings Materials · Energy Efficiency · Sustainability · Circular Economy

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1 Introduction

Humans' impact on the environment is constantly rising, especially due to an uncontrolled population expansion and the increasing consumption of natural resources, with a consequent expansion in greenhouse gas emissions, deforestation, and excessive exploitation of resources [1]. In this panorama, the construction sector shows a significant ecological footprint, with significant environmental consequences also due to the generation of huge quantities of waste [2, 3]. In the European Union (EU) alone, buildings are responsible for approximately 40% of energy consumption and about 36% of greenhouse gas emissions [4]. Anyway, the environmental pressure does not derive only from buildings' construction and management, but also from the use of unsustainable materials that often highly impact on the environment [5]. Moreover, the construction industry places considerable pressure on the available resources. Construction and infrastructure, especially in the Developing Countries where the need for new structures and infrastructures is elevated, consume between 40% and 50% of extracted resources for materials on a global scale. Additionally, it is estimated that the global consumption of materials will nearly double by 2060 and the demand from the construction sector will account for approximately one third of that increase [4]. These alarming data show that a complete depletion of non-renewable natural resources might occur and cause a wide range of new environmental impacts [4, 5]. Another complex problem, which is constantly increasing worldwide, is wastes generation with a particularly significant acceleration in recent decades, resulting of multiple converging factors such as demographic expansion, ever-increasing urbanisation, the income per capita rise, and increasing resources use. Recently, there is a growing awareness regarding the need to address these issues also linked to the concept of Circular Economy (CE) and the development of related policies [6, 7]. The objective of CE is reducing the environmental impact caused by human activities by encouraging products reuse and recycling and, therefore, limit the waste of resources, constituting a powerful connector between use of resources, waste management and emissions [8]. The European Commission issued a series of directives aimed at promoting waste reduction, reuse and recycling [9]. Among these, the Framework Directive on waste (Directive 2008/98/EC and subsequent amendments) that regulates the entire waste chain, from production to disposal, pays particular attention to recovery, recycling and reuse. This also defines the waste hierarchy and the necessary actions for a sustainable management: prevention, pre-treatment, recycling, recovery, and disposal. In line with the Community directive, the Environmental Code (Legislative Decree 152/2006) beyond providing the procedures for wastes generation and management, also classifies them between urban/special and hazardous/non-hazardous waste [9, 10]. Alongside those, the European Waste Catalogue also provides an articulated list of wastes and further classification codes.

In accordance to the CE strategy, the EU emphasizes the importance of an efficient resources' management and considers a waste not as something to be disposed of, but rather to be effectively managed and reused [11]. In this sense, the construction sector is adopting an innovative and responsible approach, moving towards a more ecological and circular model of production, considering the use of alternative building and construction materials derived from waste.

Indeed, nowadays there is an increasing interest in exploiting wastes as alternative raw materials for the production of novel building materials. In fact, their entire productive chain is often extremely unsustainable considering raw materials supply, production, transport, use, and end-of-life. From this perspective, the exploitation of wastes - or even natural materials - could play a significant role in mitigating the buildings impact on the environment throughout their entire life cycle. The presence of integrated waste gives the material the characteristics necessary to satisfy the requirements needed for the certification of the Minimum Environmental Criteria (MEC) regulation which precisely aims to encourage the construction/renovation of low impact buildings, both new and existing, through sustainable materials use, in line with the CE principles [12]. Finally, the possibility to use biomaterials in construction is a highly valuable opportunity in terms of potential benefits. In fact, due to their renewable nature, this novel category of materials could actively absorb CO_2 and its subsequent long-term immobilization exerts a positive impact on the Earth's climate [13, 14].

Among the various industries, it has been found that the agri-food sector shows a significant impact on the environment per production unit due to the massive exploitation of water, the generation of various effluents, green-house gases, and wastes of various nature, both at an industrial (production) and urban (consumption) level [15, 16]. These observations made it crucial to adopt more environmentally friendly approaches to maximize the reuse of agri-industrial wastes as a valuable resource for the production of bioproducts such as biofuels, organic acids, biopolymers, enzymes and others. That would avoid the imprudent disposal of such wastes in the environment, which otherwise might cause further pollution, both for the generation of CO_2 and methane, and of diverse effluents due to putrescence [17].

Cereal production & processing constitute a massive portion of the agri-food industry, a fundamental part of staple foods, representing over 20% of global food consumption [18]. However, while cereals play a vital role in global nutrition, it is important to recognize that the related processes generate a considerable amount of wastes, posing a big challenge in terms of management and disposal [19, 20]. In fact, contrary to what is generally believed, cereals wastes cannot be simply disposed of in fields in great quantities as that would generate issues to the agricultural practices and contribute to increasing the atmospheric pollution. With this in mind, this paper aims to analyse the most recent valorisation trends and sustainable practices that could allow to explore innovative solutions intended for applications in construction. Reuse cereal by-products represents a valid and promising option to reduce pollution and valorise this category of waste extremely widespread in the South of Italy (and not only), from an EC perspective, with particular attention to the novel performance induced in building materials.

2 The Cereal Sector and the Resulting Wastes

The cereal supply chain is a fundamental part of the global agri-food sector as it represents a significant source of food both for humans and animals, and a primary energy source [19]. The most diffuse cereal species belong to the grass family and include wheat, rice, barley, corn, sorghum, oats, and rye [19, 20]. From the most recent available data, it is observed that approximately half of the farming land globally is dedicated to cereals;

the main producers are China, Russia, USA and India [20] (cf. Fig. 1a). In Europe, the cereal cultivation plays an important role, with France, Germany, Russia and Ukraine among the main producers. The vast extents of agricultural land and favourable climatic conditions in many European regions favour the cultivation of cereal varieties such as wheat, corn, barley, and rice. According to the Eurostat data, in 2022 the EU cereal production was estimated in about 270.9 million tonnes [21] (Fig. 1b).

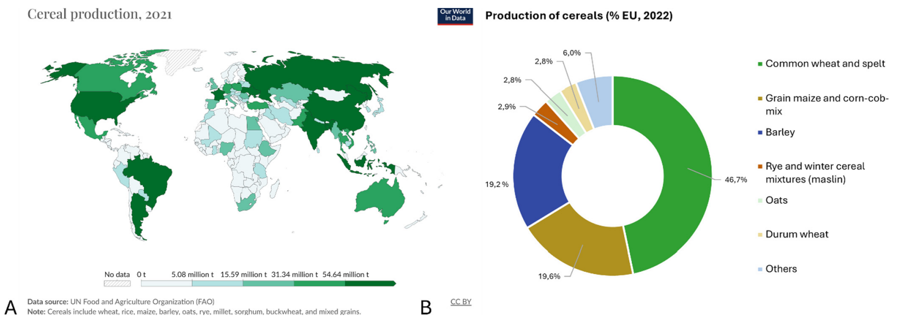

Fig. 1. Cereal production data: A - global data - © 2021, https://ourworldindata.org/agricultural-production; B - Europe - © 2022, Eurostat

In Italy, where the climatic conditions are particularly favourable, the cereal cultivation occupy approximately 45% of the farming land. Among the most diffuse varieties, the durum wheat, used for the production of pasta and flour, is mainly grown in the South and represents 50% of all the European production; the soft wheat, mainly produced in the North, is used for the production of baked products; finally rice that is largely grown in Piedmont and Lombardy [22].

The cereal production chain is quite complex and requires several phases, from harvesting to transformation into food products. After the agricultural production phase, cereal processing is an essentially physical process, aimed at cleaning the grain, regulating the moisture level and, then, mechanically crushing and sieving to the desired particle size to obtain flour and by-products such as bran [23]. The Food and Agricultural Organization of the United Nations (FAO) suggests three main phases to process cereals: preparation for conservation, which may include drying and cleaning to ensure the stability and product long shelf-life; primary processing to remove inedible parts, such as straw; secondary processing for transformation into the final products [23, 24] (Fig. 2). In addition, the cereal production can also include other processes, such as fermentation, roasting or extrusion, that are used to manufacture products with specific characteristics such as bread, beer, coffee, and cereals for breakfast [24]. However, even during these manufacturing processes enormous quantities of waste are generated (Fig. 3).

It is estimated that 12.9% of all the food waste is produced during grain processing and production and that 30% of grain weight is lost or wasted [18, 25]. In Italy, agricultural and industrial waste management is regulated by Legislative Decree n. 152 of 04-03-2006 that describes the environmental regulations.

Depending on the cereal type and the processing phases, various wastes and by-products are generated. The cereal preparation process, for example, produces straw

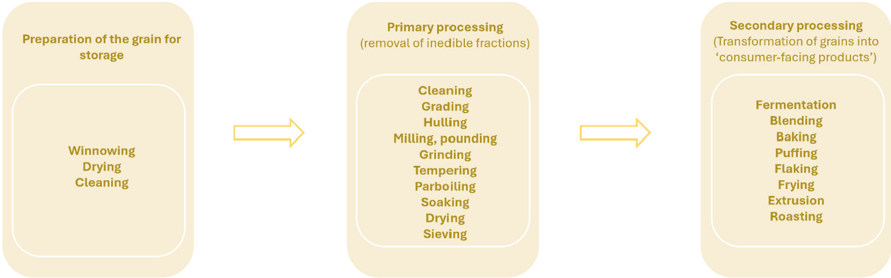

Fig. 2. Cereal principal phases of production - © 2021, Thielecke F., Lecerf J.-M., Nugent A.P. [23].

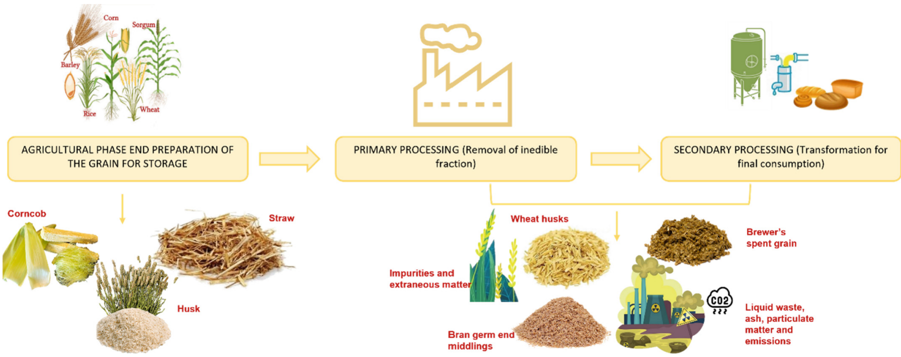

Fig. 3. Principal wastes and by-products from cereal processing phases - © 2024, the authors.

and cob as waste; milling bran and germ as by-products. Bran is also produced by extracting specific compounds, such as corn and rice oil, or during grain polishing for rice processing. That processing also generates large quantities of waste, such as straw, chaff, and husk. The brewing industry also produces a by-product known as brewer's waste grain that contains phenolic compounds with antioxidant and antimicrobial properties [19].

In general, the residues resulting from cereal processing are not considered toxic for humans and the environment and are classified into solid and liquid forms. The former includes components such as corn cob, straw, husk, spent cereals from the brewing industry and by-products from the manufacture of baked foods; the latter derives from waste water from cereal cleaning and milling processes, mainly at an industrial level, and moderately contributes to environmental pollution for the significant presence of organic matter, solid wastes and nutrient compounds that could generate unpleasant odours, ash, dust, and methane and CO_2 emissions [18, 26]. A small fraction of the residues from wheat, corn and rice crops is used on a global scale in the production of bioethanol or as animal fodder. However, most of these residues are usually discarded or burned directly in the fields, raising critical issues related to human health, the environment, animals and insects, and agricultural sustainability in general [27]. In fact, ineffective disposal, such as burning, of agricultural residues leads to several negative impacts. First of all, the emission of gases and pollutants into the atmosphere [26]. The traditional use of by-products obtained from cereal processing, such as in animal feed or composting, represents a low-value solution. However, exploiting these by-products more effectively is a major challenge for the sustainable development of the cereal sector [28].

Recently, the by-products of the cereal supply chain have been object of various scientific research and applications in many fields. For example, they were used in the production of biomass and biofuels, which are considered more efficient and environmentally friendly energy options due to their higher energy yield [18, 29]. Furthermore, straw, bran and ungerminated seeds can be reused as natural fertilizer [27, 29, 30]. Bran is also used as an alternative to synthetic pharmaceuticals and artificial additives in various industrial sectors, as well as in the production of organic acids [29]. Its characteristics make it interesting for natural cosmetics and skin care products also [30]. Furthermore, some wastes such as rice husk, wheat bran and wheat straw have been shown to be effective in absorbing heavy metals [29, 30]. Rice husk, rich in silica, has also been used for the production of nanoparticles for various applications [27, 30]. A notable example is the use of bran-derived cellulose to produce bioplastics with properties similar to the conventional plastic, but with the advantage of being almost completely biodegradable [18, 30].

These examples show the potentials of such cereal-derived wastes and by-products into useful and valuable products, more sustainable and environmentally-friendly. Research and technological innovation are trying to transform these products into high-quality materials, creating economic and sustainable opportunities for the entire cereal industry. Therefore, their valorisation and reuse are becoming increasingly interesting in the context of sustainable resource management, as many of them can find proper applications in different sectors, including construction.

3 Methodology

The reuse of wastes from cereal processing intended for the production of novel building and construction materials has recently attracted growing interest, offering innovative and more sustainable opportunities for applications in construction. Furthermore, wastes from cereal processing represent a versatile source with multiple applications. In addition to consolidated uses as animal feed or biofuels production, in recent years the potential of these wastes and by-products has also been valued for a number of applications in construction [2]. Currently, green building represents one of the most active areas of research and innovation. In fact, in addition to economic benefits, the development and use of novel, more sustainable materials offer significant environmental advantages. The applications of materials and products deriving from natural wastes reuse and recycling are currently expanding in the sector, highlighting the great potential of these materials in terms of CE and induced sustainability [5, 9].

Scientific studies conducted in the context of cereals' by-products use have paved the way for numerous innovations, offering solutions that combine sustainability, efficiency, and waste reduction in the construction industry. The wide availability of bibliometric resources represents a significant opportunity to investigate the trend of the scientific studies worldwide based on publications dealing with the valorisation of cereal processing wastes in construction. Figure 4 considers 5081 documents (papers, reviews, books, etc.) over the last decade, returned by ScienceDirect database. It is observed a constant increase of the number of studies on the topic, with a clear increase in the last years, consisting of 2074 documents. That shows the great interest in the topics of sustainability, waste reuse, green building and bio-based materials that is constantly spreading among the researchers.

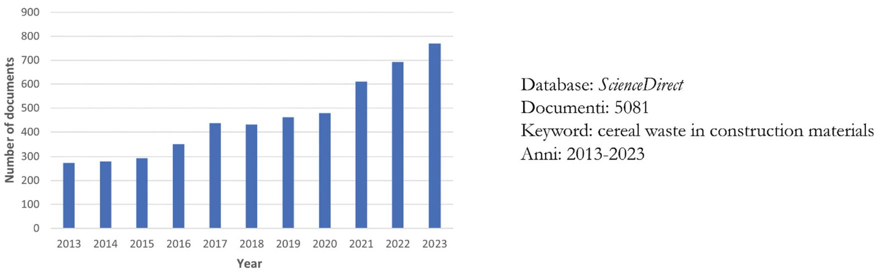

Fig. 4. Principal wastes and by-products from cereal processing phases - © 2024, the authors. Tendency of the number of scientific papers as published on ScienceDirect, years 2013–2023, keyword "cereal waste in construction materials". - © 2024, the authors.

The following Table 1 reports some notable examples of cereal waste reuse for specific applications in building materials, taking into consideration publications in the last decade (2013–2023). In the following sections, however, the main characteristics of the most common waste integrated into construction materials are briefly summarized.

4 Applications in Construction

4.1 Straw

Cereal straw represents a traditional source that has long been used as insulating material in buildings thanks to its hollow structure, low density, and - hence - exceptional thermal insulation properties. The cavities present in these materials allow air to be trapped in, reducing heat transmission through the material itself, making straw efficient as thermal insulator. Typical thermal conductivity for insulating cellulose-based materials is between 0.04 and 0.05 W/mK [35].

The integration of cereal straw, or similar fibrous residues, into composite materials for applications in construction is an extremely promising area in this field. Straw has been used for different purposes since ancient times. Even before the industrialization of building products, straw was precisely one of the most common material for roof insulation [47]. That methodology, dating back to ancient times, is still applied today, especially where a lack of technology and resources forces homes to be built according to traditional local criteria. The history of humanity shows a constant use of straw in the construction of shelters and buildings since its inception [47, 48]. For instance, the construction of buildings with straw bales dates back to the end of the 19th century in Nebraska (USA), corresponding to steam presses development. There, straw bales were

Table 1. Examples in the literature of materials deriving from the processing of cereals for construction products, considering research works from 2013 to today - © 2024, the authors

Waste type	Product	Description	Reference
Wheat straw	Transparent biocomposite	Wheat straw fibers have been used to develop transparent composites	[31]
Wheat straw	Perforated fired clay bricks	Evaluation of the thermal performance of perforated baked clay bricks filled with wheat straw for thermal insulation	[32]
Wheat straw	Cladding panel	Evaluation of the mechanical performance and fire behaviour of innovative wheat straw-gypsum composites as cladding panels	[32]
Barley straw, hemp husk and corn cob	Raw earth bricks	Hygrothermal characterization of earthy materials containing different types of plant aggregates	[33]
Straw fibres	Pavements	Performance analysis of straw composite fiber material in asphalt mix for paving	[34]
Rice straw	Thermo-acoustic insulating panels	Development of thermal insulating products made with high frequency hot pressed rice straw	[35]
Corn straw fibres	Fibre-reinforced concrete	Development of a concrete with corn straw fibers addition and evaluation of mechanical properties and resistance to chloride ions	[36]
Rice husk	Composite panels	Evaluation of mechanical, thermal and acoustic performance of composite panels made from rice husk waste intended for construction applications	[37]

(*continued*)

used as structural elements for the load-bearing walls (Fig. 5a), simply supporting the

Table 1. (*continued*)

Waste type	Product	Description	Reference
Rice husk	Raw earth brick	Analysis on the effect of rice husk ash addition on the physical characteristics and performance of clay bricks	[38]
Rice husk and straw	Concrete	Evaluation of the effect of incorporating rice husk and straw as a sealing material and evaluation of mechanical, acoustic, thermal and durability properties of cellular concrete	[39]
Rice husk and straw	Composite panels	Evaluation of acoustic properties of particleboard panels made of rice husk and straw	[40]
Rice husk	Cementitious mortar	Analysis of the mechanical and thermal properties of a cement mortar, replacing the sand with rice husk	[41]
Corn cob	Lightweight concrete	Evaluation of the mechanical performance of granulated corncob aggregate-based concrete	[42]
Corn stalk fibres	Fibre-reinforced concrete	Morphological characterization of corn stalk fibers and evaluation of their effect on the physical-mechanical properties of concrete	[43]
Corn cob	Biocomposite	Development of a biocomposite for insulation and structural purposes using corn cob and cement	[44]

(*continued*)

roof (a technology called “Nebraska” method) [49]. In the past, thatched roofs were a common feature of houses and temples. For example, in Egypt the houses of the Merimde and Fayum settlements (5th millennium B.C.) were built using a mixture of soil, Nile clay, desert sand, and straw from cereal crops [48]. The evolution of the construction technique then led to the mixing of straw and earth to produce blocks of different sizes and consistencies, used for the construction of walls (pisè and mud brick methods) [48].

Table 1. (*continued*)

Waste type	Product	Description	Reference
Corn cob	Raw earth brick	Evaluation of the effect of corn cob as additive in porous clay bricks manufacture	[45]
Corn straw	Bricks	Study of the thermal stability, flammability and fireproof mechanism of corn straw bricks	[46]

Even in Europe, this technique was quite widely used; for example, the oldest existing building using straw bales is the Maison Feuillette in Montargis (1920) (Fig. 5b) [48, 50]. The project involved the construction of walls with straw bales positioned between modular wooden columns, creating a solid and light structure, finished with plaster [48]. Construction with straw bales has also seen a widespread diffusion in Italy, and could once again become a current technique, thus becoming a real turning point towards sustainable architecture. Among the most notable constructions, Casa Dalsant in Bolzano (Fig. 5c), a building designed in 2003 by architects W. Schmidt and M. Schwarz, which become a renowned example in the field of sustainable construction [48].

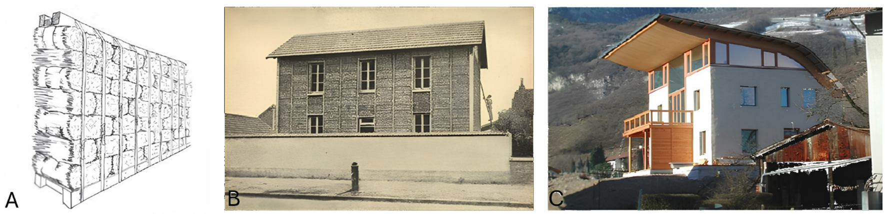

Fig. 5. Examples of buildings using straw: A - "Nebraska" technology - © 2018, https://suryanamaskara.altervista.org/piantealimurgiche/journal.php?id=34; B - Maison Feuillette, - © 2013, https://www.thelaststraw.org/feuillette-house/; C - Casa Dalsant, Italia, - © 2008, http://www.archschwarz.com/stroh/HesserhofPDF.pdf

To date, straw represents a rapidly growing material in the manufacture of biocompatible building materials. Its versatility as a component of panels and products allows for a wide range of applications in green construction. The already marketed products have shown optimal insulating properties, contributing to the energy efficiency of buildings as suggested by the most recent EU regulations. Furthermore, the biodegradable nature of this material makes it a valid ecological choice, reducing the environmental footprint throughout the building's life cycle [51, 52]. Straw has also been used inside hollow bricks with enhanced insulating properties [32, 33] where the addition of 6% by weight of straw, corresponding to a volume of approximately 45%, effectively decreased the thermal conductivity by 75% compared to reference hollow bricks [33]; in cladding or heat-insulating panels [35, 53]; or even in fibre-reinforced concrete, showing adequate mechanical properties with an increase of approximately 15% compared to the original concrete [36]. Furthermore, straw has recently been used in transparent composites, characterized by improved thermal insulation, with good resistance to UV rays, where, with only 10% by weight of fibre, the composite has reached approximately 90% transmittance and 26% opacity, representing an evolution compared to transparent wood fiber composites [32]. Therefore, straw, thanks to its natural characteristics, shows low thermal conductivity, offering excellent insulating capacity and thanks to its fibrous character, improves the mechanical properties of a material, as well as having good fire prevention performance, representing, at the same time, a sustainable solution with low environmental impact [36, 47].

4.2 Husk

The husk, or peel, is made of the protective layers of the cereal seeds and is mainly composed of cellulose, hemicellulose, lignin, and other inorganic constituents [54]. Husk is mainly used for the production of bioenergy, paper or packaging, for animal feed, and as a natural fertilizer. Furthermore, some studies have proposed the use of husk as a building material [54], in particular as thermal insulation given its low thermal conductivity equal to approximately 0.05 W/mK [37–41]. Rice husk was combined with expanded cork granules and recycled tire rubber granules to develop a composite with excellent thermo-acoustic properties [37]. Rice husk ash was exploit as a substitute for clay in bricks, due to its high silica concentration (about 20%), finding that bricks with the inclusion of 5% rice husk ash rice showed increased compressibility of 4.7 N/mm2 and reduced water absorption of 11.65% [38]. Moreover, it was incorporated together with straw as a binding material in concrete, showing a compressive strength decrease, but a flexural strength increase, sound absorption, and thermal improved performance [39]. The optimal thermal properties are also proven by the use of rice husk as a substitute for sand in cement mortars where even just 7% replacement would generate a 12% decrease in thermal conductivity [41].

4.3 Corn Cob

Beyond straw, cob is another waste product from corn processing. That is characterized by a central core (pith), surrounded by wooden rings and layers of chaff, while the outermost part is made up of the husks that enclose the grains [54]. A study revealed that corn cob has similar characteristics to expanded clay, cork, and extruded polystyrene [42, 54]. Furthermore, such residue can be used as an alternative to conventional materials, finding application in the manufacture of thermal insulating products [42–45]. For example, corn cob granulate shows a density of approximately 300–400 kg/m3 which makes it suitable for applications as light aggregate for concrete, returning values close to those of a concrete with expanded clay [42]. The fibers deriving from the cobs have also been used to produce a fibre-reinforced concrete, through eco-sustainable firing processes. These confirmed the considerable potential of corn cob as a source of fibers for the manufacture of biocomposites capable of meeting the specific needs of various construction applications [43]. A further example was the reuse of corn cob to increase the porosity of raw bricks, with a substantial increase in water absorption followed by a flexural strength reduction (3–6 MPa). This decrease in physical and mechanical properties can be attributed to the increased porosity led by corn cob combustion generating a spongy inner structure in brick material, while reducing thermal conductivity [45].

5 Limits to Cereal Wastes Reuse and Conclusions

The reuse of wastes from cereal processing intended for building materials certainly offers numerous advantages in terms of increased performance; however, it is also necessary to consider the possible disadvantages and limitations to their use. Numerous studies have highlighted their role in improving the thermo-acoustic characteristics of building materials thanks to their highly porous structure. These new class of bio-materials could bring a real improvement in buildings thermal and acoustic insulation, granting more comfortable inner environments [32–46, 53]. Furthermore, the exceptional ability of the organic matter to regulate humidity can significantly contribute to the management of relative humidity inside buildings, an important aspect for the maintenance of optimal hygro-thermal conditions, promoting a healthier and more comfortable environment [55, 56]. Furthermore, these wastes are recyclable, biodegradable, and generally compostable, bringing further significant environmental benefits compared to the traditional synthetic materials.

Despite the undoubted and demonstrated advantages, for their concrete large-scale application in the construction sector, it is also crucial to consider the possible disadvantages associated with these materials and, therefore, the possible limitations, often more linked to regulatory conditions than technological. Certainly, these products present a greater vulnerability to possible damage caused by humidity or exposure to atmospheric agents, given their biological nature. Therefore, they require additional precautions to maintain their durability over time. In fact, these materials are sometimes limited to internal applications and not strictly structural uses due to their undiscussed inferior mechanical characteristics compared to existing commercial products (i.e. cement above all). However, it must be considered that these properties, currently limiting their diffusion, seem to have a considerable margin for improvement through the application of surface treatments, resins, additives, and innovative coatings [55]. Other challenges that natural composites face include fire resistance, fiber/matrix adhesion, durability, and increased susceptibility to mold and insects [2, 55].

Other aspects to consider are the harmful effects that agricultural practices impact on the environment, such as the use of chemicals (i.e. pesticides, fertilizers, glyphosate, etc.) which could cause a series of environmental problems, including water pollution, biodiversity loss, and soil erosion as well as human health issues [57]. These chemicals can remain in agro-industrial waste, potentially affecting their suitability for reuse. Therefore, it would be necessary to process these agricultural wastes with specific pretreatments to guarantee their suitability for new uses, thus minimizing the potential environmental impact [29]. This, on the other hand, would affect the sustainability of the considered processes and products. However, the adoption of wastes of natural origin, as an integral part of building and construction materials, could represent an extremely promising field of investigation and constantly evolving field of study.

Deepening knowledge on the applicability, resistance and durability of these materials is crucial to maximise the environmental and technological benefits in the context of innovative and sustainable construction. Indeed, optimizing the performance of buildings, in terms of sustainability and environmental health, requires a continuous effort to refine and further develop these innovative materials.

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