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Management of agricultural waste biomass as raw material for the construction sector: an analysis of sustainable and circular alternatives

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Abstract

Background: The agricultural and construction sectors demand enormous amounts of natural resources and generate environmental impacts that negatively affect ecosystems. One of the main problems is the generation and inadequate management of waste. For this reason, under the approaches of the new sustainable and circular models, waste valorization has been prioritised as a strategy for advancing towards the sustainability of production systems. This research aims to carry out a general analysis of Agricultural Waste Biomass (AWB) in the production of bio-based products for the construction sector. Bibliometric techniques were applied for the general analysis of the scientific production obtained from Scopus. A systematic review identified the main research approaches. In addition, European projects were reviewed to assess the practical application. This study is novel and provides relevant contributions to new trends in the valorisation of AWB in the building sector and the sustainability benefits. For policymakers, it is a source of information on the contribution of new policies to scientific advances and the aspects that need to be strengthened to improve sustainable and circular practices in both sectors.

Results: The results show that 74% of the research has been published within the last 5 years. Regarding the main types of AWBs, rice husk ash and sugar cane bagasse ash are the most commonly used in manufacturing a wide variety of bio-based building products. Cement, concrete and bricks are the main bio-based products obtained from AWB. However, a new approach to utilisation was identified in road construction.

Conclusions: The findings indicate that the AWB is an important resource with great potential for the construction sector. Similarly, that policies on sustainable and circular development have driven scientific progress on new alternatives for the valorisation of AWB to improve sustainability in the construction sector. Although the practical application has also been driven through European projects, development at this level is still low. Therefore, it is necessary to strengthen partnerships between these two sectors and improve government strategies on sustainability and circularity to overcome existing constraints.

Keywords: Bioeconomy, Agricultural waste biomass, Waste valorization, Construction sector, Building products, Eco-friendly materials

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Background

Agriculture and the construction industry are essential sectors for a country's economic growth. Both have a significant impact on employment generation and the

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quality of life of the population. However, the growth and dynamics of these two sectors have made these locations large consumers of natural resources and generators of polluting emissions [1, 2]. Over the last 5 years, there has been an accelerated increase in methane concentration in the atmosphere, mainly due to the expansion and intensification of agriculture and inadequate waste management [3]. The extraction of materials and manufacture of building products consumes enormous amounts of energy and generates between 5 and 12% of total GHGs emissions [1]. The generation and management of waste created by both industries is one of the main challenges for these sectors. It is estimated that more than 3,300 megatons of waste biomass from the main crops [4]. Thirty-five percent of total European Union (EU) waste generation is in the construction sector [1]. In many countries, the management and disposal of waste from these sectors poses a serious problem, mainly from an environmental and social point of view [5, 6].

To address these important challenges, the 2030 Agenda included some of 15 Sustainable Development Goals (SDGs) some that promote sustainable and circular production and consumption (SDGs 11 and 12). Waste reduction is also one of the main targets [7]. Under the circular economy and bioeconomy (CE-CB) approach, construction and demolition waste and AWB are priority inputs with great potential for new, high value-added products [8]. The valorisation of this secondary raw material generates economic benefits. It contributes significantly to the sustainable management of natural resources, reducing dependence on non-renewable resources and negative environmental impacts [9, 10].

Based on the above, the last 5 years have seen the development of a growing number of legal instruments and strategies promoting the manufacture of bio-based products from AWB for use in the construction sector. For example, the 2018 EU bioeconomy strategy highlights the need to substitute fossil raw materials in the construction industry. It also points out that bio-based materials contribute to the defossilisation of this industrial sector [4]. The EU's new circular economy plan, "*For a cleaner and more competitive Europe*" 2020, prioritises the construction and building value chain and highlights the need to introduce recycled materials in certain construction products [11]. The document "*Circular Economy. Principles for Buildings Design*" of 2020, guides builders in the construction value chain on the principles for the circular design of buildings. This guide points out the need to minimise the use of natural resources in building products. It calls for reused or recycled materials that offer environmental benefits and also meets the technical requirements and standards of the primary material [12].

With the aim of improving the circularity, energy efficiency and other aspects of environmental sustainability of EU products, the new proposal for an Ecodesign Regulation for sustainable products was presented in March 2022. This proposal sets out ecodesign requirements for specific product groups including those in the construction sector [13]. The revision of the Construction Products Regulation is one of the sector-specific initiatives that are part of the Sustainable Product Package. This regulation includes measures based on the Circular Economy, such as the use of recyclable materials and those produced from recycling. In addition, the prioritisation of materials with a low environmental footprint [1].

These important sustainability challenges for agriculture and the construction industry require a more significant effort from a scientific–technical point of view to identify waste valorisation alternatives, such as AWB, to produce more efficient and sustainable bio-based products. Therefore, the main objective of this research is to carry out a general analysis of the use of AWB in the production of new bio-based products for the construction sector. Specifically, this study aims to answer the following research questions: 1. *What has been the evolution of the scientific production related to the valorisation of AWB in the production of bio-based products for the construction sector?* (Objective 1) 2. *What are the main research approaches to the type of AWB and bio-based products obtained? 3. Is sustainability a relevant aspect of the research?* (Objective 2) 4. *Have EC and CB policies and strategies contributed to advancing scientific production and projects on AWB valorisation in the construction industry?* (Objective 3). In this paper, Agricultural Waste Biomass (AWB) includes crop residues, those resulting directly from harvesting and agro-industrial waste, obtained after crop processing. Similarly, the term biomaterial refers to materials made from biological resources. The term bio-based product is used to describe products partially derived from biomaterials. This is in line with the bioeconomy policy approaches of the European Union (EU) [4, 14].

Previous studies have evaluated the use of some types of AWBs in the manufacture of specific bio-based products in construction. Examples include activated binders, insulation products, alternative cementitious materials in concrete, bricks, and reinforced concrete panels [5, 15–36]. Other studies have analysed the feasibility of its use in specific regions [31, 37]. However, the authors are not aware of extensive and comprehensive research on the use of AWB in the construction industry. That is the central research gap identified. This study is novel mainly because it uses a large sample that does not limit countries, publication periods, types of AWB, bio-based products, applications or other related aspects. It uses the most extensive database as a source of information, which is also considered one of the most appropriate for evaluating scientific production [38].

The contributions of this research from a theoretical and practical point of view are significant, providing relevant information on a greater variety of AWB that can be used, as well as new trends in the manufacture of bio-based products for construction. This is a valuable input for actors related to agriculture and the construction industry who will be able to learn about new alternatives for the valorisation of AWB and different types of bio-based products with multiple applications in the construction of buildings and civil works. Moreover, they will be able to identify the main advantages in terms of sustainability derived from this type of circular practice. For policymakers, it is a source of information on how sustainability policies and strategies influence scientific advances in this field.

Methods

Bibliometric analysis process

The first stage of the study consisted of analysing the main characteristics of the scientific production (90 studies from Scopus) using bibliometric techniques. The VOSviewer software, version 1.6.18, was used for the graphical representation of the data.

Systematic review process

After the general analysis, the 90 studies in the sample were analysed in detail to obtain information on the main types of AWBs, biomaterials and bio-based products, and the most evaluated properties and parameters. Limitations and improvement alternatives for bio-based products and their feasibility from an environmental, economic and social point of view were also part of the categories analysed.

Analysis of European projects

The Community Research and Development Information Service (CORDIS) database [39] was searched for projects whose main objective was the valorisation of AWB in the construction sector. Forty-six projects were obtained and reviewed to obtain the final sample. Nine projects were analysed in detail to identify: the objective, the main types of AWB, bio-based products, and the implementation period. Figure 1 shows in detail the activities that were part of each of the stages.

Results and discussion

Main characteristics of scientific production

Types of publications and evolution of scientific production

The studies included in Fig. 2 correspond to articles (69%), reviews (22%) and book chapters (9%). The first two articles, "*New Building Materials from Industrial and Agricultural Wastes*" and "*Low Cost Building Materials Using Industrial and Agricultural Wastes*", were published in 1978 [40, 41]. The last article was published in December 2021 "*Development of White Brick Fuel Cell Using Rice Husk Ash Agricultural Waste for Sustainable Power Generation: A Novel Approach*" [42]. A significant increase in publications is evident from 2016 onwards. This trend is similar to that of another study on the application of agricultural waste ash in cement, which showed an increase in the number of publications since 2016 [33].

Of the studies analysed, 74 percent were published between 2017 and 2021. These results coincide with those of similar studies, which indicate that in the last 5 years, there has been an increase in the scientific research on the use of AWB in concrete [26, 33]. This leads to the conclusion that the policies and strategies on sustainable development, which have become more relevant since 2015 with the 2030 Agenda, have boosted scientific research on this subject. Furthermore, it supports previous research findings that highlight the important role of the SDGs and circular economy and bioeconomy strategies on the increase of publications on AWB valorisation in the last 5 years [8, 43].

Publications by country

India is the country with the highest number of publications (22%), followed by Malaysia (13%) and Egypt (10%). The countries shown in Fig. 3 published 84% of the publications in the sample. Other studies rank India as the country with the third-highest number of publications on agro-waste in concrete production [26, 33]. These results align with a previous study that analysed AWB valorisation alternatives and identified India as one of the countries with the highest scientific production on the subject [43]. China and India are two of the world's leading producers and consumers of cement. India's cement production increased significantly in 2017 compared to 2016 [25]. In addition, these two countries have focused their bioeconomy policies on industrial and high-tech innovation [43].

In Malaysia, the construction sector is of great importance and has seen significant growth in recent years [44, 45]. Similarly, the regulations governing the construction industry in this country promote sustainable and environmentally friendly construction [46, 47]. Furthermore, the government prioritises this type of construction in its "*Green Public Procurement (GPP)*" guidelines [45]. For example, it encourages the use of organic fiber in the cladding materials of public buildings [48]. This could be a reason for the particular interest of these countries in

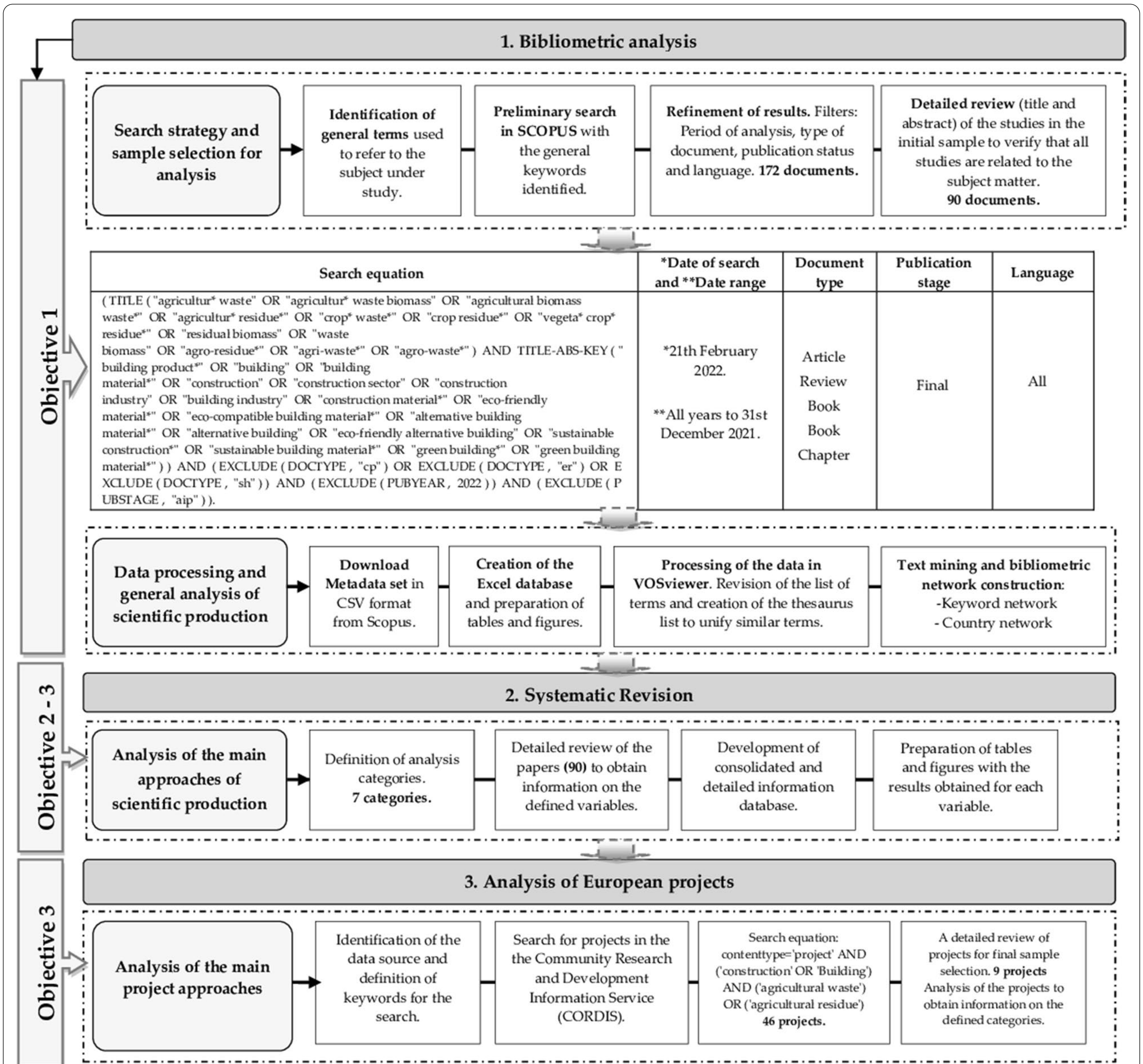


Fig. 1 Stages of methodology used

the use of AWB as a sustainable raw material for the construction sector.

Keyword analysis

The co-occurrence of the keywords network was made using all keywords as analysis unit (author keywords and index keywords). Terms that are part of the search equation were excluded from the VOSviewer keyword list. The keyword network (Fig. 4) groups 41 terms in 5 clusters. Cluster 1 (red) is the central cluster with 13 items. The most relevant terms in this cluster are "*compressive strength*", "*water absorption*", "*mechanical properties*", "*thermal conductivity*", and "*thermal insulation*". These descriptors reflect the importance given by the studies to the analysis of the physical, mechanical and thermal properties of AWB and the bio-based products obtained from its use. This cluster also includes "*rice husk ash*" as the main type of by-product obtained from rice husks' incineration and widely used to manufacture sustainable building materials [49–51].

India is one of the world's leading producers and consumers of rice [34, 52], which also explains the

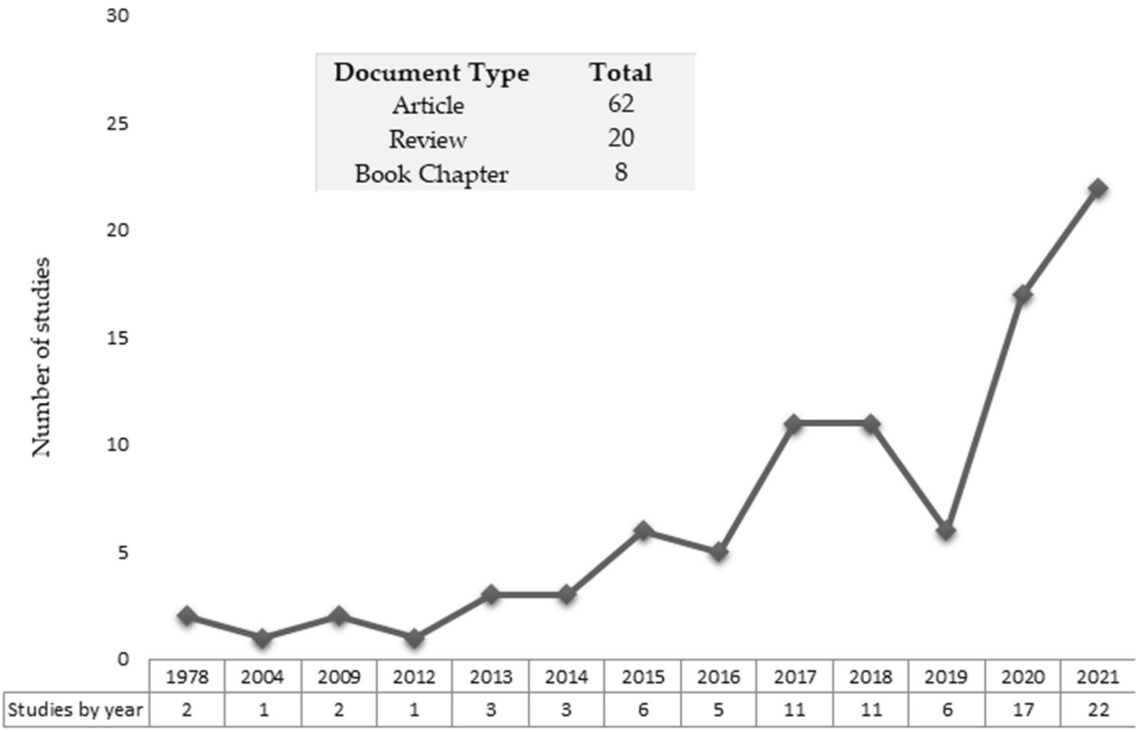
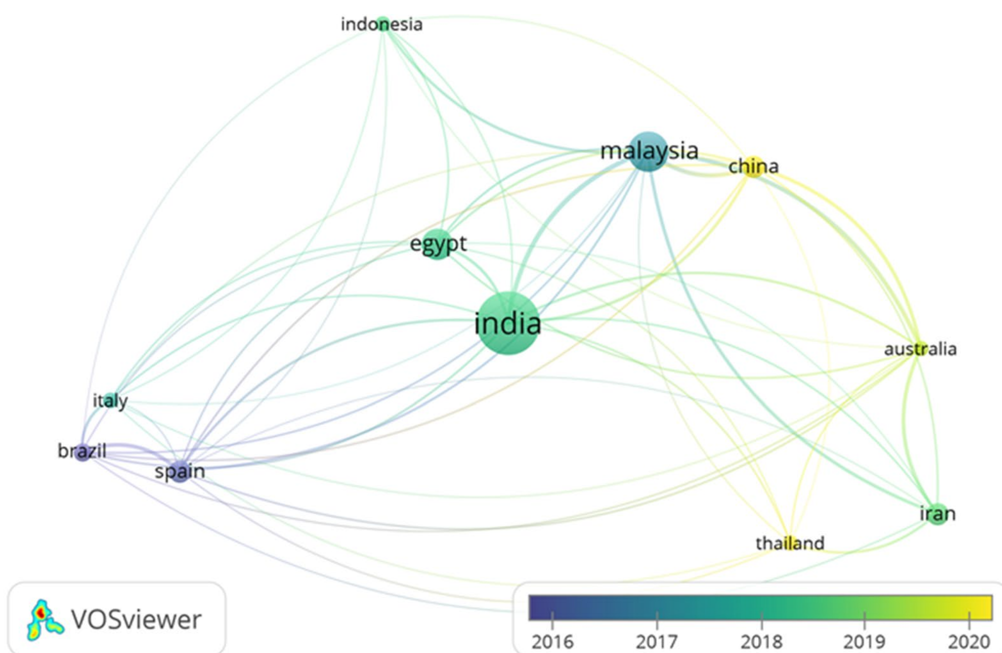


Fig. 2 Evolution of publications on this subject per year



India	Malaysia	Egypt	China	Iran	Spain	Brazil	Australia	Indonesia	Italy
20	12	9	6	6	6	5	4	4	4

Fig. 3 Number of publications by country

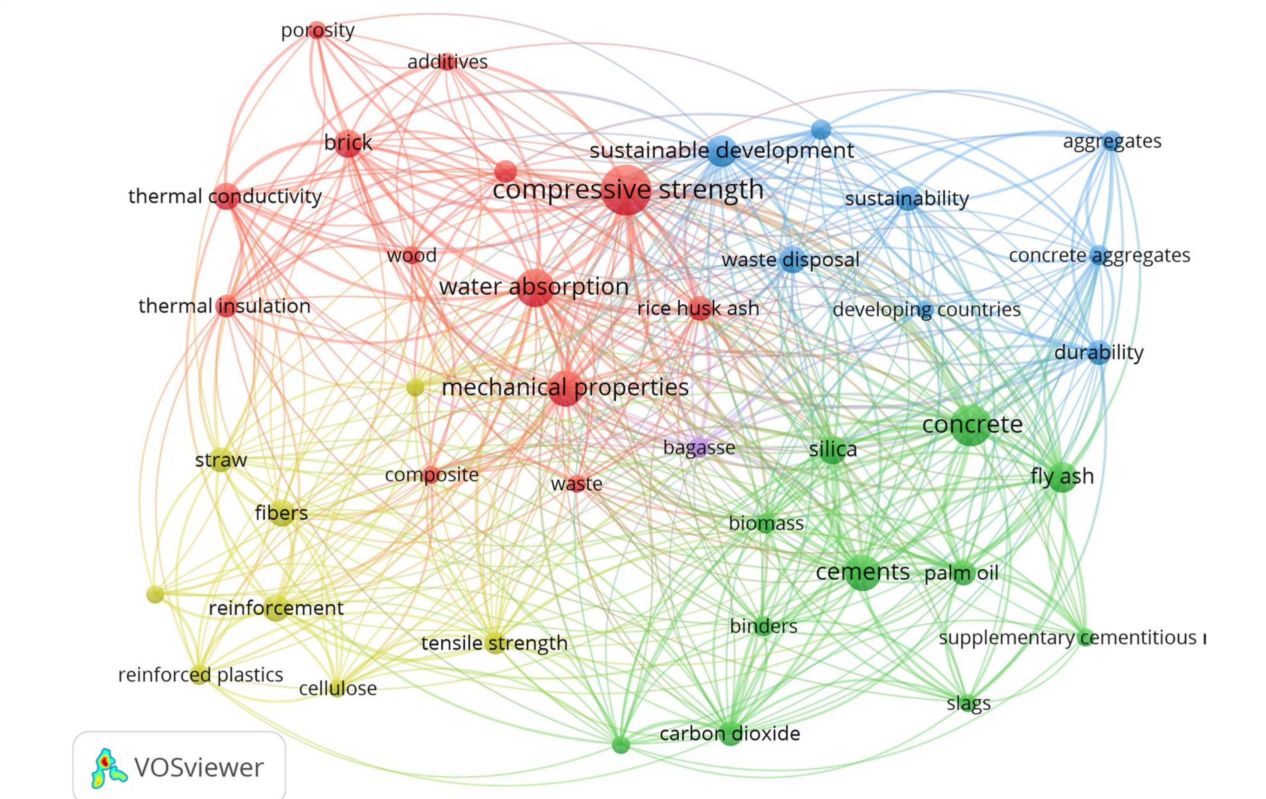


Fig. 4 Keyword network based on co-occurrence

country's interest in valorising this type of AWB. Cluster 2 (green) groups 11 items, mainly related to biomaterials and bio-based products obtained from AWB. For example, "*supplementary cementitious mat*", "*cements*", "*binders*", and "*concrete*". Similarly, this cluster highlights the term "*silica*" as one of the main components of AWB ashes and is of particular interest in manufacturing bio-based products [19, 33, 53, 54].

Cluster 3 (blue) consists of 8 items, including "*sustainable development*", "*sustainability*", "*recycling*", "*waste disposal*" and "*developing countries*". These descriptors are associated with the main benefits that can be derived from the use of AWB in the construction sector. Cluster 4 (yellow), with eight items, integrates the word "*straw*" as another main type of AWB used in the construction sector, mainly in the form of "*fibers*" because of its high "*cellulose*" content, which makes it an ideal by-product for the "*reinforcement*" of building materials [55–57]. The keyword "*bagasse*" forms cluster 5 (purple). This term refers to the by-product of the extraction of sugar cane juice [54]. The ash obtained from the burning of this sugar cane bagasse has important qualities that improve the properties of different building materials [50, 51, 54]. India is the second-largest producer of sugar cane after Brazil [16]. This also suggests a correlation with the number of studies corresponding to this country.

Main approaches to scientific production—systematic review

Type of agricultural waste biomass used and main form of by-products Figure 5 shows the main types of AWBs assessed in the investigations. A total of 32 AWB types were identified. Forty-eight percent of the studies used rice husk, and thirty-four percent used sugar cane bagasse. These are the two main AWBs generated in the highest volumes worldwide [34, 50]. In the investigations, straw from cereal crops was the third most analysed type of AWB (28%). The main type of cereal crop from which the straw is derived is wheat (65%), followed by rice (50%). To a lesser extent, barley, sorghum, rye and oats was studied. Another study analysing approaches and alternatives for AWB utilisation identified cereal straw as the most relevant, mainly from wheat and maize [43].

Coconut husk is also one of the main types of AWB used in the research (24%). To a lesser extent, maize cob (20%) and oil palm (18%) and maize husk (6%) were identified as relevant. A further 24 types of AWB were used, including; cork, banana and pineapple leaves and/or

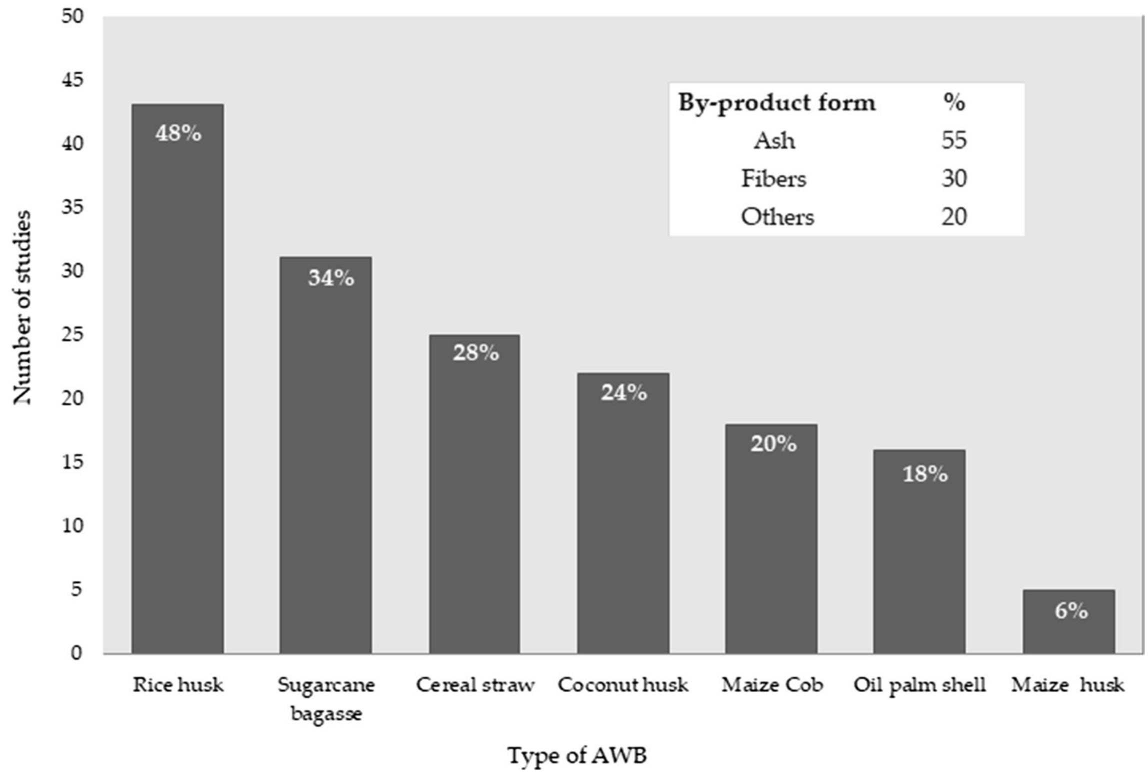


Fig. 5 Main types and forms of AWB used

peels, maize, soybean and cotton stalks, pomace and/or oil mill residues and coffee husks, nuts, cassava and grape sprouts, among others. The vast majority of crop parts (leaves, stems, fruits, seeds, sprouts) are used to manufacture new bio-based products. Contrary to [21], it is evident that more than half of the studies in the sample used more than one type of AWB [16, 58–62]. This was possibly to improve the properties of the final products [63].

Rice husks and straw, wheat straw, maize stalks and cob, and coconut husks were the main types of AWB used as raw materials in the first investigations in 1978 [40, 41]. Regarding the main form in which this type of AWB is used, it was found that more than half of the studies in the sample (55%) used it in form of ash. Twenty-nine percent used this biomass in the form of fiber. Other forms identified were granules and/or small particulate shredded material (20%). Most of the studies analysed the physical, chemical, thermal and other properties of the by-products (ash, fibers and AWB particles). This was mainly to characterise them, evaluate their potential, determine the best alternatives for their use and/or define optimum substitution percentages [19, 55, 56, 64].

The main parameters evaluated were; specific gravity, surface area, bulk density, particle size and fineness, water absorption, porosity, microstructure, and thickness [5, 18, 24, 26–29, 33, 35, 62, 65–67]. Concerning chemical properties, they analysed the cellulose, hemicellulose, and lignin content. Similarly, percentages of Loss on Ignition (LOI) and chemical components, such as SiO_2, Al_2O_3, CaO, Fe_2O_3, Na_2O, P$_2$O5, MgO, MnO, K_2O [6, 16–20, 25–29, 35, 50, 52, 53, 55, 56, 60, 62, 68–81]. Other main properties evaluated were thermal conductivity, microstructure and sound absorption [5, 18, 21, 22, 26, 28, 33, 60, 65, 74, 82].

Main biomaterials Fifty-one percent of the research focuses on obtaining bindings, aggregates and/or additives in soil, cement and/or concrete. Supplementary Cementitious Materials (SCMs) are the most studied in this first category. Seventy percent of the research evaluated the potential use of AWBs as an alternative material for the total and/or partial replacement of cement in concrete [6, 15, 17–19, 24–27, 33–35, 40, 50, 52, 54, 59, 62, 64, 68, 71–75, 83–88]. The relevance of this type of biomaterials is also reflected in their evolution. From 1978 to the present day, they have been studied as an alternative for the valorisation of AWB in the construction sector. One of the first biomaterials obtained from agricultural waste by the Central Building Research Institute in India in 1978 were pozzolanic reaction additives for cement production. Contrary to [84] and in line with the findings of [24], there is a large and long-standing field of research in AWB-based SCMs for use in concrete production.

In this same category, 24% of the studies in the period 2004 to 2021 used AWBs as a total and/or partial substitute material for conventional fine and/or coarse aggregates in concrete [21, 28, 29, 36, 66, 67, 83, 89–92]. A smaller percentage (3%), between 2019 and 2021, analysed the potential of AWBs as additives and/or aggregates for soil stabilisation and/or improvement of geotechnical properties [69, 70, 93]. Other studies used a similar classification for the categories of use of agricultural residues in concrete [15, 66]. The second category integrates the studies (22%) that evaluated the use of AWBs as biomaterials for brick production. According to the number of studies and the publication period (1978–2021), this is the second most common type of AWB used in the construction sector.

The third category (20%) integrates studies that evaluated materials and/or bio-composites for specific use in structural and/or reinforcement applications. The composite materials mentioned in most of the studies in this category are made from a mixture of plastic polymers and natural fibers [14]. Ten percent of the research in the period 2013 to 2021 analysed AWBs as specific materials for thermal and/or acoustic insulation of buildings (category 4). A smaller percentage (4%), category 5, grouped more recent studies (2016–2021). These studies evaluated the potential use of AWBs as a full and/or partial substitute for traditional asphalt binders and/or aggregates used in road construction. In 1978, agricultural residues were also used as substitutes for hydraulic components in bricks and other products, such as boards and panels without synthetic binders. Some of these biomaterials were incorporated into walls and shade roofs for livestock [40, 41].

Main bio-based products Table 1 summarises the main bio-based products evaluated by the sample studies. These bio-based products were manufactured from mixtures of the above biomaterials with other types of waste and/or materials. For example; bamboo fiber and leaves [27, 33, 60, 75], bauxite process wastes [63], sheep wool [61], fluid catalytic cracking residue, ceramic sanitary ware, waste from beer filtration [68], construction demolition waste (C&DW) [51, 69], granulated tires [58, 94], glass powder/fiber [62, 95], sawdust [15, 19, 29, 40, 53], wood [17, 19, 27, 85, 86], sunflower stalks and seed [91, 96], egg shell powder [93], cow dung [23], reclaimed asphalt pavement, reclaimed asphalt shingles [94], water treatment plant sludge [79, 97], and recycled plastics [98].

Materials traditionally used in the construction sector, such as lime, sand, and Portland Cement, were also used to prepare the mixtures from which the bio-based products in Table 1 were obtained [6, 50, 69–71, 74, 90, 91]. This extensive listing of each category highlights the wide variety of bio-based products in which AWBs can be used. Furthermore, the diversity of industrial and/or other wastes with which they can be combined further enhances the overall waste valorisation.

Most of these bio-based products have traditionally been used in the construction sector, especially in categories 1 and 2. However, it is noticeable how the terminology has evolved in recent years. The most recent research refers to agro-concrete/cement, agro/bricks, sustainable cement/concrete, sustainable bricks, green concrete, ecological concrete, eco-friendly bricks, thermally efficient bricks, zero cement concrete, sustainable bio-modified asphalt, sustainable green highways [18, 26, 50, 54, 63, 67, 77, 91, 100]. These new concepts align with recent policy approaches on sustainable development and, more specifically, with the circular economy and bioeconomy [4, 11].

In addition, novel uses and futuristic bio-based products for the construction sector are evident. For example, bricks made from rice husk ash can be used as an alternative sustainable energy source [42]. Category 3 integrates an extensive and varied list of bio-based products, demonstrating the potential of AWB for use as a biopolymer in various applications in the construction sector [108]. Furthermore, 78 percent of the studies in this category have been published in the last 5 years, confirming the important evolution and relevance of bio-composites for structural and/or reinforcement applications. Bio-based products for buildings' thermal and/or acoustic insulation have mainly been analysed in the last 4 years.

Bio-based products in category 5 are entirely novel. A few recent, related pieces of research show that it is an emerging approach. This is also an indicator of important new alternatives that may emerge for the valorisation of AWBs as high value-added biomaterials. In this category are also terms from new models of sustainable development, such as "Sustainable bio-modified asphalt" [80]. Furthermore, they refer to using these bio-based products to construct sustainable greenways [114]. Other studies identified biomaterials and/or bio-based products similar to those in Table 1, mainly from categories 1 to 4 [15, 21]. However, none of them includes those used for road construction.

The influence of AWBs on the properties of bio-based products depends on their characteristics, the processes they undergo and the proportions in which they are mixed with other materials, among other aspects

Table 1 Main types of bio-based products

Biomaterials by category	Type of bio-based products	References
Category 1 Binding materials, aggregates and/or additives for soil, cement and/or concrete	Sustainable cement Green, ecological and/or sustainable concrete Concrete blocks Hardened concrete Agro-concrete/cement Ordinary Portland cement (OPC) concrete Lightweight aggregate concrete Cement concrete Geopolymer concrete Clayey sand and soil Cement mortars Activated cement mortar Cement-based panels Wood-cement blocks Roofing tiles Clay and laterite soils	[6, 17, 26–29, 33, 34, 50–52, 54, 62, 66–69, 71, 72, 75, 81, 83, 86, 88–91, 99]
Category 2 Brick materials	Ceramic bricks Clay bricks Clay matrix bricks Fired clay bricks Agro bricks Earth bricks Light fired clay bricks Lightweight bricks Thermally efficient burnt clay bricks Eco-friendly clay bricks Eco-friendly porous ceramic bricks Unfired earth blocks/bricks White brick fuel cell Building block for masonry wall	[5, 15, 16, 21, 29, 41, 53, 55, 57, 63, 76, 77, 79, 85, 96, 100–104]
Category 3 Materials/biocomposites for structural and/or reinforcement applications	Natural fiber/polymer composites (NFPCs) Polymer matrices for lightweight structural applications Reinforced polypropylene composites (wall panel) Bio-epoxy resin reinforced green composites Bio-based polymers Wallpaper Hybrid polypropylene composites False ceiling tiles Fiber-cement Concrete walls Cement-bonded particleboard Binderless fibre-board Reinforced polypropylene Reinforced composites Particleboard Fibreboards Unitary (or "monolithic") structural components and assemblies Earth Plaster Composites Panels, door shutters, door frames, roofing sheets and dough molding compounds Roofing tiles, ceiling plates, thin sheets, wall panels Lightweight building components Structural sheathing materials Composite boards/panels	[20, 41, 55, 56, 60, 78, 82, 95, 98, 99, 105–112]

Table 1 (continued)

Biomaterials by category	Type of bio-based products	References
Category 4 Materials for thermal and/or acoustic insulation in buildings	Joints between walls, windows, floor, and roof Recycled waste panels Insulation panels Bio-based insulations Structural materials for low-energy buildings Thermal insulating plate Reinforced panels Particleboards Bio-Based Plastics	[21–23, 58, 61, 65, 97, 109, 113]
Category 5 Road construction materials	Sustainable bio-modified asphalt Asphaltic concrete Modified Asphalt Binders	[80, 94, 114, 115]

[33, 92]. Therefore, most of the studies in the sample analysed considers physical, chemical, mechanical and other properties of the bio-based products. This was to identify the effects of AWBs and determine compliance with the standards of the regulations governing the quality of building materials [90]. Table 2 summarises the main parameters evaluated for each of the properties.

In line with the findings of other studies, it was identified that the main tests bio-based products were subjected to are compressive strength, density and water absorption [5, 25, 100]. Compliance with these parameters is essential to guarantee the obtained bio-based products' quality, longevity, and durability [26, 29, 100–102].

Main types and properties of AWBs used by category Rice husk and sugarcane bagasse are two of the main types of AWB used as biomaterials for the production of cement, concrete and bricks. The main form in which this biomass is used is ash, followed by a smaller percentage of fiber. These findings are in line with other researchers that highlighted rice husk ash and sugar cane bagasse as the most studied alternative materials used in building materials, mainly in the concrete industry [18, 21, 26, 29, 33, 35, 86]. Table 3 summarises the three main types of AWBs that are used for each category. It also highlights the most relevant aspects that impact the improvement of the properties of the bio-based products obtained.

A study analysing the use of industrial and agricultural wastes in cement identified general properties and applications of AWBs similar to those of category 1 [35]. Of the three types of AWB prioritised for each category according to the number of studies that have used them, it is evident that rice husk ash is the most versatile type of waste that can be used in all applications in each category. One of the first researches from 1978 highlights rice husk as a highly reactive pozzolanic material, which makes it a good alternative for producing new cementitious materials [40].

Several studies indicate that the main component of agricultural residue ash is silica [19, 33, 53]. However, some of them point out that silica in rice husk ash and bagasse ash is significantly higher (between 60 and 95%) [24, 26, 49, 54, 86, 92]. In turn, the pozzolanic nature of these ashes [71] makes them efficient biomaterials for improving the physical, mechanical and thermal properties of bio-based products. Among them: strength, durability, workability, porosity, thermal conductivity, and other properties that are highlighted for each type of biomaterials in Table 3.

Cereal straw fibres have significant use in the production of bricks and biomaterials used as fillers in polymeric matrices for structural reinforcement (increased strength and stiffness) and thermal and/or acoustic insulation [55–57, 82, 95, 99, 107, 109–111]. Fiber length and width affect bio-based products' physical, mechanical, and thermal properties [56, 109, 111]. In the manufacture of bio-composites, these fibres replace all or part of the wood [56, 110]. Coconut husks are another by-product with great potential due to their high natural fiber content [56]. A study identified coconut and rice husks as one of the main AWBs used to produce biopolymers for construction applications [20]. In line with the findings of other studies, it is evident that fibrous AWBs such as rice husks, cereal straw and bagasse are suitable for thermal and acoustic insulation applications [21, 37, 65].

Some of the research in the sample does not specifically highlight additional positive effects on bio-based products resulting from AWBs. However, most of them confirm that the use of AWBs to manufacture bio-based products is technically feasible from a technical point of view. Mainly because these bio-based products meet the properties and performance requirements for building materials. In addition, they are similar to commercial products and conform to regulatory specifications [5, 18,

Table 2 Main properties and parameters of the bio-based products

Properties	Parameter	References
Physical	Sorptivity Bulk density Microstructure Specific Gravity Drying shrinkage Apparent Porosity Water absorption	[5, 6, 15, 18, 22, 25, 33, 36, 51, 53, 56, 58, 60, 63, 64, 76, 77, 79, 80, 87, 88, 91, 92, 94, 96, 97, 99, 101, 103–109, 111, 113–115]
Mechanical	Durability Workability Flowability Flexural strength Tensile strength Impact strength Young's modulus Thickness swelling Compressive strength	[5, 6, 15–18, 21, 22, 25–27, 29, 33, 51, 55, 56, 58, 60–63, 67, 69–74, 81, 87–89, 91–93, 95, 96, 98, 99, 101–108, 110, 112, 113, 115]
Chemical	Loss on ignition Chloride resistance Resistance to chloride Acid and sulphate resistance Heavy metals content/leaching toxicity	[6, 18, 26, 33, 36, 51, 53, 63, 77, 97]
Others	Mineralogical analysis Sound absorption Thermal conductivity High temperature resistance Thermogravimetric analysis	[5, 6, 16, 21–23, 29, 53, 55, 57, 58, 61, 63, 67, 72, 76, 77, 92, 97–99, 101–106, 108–110, 113]

26, 28, 66–68, 75, 79]. On the other hand, concerning the properties of bio-based products, most studies emphasise that a generalised substitution of AWBs is not possible. Therefore, it is essential to achieve mixture compositions with optimal AWB substitution percentages [33, 49, 54, 64, 86, 105].

To improve the properties and/or guarantee the performance of most of the bio-based products in Table 1, studies suggest substitution percentages between 5 and 15% by weight of AWBs [6, 16, 18, 19, 21, 25, 33, 50, 51, 53, 66, 69, 77, 90, 100, 103, 115]. These findings align with a study that identified similar percentages, between 5 and 10% AWB for fired clay bricks [100]. Several studies in the sample identified that higher substitution levels could generate counter (negative) effects on bio-based products' properties and/or performance [19, 25, 53, 67]. However, higher percentages of AWB (30–50% of oil palm shell) were suggested for the construction of roads with medium and/or low traffic [114]. In addition, in other applications used to improve the thermal performance of buildings (21–63%) [23, 58]. On the other hand, lower AWB percentages (2–4%) were considered for soil stabilisation [70, 93].

Main limitations and/or disadvantages of the use of AWB in bio-based products As indicated in Table 4, several of the studies analysed point out some limitations and/or disadvantages derived from the use of AWBs as biomaterials for the production of bio-based products. Increased water absorption and reduced workability are some of the main disadvantages identified [15, 53, 92, 113]. Some of the limitations and/or disadvantages in Table 4 coincide with those identified by other studies that analysed them for specific applications, such as thermal and acoustic insulation [22, 32].

On the other hand, most of the studies in Table 4 also identified mechanisms to avoid and/or reduce the negative effects of AWBs on bio-based products. Applying appropriate processing methods including both pre- and/or additional treatment processes is crucial. These include immersion of fibers and/or ashes in chemicals, cooking, drying, filtering and/or screening [26, 33, 91, 106, 109, 111, 113]. Some research has also suggested the incorporation of other types of materials and/or microorganisms [19, 25, 72]. In line with the approaches of [21], the findings of this study confirm that the indicated pretreatments and/or additional processes are necessary under certain circumstances and/or for certain types of biomaterials or bio-based products. A wide variety of biomaterials and bio-based products (Table 1) can be obtained through direct utilisation or minimal transformation processes.

These identified corrective actions and/or improvement alternatives (Table 4) reinforce the approach on the

Table 3 Main types and properties of AWBs used by category

Type of biomaterials	Main type and form of AWB	Main characteristics of the by-product	Effects on the properties of bio-based products	References
Category 1 Binding materials, aggregates and/or additives for soil, cement and/or concrete	Rice Husk (Ash) Sugarcane bagasse (Ash) Coconut husks (Ash)	Rich in amorphous silica High pozzolanic activity Pore-forming additives Lower specific gravity Increases setting time lower thermal conductivity	Improved mechanical properties (Compressive, flexural, shear and tensile strength) Reduction of thermal conductivity Density reduction (lighter materials) Better resistance to acid attack Increased resistance to chloride penetration Lower water absorption Reduced permeability Improved durability Improved workability Improvement of the geotechnical properties of the soil	[5, 6, 15, 18, 21, 24–26, 29, 33–35, 50, 51, 54, 59, 62, 66–71, 73, 74, 81, 90, 92, 112]
Category 2 Brick materials	Rice Husk (Ash) Cereal Straw (Ash –fibers) Sugarcane bagasse (Ash)		Increased ceramic strength Increase in amount and size of pores Reduction of bulk density Reduction of brick weight Reduction of the thermal conductivity coefficient Lower dead load Improved thermal insulation properties Improved static properties Reduced plasticity	[15, 16, 21, 53, 57, 63, 76, 77, 79, 101, 103, 104]
Category 3 Materials/biocomposites for structural and/or reinforcement applications	Cereal Straw (Fibers) Rice Husk (Ash) Coconut husks (Fibers—Ash)	Lower specific gravity High percentage of fibers Longer fibers Tubular internal structure, strong and efficient Low density High cellulose and hemicellulose content	Improvement of impact, tensile and flexural strength Better resistance to water and thickness swelling Low weight Good sound absorption Improved load transfer and crack arrest efficiency Improved thermal insulation/thermal stability Better structural integrity and energy dissipation Good stiffness for civil infrastructural applications Control of shrinkagecracks Decreases erosion of materials Improveds shrinkage properties Better absorption of impact energy	[15, 20, 55, 56, 60, 82, 95, 98, 99, 105, 107–111, 113]

Table 3 (continued)

Type of biomaterials	Main type and form of AWB	Main characteristics of the by-product	Effects on the properties of bio-based products	References
Category 4 Materials for thermal and/or acoustic insulation in buildings	Rice Husk (fibers) Cereal Straw (fibers) Sugarcane bagasse (fibers)		Better thermal and environmental performance Good thermal conductivity and resistivity Satisfactory results in mechanical and thermophysical performance High sound absorption coefficients Lower density	[21–23, 58, 65, 97, 113]
Category 5 Road construction materials	Rice Husk (Ash-fibers) Coconut Shell (Small aggregate) Sugarcane bagasse (Fibers) Palm shells (coarse aggregate)		Increased resistance to thermal cracking of the pavement at low temperatures Reduced permanent (plastic) deformation at high road surface temperatures under traffic loads Improvement of -the rutting factor Improved fatigue resistance of the asphalt binder Good range stability Marshall Improved mechanical properties	[80, 114, 115]

feasibility of using AWB as a biomaterial for the production of bio-based products. However, it is important to consider that some of the studies in the sample suggest that further research is needed to improve the utilisation of AWB, understand its influence on bio-based products and ensure its application in large-scale structures [24–26, 29, 33, 67, 73, 95].

Feasibility of the use of bio-based products Table 5 shows the main aspects highlighted by the sample studies for each dimension of sustainability. The environmental dimension is the most relevant. More than sixty percent of the analysed studies highlight, in a general and/or specific way, contributions towards the improvement of the environment derived from the use of AWBs in the construction sector. Positive impacts on air, soil and water resources are comprehensively listed in Table 5. Among the main benefits mentioned are reduction of carbon dioxide emissions and global warming [24, 25, 52, 54, 68, 83, 86, 91, 104]. Similarly, aspects related to the efficient management of AWB, such as volume reduction, recycling, recovery, reduction of landfills and open burning [5, 33, 63, 77, 85, 101]. Reducing energy consumption and increasing energy efficiency is another environmental highlight [5, 55, 58, 77, 104]. On the other hand, some of the studies refer to the green economy and the circular economy as basic strategies, which are also supported and/or promoted by the valorisation of AWB in the building sector [27, 58, 75, 86].

Second, economic aspects were also analysed in the research. Some studies carried out profitability analyses and/or technical/economic feasibility studies [18, 73, 81, 106]. These analyses indicate that the manufacture of bio-based products is cost-effective and they can be suitable products to compete in the market. Furthermore, their use reduces the cost of construction. A key aspect they highlight to make costs feasible is using local AWB to reduce pre-treatment and/or transport costs [18, 73]. This aspect contributes to the socio-economic viability of bio-based products [104]. Although they do not perform this analysis, other studies highlight that bio-based products made from AWB help the obtainment of economic benefits derived from reducing the cost of biomaterials, structures and/or construction in general [15, 63, 77, 85, 100, 101].

The findings for this economic dimension confirm the theorisation of a study that analysed the use of AWB in concrete production [18]. This concerns the low number of studies that have conducted economic analyses to estimate the costs of producing bio-based products from AWBs and determine their feasibility. However, this study adds new evidence that this type of analysis has been conducted for various AWBs. For example, in addition to rice husk ash, as indicated by [18], costs have been evaluated for the use of coconut husk [73], sugarcane bagasse [81] and pineapple leaf fibers [106]. However, given the large variety of AWB types identified (32 types); it is evident that a low percentage has been evaluated from an economic point of view. This could be one of the key factors necessary to boost bio-based products' application and commercialisation. So far, as derived from the findings of this study have mainly been developed at an experimental level. One study points out that some bio-based products used for insulation are in their early stages of development and will still have a long way to go before reaching the market [22].

A smaller percentage of the publications (11%) highlight some aspects related to the social dimension. Mainly, the reduction of housing and infrastructure costs in rural areas and/or developing countries [86, 89, 99, 114], the creation of new jobs [22, 104], among other aspects associated with the health and well-being of the population. One of the publications from 1978 already pointed out that the use of AWB in the manufacture of building materials contributed to solving waste disposal problems and reducing the costs of transporting materials. It also generated savings in production costs and energy consumption [40]. This broad analysis of contributions for all dimensions reinforces the theorisation of this first publication. It indicates the relevance that the

Table 4 Limitations and improvement alternatives for bio-based products

Limitations and/or disadvantages	Alternatives to reduce adverse effects	References
Increase LOI Reduction of workability Lower strength activity index (SAI) Higher drying shrinkage High water absorption Susceptibility towards chemical attack Effect of moisture content on internal bonding Dimensional stability Lower durability Crack formation	Additional treatments Chemical and/or heat treatment of fibres Pre-treatment methods (screening, burning, drying, firing) Incorporation of nanomaterials nano silica, nano alumina Inclusion of bacteria in rice husk Addition of stone dust	[15, 19, 21, 22, 24–26, 32, 33, 36, 52, 56, 61, 91, 105, 106, 109–111, 113]

Table 5 Main benefits by dimension

Dimension	Description of main benefits or advantages	References
Economic	New value chains New market opportunities Savings raw materials Reduction of material production costs Reduction of waste landfill fees Reduction of transportation costs Reduction in construction cost Reduction of road construction and maintenance in rural areas costs	[6, 15, 16, 18, 19, 21, 22, 28, 34, 40, 53, 56, 59, 63, 66, 69, 73, 81, 84, 85, 91, 95, 96, 98–100, 104, 106, 114]
Environmental	Carbon dioxide (CO2) emissions reduction Reducing global warming and climate change Increasing energy efficiency Reduction in consumption of thermal and electrical energy Landfill reduction Improving the management of the AWB Recycling and valorisation of AWB Values of leaching toxicity much lower Reduced consumption of natural clay reserves Reducing the exploitation of natural resources Reduction of AWB burning Reduction of water consumption Reduced consumption of virgin raw materials Reduction of soil erosion	[5, 6, 15, 16, 18, 19, 21–25, 27–29, 34, 35, 40, 50, 52–56, 58, 62, 63, 65–69, 71–77, 81, 82, 84–86, 91, 93, 96–100, 102, 104, 105, 107, 110, 113, 114]
Social	Creation of new jobs Enhancing the economic power of local communities Low-cost building and/or infrastructure development in low-income regions Use of locally available materials for infrastructure works in developing countries Reduce social housing cost Functional, high quality, comfortable and affordable environments for building occupants Societal welfare Healthy indoor environment Population health benefits	[21–23, 58, 86, 89, 91, 99, 104, 114]

integration of environmental and social aspects as pillars of sustainable development has gained in research. However, it is essential that such studies include broader feasibility analyses, integrating all dimensions (economic, social and environmental) from local contexts.

Furthermore, these findings coincide with the findings of other studies regarding the potential of AWBs for the production of bio-based products and their contribution to sustainability [21, 52, 104]. Although this suggests positive aspects in advancing the application of bio-based products on an industrial scale, it is important to bear in mind some considerations. For example, identifying and quantifying locally available agricultural residues is key. This is to ensure that there are no supply constraints [22, 26, 75].

European Union projects

Table 6 summarises the projects related to the valorisation of AWB in the construction sector. Of these projects, 67% were financed by the first EU framework programme for research and innovation—Horizon 2020. The oldest project, dating back to 1994, was carried out with the "*Research and Technological Development in the Field of Industrial and Materials Technologies FP3-CRAFT (1990–1994)*" programme. This project used straw and husks to obtain mineral binders [116]. The second older project carried out between 2004 and 2007 was part of the EU's "*Focusing and Integrating Community Research*" programme (2002–2006). Rice straw was also one of the main inputs for this project, which produced composites for structural components as a bio-based product [117]. The SYNPOL project, which produced biopolymers from rice straw, was part of the FP7-KBBE programme "*Cooperation: Food, Agriculture and Biotechnology*" [118].

In general, straw is the most commonly used type of AWB for producing bio-based products, such as cement, wooden boards, thermoplastic adhesive, biopolymers and composites. However, in line with the findings of the research analysed, it is evident that these projects have used different types of AWB in recent years, which confirms their potential for obtaining high added-value products. All the applications of AWBs prioritised by the projects are similar to those identified in the research analysed. The focus on the production of biopolymers and bio-composites confirms that this type of AWB application has become more relevant in the construction sector in recent years. This makes sense considering that it has been one of the fastest evolving areas of the bioeconomy [9].

Other projects identified in the CORDIS database obtained eco-sustainable concretes from other types of waste, such as plastic, electrical and electronic equipment, municipal solid waste and pneumatic components [119, 120]. They also made ceramics from the sludge from wastewater treatment [121]. Most of the projects in Table 6 address all three pillars of sustainability. They emphasise that from an environmental point of view, there are benefits associated with improved energy consumption, waste reduction and reduction of CO2 emissions [116, 122, 123]. Similarly, the creation of new jobs in the bio-based products sector and the improvement of industrial competitiveness [122]. Economic benefits are derived from the reduced costs of new bio-based products [116]. This is in line with the approaches of the European bioeconomy strategy [4].

Besides the manufacturing of bio-based products, some of the projects in Table 6 include market potential analysis, marketing improvement strategies, and other activities aimed at improving the information on technical aspects of bio-based products to boost and/or enhance their market share [122–124]. The opening of bio-based markets through educational tools and campaigns aimed at improving knowledge and increasing public acceptance of bio-based products was also one of the objectives of the projects [125, 126]. This is a crucial aspect in advancing the application of bio-based products on an industrial scale.

Furthermore, the EU encourages synergies between European and Indian research programmes dedicated to biowaste conversion and biomass production through such projects [127]. Sixty-seven percent of the projects were implemented in 2016–2021, indicating that the Horizon 2020 programme (2014–2020) prioritised the deployment of projects focused on bio-based alternatives to improve the sustainability of building products. This is to some extent, because this research and innovation framework programme is the primary source of funding for the bioeconomy in Europe [128]. Some of the projects are specifically framed within the action line "Societal challenges" of the Horizon 2020 programme, which prioritises sustainable agriculture and the bioeconomy. In general, these projects highlight the contributions of the bio-based construction sector to the consolidation of the European circular economy and bioeconomy.

These two models have become essential axes for sustainable development in Europe. For 2021–2024, the EU has included the bioeconomy among the vital strategic orientations for research and innovation (Horizon Europe) [133]. This represents an opportunity to further strengthen the bio-based construction sector, especially in the production of bio-based products from AWB and improve the market's functioning for these products [134]. The circular approach of the bioeconomy has demanded new lines of research on biomass valorisation alternatives in the construction sector. This has increased the number of studies and projects on this subject in the last 5 years. The resources that have been allocated through projects have been and will continue to be vital to the application and consolidation of the circular economy and bioeconomy as the primary strategy for sustainable development.

Conclusions

Regarding the first research question, the findings allow us to conclude that a great variety of AWB has been studied for more than 40 years as a secondary raw material for obtaining biomaterials and/or bio-based products with multiple applications in the construction of buildings and civil works. However, in the last 5 years, there has been an increase in publications. India is the country that leads the ranking of research on this subject basically, because it is one of the leading producers and consumers of cement and the second-largest producer of rice and sugar cane in the world. Concerning the second research question, the residues of these two crops, mainly rice husk and sugar cane bagasse, are the two most commonly used types of AWB (in the form of ash) in the manufacture of a wide variety of bio-based products for construction.

Rice husk ash has been the most studied type of waste, since 1978, mainly because of its versatility for multiple applications. However, its use has historically been prioritised in cement and/or concrete production. The latter, together with bricks, are the types of bio-based products most analysed by research. The results also show that bio-composites for structural applications and bio-based products for thermal and/or acoustic insulation have gained more relevance in recent years as an alternative for the valorisation of AWB. The findings also point to a novel and emerging approach for utilising AWB in road construction. This confirms the potential of this type of biomass as input for obtaining a wide variety of bio-based products with multiple uses in the construction industry.

Concerning the third research question, the new names of bio-based products related to sustainability and the analysis of the dimensions that comprise it guide the importance of this concept in research. The studies

Table 6 European Union projects

Proyect name	Objetive	Type of AWB	Type of bio-based prodcuts	Project implementation date	References
Grant agreement ID: CR147691-BRE21154	Development of new construction materials based on mineral binders derived from waste	Straw and husk	Mineral binder	May–July 1994	[116]
ECO-PCCM	To introduce a new class of eco-friendly and cost-effective polymer composite construction material	Rice straw, hemp, kenaf, cotton, sisal, flax	Renewable eco-friendly composites for structural components	October 2004–September 2007	[117]
SYNPOL–Biopolymers from Syngas Fermentation	Establish a platform for integrating synthesis gas production and fermentation technologies for cost-effective commercial production of high value-added biopolymers	Straw	Biopolymers	October 2012–September 2016	[118]
REHAP	Development of new materials for the construction sector from agricultural and forestry residues	Wheat straw	Thermoplastic PU Adhesive Wooden boards Cement	October 2016–March 2021	[122]
AgroCycle	To convert low-value agricultural waste into highly valuable products, achieving a 10% increase in waste recycling and valorisation by 2020	Horticultural waste	High value-added biopolymers	June 2016–May 2019	[129]
Mycotaff	A renewable bio-based material that enables efficient, cost-effective production of high-quality insulation, packaging, dry-wall, and other building materials	Mushroom mycelia	Prefabrication walls material for insulation and other building applications	June–september 2018	[130]
BARBARA	The development of novel bio-based engineering bioplastic materials to be validated as functional prototypes with advanced properties for the building and automotive sectors	Lemon, carrot, pomegranate and almond shell	Polyester-Based Biocomposites Moulds for Resin Transfer Moulding and truss joint prototypes	May 2017–October 2020	[131]
B-SMART	To develop new intelligent cementitious nanocomposites for multifunctional built infrastructure made by combining ordinary Portland cement (OPC) with cheap bio-nanomaterials synthesised from root vegetable waste, such as carrot and beetroot waste streams produced by the food processing industry	Carrot and beetroot waste	Intelligent cementitious nanocomposites for multifunctional built infrastructure	September 2018–September 2020	[132]

Table 6 (continued)

Proyect name	Objetive	Type of AWB	Type of bio-based prodcuts	Project implementation date	References
NoAW: No Agro-Waste	To generate innovative efficient approaches to convert growing agricultural waste issues into eco-efficient bio-based products opportunities with direct benefits for both environment, economy and EU consumer	Maize silage grape stalks Vine shoots /wine pomace Fruit and vegetable wastes	Biocomposites/Biodegradable polymers—polyhydroxyalkanoates (PHAs)	October 2016–January 2021	[123]

R Reference

highlight relevant contributions from an economic, environmental and social point of view, which indicates that they are based on the approaches of the new policy framework on sustainable development. This, regarding the fourth research question, shows that under the approaches of this policy framework, especially the Circular Economy and Bioeconomy, agriculture and the construction industry are vital sectors and major allies for sustainability. It is also evident that the prioritisation of AWB as a secondary raw material has promoted more significant scientific progress. This is because it is necessary to identify more and better valorisation alternatives to improve the sustainability of construction products. The increase of projects with this approach has also allowed further progress in the practical application of these alternatives. However, the findings allow us to conclude that the application of bio-based products on an industrial scale is still low in relation to scientific advances. In this sense, it is hoped that new governmental strategies on sustainability and circularity will contribute to overcoming the limitations faced by this type of bio-based product from their manufacture to their launch on the market.

With respect to the limitations of this research, it is important to highlight that the search equation includes the most common and general terms on the subject, which possibly excludes studies that have used more specific terms. Similarly, the projects analysed are obtained from a single data source, which, although representative at the European level, does not include all the projects that have been developed through other sources of funding and/or in other countries. Therefore, future research could focus on the analysis of other data sources to evaluate the practical application of bio-based products obtained from AWB more extensively. Similarly, as a line of research, the findings suggest that further studies, including cost analyses of the production of bio-based products from AWB, are needed to determine their cost-effectiveness and/or technical/economic feasibility. In the same vein, other studies could include broader feasibility analyses, incorporating economic, environmental and social dimensions.

Abbreviations

AWB: Agricultural Waste Biomass; GHG: Greenhouse gases; EU: European Union; SDGs: Sustainable Development Goals; CE: Circular economy; CBE: Circular bioeconomy; CORDIS: Community Research and Development Information Service; LOI: Loss on Ignition; SCMs: Supplementary Cementitious Materials.

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Availability of data and materials

The data sets used and/or analysed during the current study are available from the corresponding author on reasonable request.

Declarations

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Competing interests

The authors declare no competing interests.

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