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Biocities with wood and bamboo: A path to low-carbon urbanization for greener societies

Victor De Araujo [a,b,*], Fernando Mascarenhas [c,d], Frederik Laleicke [e], Andreja Kutnar [f,g], Alfredo Dias [c,d], Jan van de Kuilen [h,i], Martin Hubbe [e], Francisco Lahr [j], André Christoforo [b,a]

[a] São Paulo State University (UNESP), 56 Brasil Sul, Ilha Solteira, Brazil
[b] Federal University of São Carlos (UFSCar), 235km Rodovia Washington Luis, São Carlos, Brazil
[c] University of Coimbra (UC), 290 Rua Luis Reis dos Santos, Coimbra, Portugal
[d] Forest Innovation and Competence Centre (serQ), 9 Rua J, Sertã, Portugal
[e] North Carolina State University (NCSU), 2820 Faucette Dr, Raleigh, United States
[f] University of Primorska (UP), Titov trg 4, 6000, Koper, Slovenia
[g] InnoRenew CoE Renewable Materials and Healthy Environments Research and Innovation Centre of Excellence (InnoRenew CoE), Livade 6a, 6310, Izola, Slovenia
[h] Technical University of Munich (TUM), Winzererstrasse 45, 80797, Munich, Germany
[i] Delft University of Technology (TUDelft), 2628 Stevinweg 1, Delft, Netherlands
[j] University of São Paulo (USP), 400 Avenida Trabalhador São Carlense, São Carlos, Brazil

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ABSTRACT

By using minerals instead of bioresources in construction, greenhouse gas emissions are nearly doubled. It is vital to transition from this traditional paradigm to a low-carbon model in which woods and bamboos are essential components. To proliferate bio-urbanization, challenges must be overcome in forestry and construction. Our study is a necessary starting point for more sophisticated studies and policies to support the valorization and utilization of bioresources, especially wood and bamboo, in greener construction solutions for a sustainable urbanization. Our main results elucidate examples and benefits of biobased cities and buildings, raise issues and current challenges, and suggest opportune actions to be globally addressed in collaborative proposals. Assertive codes, well-managed resources, resolution of challenges, and clarification campaigns on decarbonization are priority targets in future environmental and societal commitments.

1. Introduction

More and more, environmental issues are being looked at as leading priorities for future buildings, as there is an increasing demand to reduce greenhouse gases. Environmental impact evaluations of building materials supported by product declarations and life cycle analyses are being considered in new urban projects due to construction liabilities, including waste generation, energy and raw material consumption, work failures, building defects, and others – repairs are necessary to fix failures and defects, generating additional waste and affecting the life cycle. The mitigation of severe climate change effects becomes relevant in obtaining healthier alternatives than traditional solutions. Increases in population growth and economic development should be controlled as technology should be continuously and increasingly developed to achieve a more sustainable progress of nations – in this process, Lee and Zhao [1] assume the importance of the role of human capital, urbanization transition and foreign direct investment as possible strategies to be considered in the context of CO_2 reduction.

Both transitional (e.g., clean electrification, digitalization, etc.) and traditional activities (e.g., construction, fossil fuels, etc.) depend on impactful extractions of petroleum, lithium, copper, iron, gravel, and other minerals [2]. The construction sector is responsible for about one-third all global waste and more than one-third of all energy demands and carbon dioxide emissions [3]. This high demand is

* Corresponding author. São Paulo State University (UNESP), 56 Brasil Sul, Ilha Solteira, Brazil.
E-mail addresses: va.araujo@unesp.br, victor@ufscar.br (V. De Araujo), fer.jr.resende@hotmail.com (F. Mascarenhas), pflaleic@ncsu.edu (F. Laleicke), andreja.kutnar@upr.si (A. Kutnar), alfgdias@dec.uc.pt (A. Dias), vandekuilen@hfm.tum.de (J. van de Kuilen), hubbe@ncsu.edu (M. Hubbe), frocco@sc.usp.br (F. Lahr), alchristoforo@ufscar.br (A. Christoforo).

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attributed, in part, to a lack of a defined pathway to achieve climate neutrality [4].

Overcoming this involves recognizing that any bioresource, when converted into bio-based durable goods, usually plays a role in reducing environment impacts. Natural and biobased products offer a sustainable way to replace outdated building paradigms, although they are the basis of many buildings in nations with traditions in building with wood and bamboo.

Duan et al. [5] established that greenhouse gases from concrete-reinforced buildings are 49 % greater than average emissions from mass timber solutions. Distinct levels of carbon storage can be achieved in timber buildings design, which can use conventional examples or combinations of new wood species and building systems and techniques [6]. Timber, bamboo, and palm-based buildings can reach a net-negative embodied impact [7]. Benefits can be obtained by reducing methane emissions in forest products at the end of service lives [8]. Even so, low-carbon material solutions have been scientifically addressed to a lesser extent than traditional solutions [9]. Increasing evaluations using sustainability indicators evince that bioresource-based buildings cause less environmental impacts than mineral-based buildings. For example, 'woody' bioresources can be continuously produced sustainably from well-managed natural forests and plantations. Good forestry practices become convenient – especially given a decreasing trend of carbon accumulation verified in long-term forests [10]. According to Rais et al. [11] and Lowell et al. [12], forestry genetics and silviculture practices can increase productivity in terms of yield and quality. Trees provide efficient carbon storage and oxygen production from planting to crop. Ergo, long-lived bio-based products and buildings take advantage in environmental terms due to the prolonged carbon sink capacity [13].

Adequate information and affirmative attitude may change the traditional mindset to a low-carbon model. This review offers a comprehensive overview of the use of wood, bamboo and other renewable bioresources in the development of innovative bio-based urban centres, including the main issues that needs to be thought, challenges that requires mitigating actions, and choices and decisions that influence this. Accordingly, this article summarizes current knowledge, raises essential issues, discuss challenges, and provide convenient insights at different levels, all of which are necessary to be considered in future developments and policies to support the valorization, and utilization of bioresources in greener construction solutions for the bio-urbanization. Here, bioresources as versatile materials for greener construction and urbanization, timber rediscovery and uses in wide and tall buildings, bio-urbanization from engineered wood and bamboo and main examples, and challenges and actions towards a carbon-neutral urbanization topics were contextualized to contrast alternatives, foster discussion, and indicate directions for future developments in research and affirmative policy on bio-based construction and urbanization in this transitional moment worldwide.

2. Bioresources as versatile materials for greener construction and urbanization

As an aid in understanding the great potential for using wood and bamboo in new buildings, including everything from smaller houses to long-span structures and taller buildings, it is important to consider aspects of using lignocellulosic materials in a broader context.

For decades, bioresources and their products have been addressed as multipurpose solutions. In civil construction, they have attracted attention for aesthetics and versatility. Vigorous proposals to proliferate their uses in substitution for non-renewable fossil-origin products were started almost 50 years ago [14,15]. Wood and bamboo were the bioresources intensely used at the dawn of human urbanization as raw materials in the edification of habitable spaces and basic infrastructures, essential to the formation of the first human societies. Due to remaining centenary towns and millenary examples built in wood in the West and in bamboo in the East, perennial uses of bioresources in construction have been confirmed worldwide.

Today, fifteen locations built from wood and/or bamboo are already recognized by the United Nations Educational, Scientific and Cultural Organization (UNESCO) as World Heritage Sites, which include towns in The Americas, Europe, and Asia. While it is difficult to confirm all habitable sites built predominantly with wood and bamboo, at least 30 urban centres meet this condition, including locations with relevant and expressive concentrations of bioresource-based buildings (Suppl. Tables 1 and 2). While bamboo has been used to build historic cities in Asia and South America, wood has been prevalent in urban landscapes from Europe, North and South Americas, and Asia.

Bio-based resources have played a central role in construction since the earliest civilizations, as they are essential for several cities. At that time, bridges and footbridges were built from wood trunks or bamboo culms to connect villages and towns separated by surface waters and slopes. A few millennia ago in Asia, wood and bamboo were intensively used in temples [16]. During the medieval period, bio-based materials were also essential in another form of connectivity, as these bioresources were used to build ships for naval expeditions in eventually resulting in the colonization of territories. Usage practices of bioresources generally followed the global industrialization process. While branches, twigs, and stems were initially used by nomadic and indigenous peoples in dwellings, wooden logs and trunks of fallen trees were destined to vernacular habitations. Centuries ago, the transformation of bioresources into sawn parts allowed for greater durability of buildings from more permanent solutions supported by different types of construction technology. The machining of bio-based materials into prefabricated parts ensured rectangular cross sections and higher finishing qualities, allowing replication at factory scales. The evolutionary process of bio-based buildings reached its apogee when wood and bamboo were reconstituted and re-engineered from elementary compositions into a range of industrialized products – this versatility can be observed using solid blocks to build a log-home (Fig. 1a), machined wood in nailed clapboard house (Fig. 1b) or panels in a light-woodframe house (Fig. 1c). Engineered products are designed to obtain more homogeneous solutions by advanced grading methods and selective built-up with more stable properties in terms of performance and dimension. Available as panels and beams manufactured using distinct material shapes (e.g., particles, laminae, and lamellae) with structural adhesives or connectors, they are highly industrialized, commodity building products that add economic activity (e.g., manufacturing, work, income, etc.) and environmental value (e.g., lean transformation of resources, product prefabrication, cleaner assembly, etc.) to wood and bamboo in natural forms.

Improved levels of material stability, quality standardization, weather protection, and safety can be reached using engineered products compared to solid forms of wood and bamboo. Using flexible and scalable manufacturing powered by a wide range of structural-featured engineered products, low-carbon buildings can be industrialized.

Whether in the raw or the most technologically advanced forms, bioresources have been used in different building techniques, whether using artisanal or industrial processes, for several ends. Residential, educational, commercial, industrial, agricultural, infrastructural, sporting, and military applications are among the main possibilities served by bioresource-based buildings, including houses, kiosks, apartment towers, skyscrapers, arenas, pavilions, hangars, silos, etc. [17]. This diversity can be seen in lumber-based buildings for rural purposes (Fig. 2a) and industrial plants made from engineered wood (Fig. 2b). Furthermore, this plurality exemplifies versatility and practicality of bioresources in civil construction.

Positive results in construction and architecture scopes of bio-based buildings are obtained as to innovation, flexibility, production, assembly, aesthetics, and biophilia. Greener buildings are more advantageous in terms of energy, water, land, material savings and also environmental protection [18].

Wood is an ideal material for so-called concept of restorative environmental and ergonomic design, for which the goal is not only to

(a) (b) (c)

Fig. 1. Versatility in building systems and manufactured materials: (a) solid blocks in a log-home in Czechia, (b) machined wood in a nailed clapboard house in Brazil, and (c) panels in a light-woodframe house in Austria. Photo credits: Victor De Araujo.

(a) (b)

Fig. 2. Versatility in construction applications: (a) agriculture shed and stable in Germany, and (b) Rothoblaas© industry headquarters in Italy. Photo credits: Victor De Araujo.

achieve sustainability, but also to connect humans to nature. Natural materials such as wood and bamboo have favourable impacts on us, as they connect people to nature while indoors and provide benefits as the society cares about the environment [19]. Modern examples based on sustainably built environments are being globally developed (e.g., InnoRenew CoE headquarters in Fig. 3a), mixing engineered products, prefabricated building systems, and regenerative environmental and ergonomic design. The inclusive spaces minimize environmental impacts through decarbonization and lead to positive societal and economic impacts (Fig. 3b). Non-exhaustively, this includes design, land and material uses, functionality and beauty, low environmental impacts via circular principles, co-creation, and user perspectives including health and wellbeing. Moreover, prefabrication and modularity have the potential to provide disassembly and reuse of industrialized parts after demolition, contributing to waste reduction and increased recycling opportunities.

3. Timber rediscovery and uses in wide and tall buildings

The revaluation of wood as a primary construction material has been realized worldwide. This breakthrough has included both large-freestanding and high-rise buildings. Groups have erected airport complexes using engineered biobased products. Terminals were built using engineered bamboo in Spain [20], and timber in Canada [21], the United States [22], the Philippines [23], New Zealand [24], Norway [25], Malaysia [26], and Denmark [27]. New airport plans include wood in Japan [26]. Also, a 155,000-square-meter logistics hub was recently built using timber in the Netherlands [27].

Timber has been used in the design of schools and universities. Several habitable prototypes using timber building systems have been multiplying in universities from Germany, Canada, Switzerland, China, Brazil, and Chile. Globally, new institutional headquarters, classrooms, laboratories, and offices are being edified using wood and bamboo products.

For example, a wood-built school building in the Brazilian Amazon

(a) (b)

Fig. 3. (a) InnoRenew CoE in Slovenia uses sustainable practices and cross-laminated timber (b), and this innovative building was recognized as a best practice of New European Bauhaus. Photo credits: Miran Kambič.

won an international architecture award due to its innovative inclusion of mixed spaces, classrooms, and dormitories for indigenous and needy children [28]. In Brazil, a timber complex with academic facilities and an amphitheatre is being planned to be the first public university building [29]. Singapore [30], the United Kingdom [31] and Canada [32] also developed timber complexes to modernize university campuses with higher efficiency and sustainability levels. A modern campus will be built using wood in the Faroe Islands [33]. This suggests an inclusive green movement sprouting in global nations, including smaller and less wealthy territories.

Over the centuries, urban skies have been invaded by tall structures. Some of these have been built entirely of wood or jointly with other raw materials to raise castles, military towers, churches with bell towers, and mosques with minarets, many of which are still active and well-preserved in European, Asian, and American territories [34]. There have been superseding news announcements of the tallest buildings in the world. A revival started at the end of the 20th Century and expanded in the last years, regarding the greater use of wood as the main structural material to reach greater heights [35–37]. Not quite a decade later, nations from Asia, Europe, and North America have developed dozens of habitable developments with more than 10 floors, and others close to the milestone of 24 floors, or 90 m. Tall buildings can offer multifunctional roles, mixing residences, hotels, malls, offices, and garages.

These heights will be exceeded by next generations of timber skyscrapers, especially when engineered products and advanced composites are upgraded in their performances and combined with reinforced cores and hybrid structural solutions [17,35–41]. Considering that the largest tree in the world, a coastal redwood called 'Hyperion', can exceed 115 m in height, the tallest timber building is still below this size [39]. This race for the highest height using engineered wood products has gained additional contours and new players – although a former antenna of 156 m high had already been built from wood in Germany. According to Wimmers [37], an unprecedented record is registered year after year. The situation is analogous to the period when steel and concrete-based skyscrapers were progressively erected in North American cities during the early 20th Century, although the current dispute for the tallest sustainable building has a global scope and prioritizes bioresource-based inputs. In early 2025, Ascent MKE in the United States, Mjøstårnet in Norway, and HoHo Wien in Austria are the tallest completed timber-based buildings, all exceeding 80 m in height [40].

Multistorey projects 100 m in height or more are being designed from engineered wood to be built in the coming years in Europe, North America, and Oceania [38]. New plans foreshadow even more ambitious milestones, in which superstructures will be designed to effectively become the first timber skyscrapers.

Large urban centres such as Philadelphia, Chicago, Perth, and Eindhoven will erect buildings taller than the Hyperion tree, although audacious plans in Tokyo and London will provide skyscrapers with unimaginable heights for the current uses of wood, basically tripling the Hyperion's height in the coming decades [41].

On another less-mentioned path, urban centres around the world are replicating tall timber buildings. A recent global study [38] listed around 300 timber multistorey buildings, of which their main presences of these high-rise solutions are confirmed in London, Berlin, Zurich, Portland, Vienna, Paris, Vancouver, Munich, Amsterdam, Hamburg, and Helsinki. Of these, only Finnish capital city is among the urban centres with a relevant concentration of bio-based buildings (see Suppl. Table 1).

4. Bio-urbanization from engineered wood and bamboo and main examples

As a result of large and tall buildings, urban landscapes are changing, with distinct shapes and nuances, especially regarding the proliferation of green buildings from engineered wood and bamboo. These industrialized inputs can provide intense construction versatility and architectural flexibility due to multiple combinations with diverse building materials, systems, and techniques. The conjunction of these buildings provides a "bio-urbanization" at high levels of sustainability, given the use of engineered biobased products from clean and lean manufacturers powered by bioresources harvested both in planted and managed forests, the combination with comfort in garden areas and pet-friendly spaces, and the urban interconnection from tree-lined paths and non-polluting public transport. In addition, any building space – for example, without a garden, small in area and/or based on mineral materials – can easily become greener inserting greenery such as herbs, flowers, grasses, climbers, bushes, creepers, and miniature trees. According to Wang et al. [42], green infrastructures include vertical and horizontal, exterior and interior, exposed and enclosed building spaces to allocate plants.

Biodiversity provides us with a wide range of textures and tones, in which about 50 exotic and native wood varieties and 15 bamboo species have been commercially used in structural construction parts in Brazil [6,43]. Globally, these numbers could double. Including non-structural application (e.g., flooring, ceiling, facing, etc.), the sum could easily be multiplied by a much larger number – around 20,000 wood species from temperate and tropical regions have commercial uses [44,45], of which 1575 species were confirmed as commercial timber by Mark et al. [46], and, only in Brazil, about 230 woods can be industrially used [47].

This becomes a contributing factor both to human well-being and input rationalization by industry, since the use of natural resources and forms, valorising grains and colours, dispenses with the addition of finishing materials from minerals and ceramics. Integrating buildings with nature has positive effects on populations. Costello et al. [48] conclude that "a step towards low-carbon living has health benefits that will improve quality of life by challenging diseases arising from affluent high-carbon societies – obesity, diabetes, and heart disease especially – and reducing the effects of air pollution". Although the full capabilities of nature-based spaces are not yet fully understood, more sustainable bioresource-based solutions can positively influence public health, and environmental, social, and economic assets [49]. Anyway, green façade, green wall, green terraces, elevated forest, and vertical forest represent some very efficient alternatives to obtain greener infrastructures using plants, as they offer benefits on urban and building scales [42].

Human coexistence in these welcoming greener spaces is favoured by the greater naturalness of bioresource-based buildings and by the proximity to nature of future "biocities".

Given this complexity of design qualities and characteristics, Beatley [50, p.6-8] defines some examples of green urbanism applied in:

- "*Cities that strive to live within their ecological limits, fundamentally reduce their ecological footprints, and acknowledge their connections with and impacts on other cities and communities and the larger planet.*";
- "*Cities that are green and that are designed for and function in ways analogous to nature.*";
- "*Cities that strive to achieve a circular rather than a linear metabolism, which nurtures and develops positive symbiotic relationships with and between its hinterland (whether that be regional, national, or international).*";
- "*Cities that strive toward local and regional self-sufficiency and take full advantage of and nurture local/regional food production, economy, power production, and many other activities that sustain and support their populations.*";
- "*Cities that facilitate (and encourage) more sustainable, healthful lifestyles.*";
- "*Cities that emphasize a high quality of life and the creation of highly liveable neighbourhoods and communities.*".

From another perspective, Newman [51] describes the green urbanism through seven features and respective functions and examples of archetypal cities (Table 1).

Considering these diverse possibilities, a given municipality built

Table 1
Archetypal cities according to different green urbanism strategies. Source [51].

Type of city	Function	Existing examples
Renewable energy	Self-sufficiency in renewable energy production	Masdar, Vancouver and Freiburg
Carbon-neutral	Reduced carbon emission and energy utilization	Malmo, Newcastle and Adelaide
Distributed	Low-impact small-scale energy and water system	Toronto, Malmo and Malang
Biophilic	Use of natural processes and local green resources	Växjö, Helsinki and Madison
Eco-efficient	Reduced waste generation and resource utilization	Kalundborg, Stockholm and Cairo
Place-based	Place-oriented self-sufficiency and local economy	Esperance, Freiburg and Bangkok
Sustainable transport	Transit-oriented options from renewable energy	Singapore, Beijing and Perth

purely or hybridly from renewable bioresources goes beyond examples built using non-renewable resources, which is why we could understand this process as "bio-urbanization" and, therefore, its related study as "bio-urbanism".

Taking inspiration from real examples (Suppl. Tables 1 and 2) and distinct possibilities (Table 1), when will we have a green contemporary city intensely designed and fully (or predominantly) built from "woody" engineered products? Possibly in a few years and probably still in this decade.

Modern urban designs are benefiting from progress in sustainable concepts and goals prescribed by progressive movements and conscious institutions such as the United Nations, the New European Bauhaus, BiodiverCities, and others. Bio-based products strengthen the justification for industrialized construction built on a larger scale, which are manufactured from both coniferous and deciduous trees harvested from planted and managed forests. Today, engineered products can be obtained through a specific wood or a mix of species. Updated building codes and policies aimed at embodied energy and mass timber can be used to increase market uptake of long-lived wood products [8]. Using these bioresource-based products in human settlements is reinforced by congenial, modern, sustainable, and sophisticated forms [13].

A central district in Helsinki used the versatility of engineered products to build medium-rise buildings in Finland [52]. A hybrid community is being built with wood and sustainable architecture and environmental principles to balance city and nature in Denmark [53]. For this decade, timber districts are being planned in Norway [54]. Växjö is called as the "greenest city in Europe" due to high reductions in carbon dioxide emissions by using wood [55]. The Stockholm's metropolitan region is planning for a biocity to be built predominantly from mass timber by 2027, when the first buildings will be concluded – this Swedish plan extends over 250000 square meters in 7000 offices and 2000 houses to attract people to a greener urban centre [56]. At the foot of Mount Fuji, automaker Toyota is designing a bio-based city of the future, in which low-carbon timber buildings and autonomous vehicles will live together using clean bioenergy and a communication structure integrated by sensors and artificial intelligence [57].

Plans are being designed to solve some urban problems such as the lack of housing and the high concentration of populations in large centres from a new concept of "biocities". This model offers efficient indexes in sustainability, housing, health, well-being, mobility, social integration, services, industry, energy, and waste recycling. There is a clear interest from global nations in prioritizing bioresource-based buildings in urban expansions and renewals.

According to Mishra et al. [58], "if 90 % of the new urban population would be housed in newly built urban mid-rise buildings of wooden construction, 106 Gt additional CO_2 could be saved by 2100, which is about 10 % of the remaining carbon budget for the 2 °C climate guard rail". Modernization is being designed in the context of a mandate to achieve net-zero greenhouse gas emissions by 2050. Upcoming strategies must maximize the use of renewable resources, the design towards energy efficiency and carbon storage practices, the deployment of smart infrastructures using mobility and interconnection, and the intensification of circular economy from cleaner industries [59].

Aligned with sustainable goals by 2050, the Paris Agreement calls for carbon neutrality using bioresource-based buildings in future public works. This milestone was started with solutions for the 2024 Olympic Games [60]. In a way to develop high technology and create alternatives for the Galician forestry sector, Lugo city has strived to build a biodynamic neighbourhood with timber buildings in Spain [61].

Passive solutions and mass timber buildings will be used to build a new mixed-use Chinese district in Xiong'an [62]. A wood-based district is being erected on the outskirts of Tegel airport in Berlin [63]. Also in Germany, an attempt to alleviate housing deficits and increase sustainability is calling for a third of new residences to be built with wood by 2030 [64].

In South America, Chile is proposing the use of local wood as a viable solution to edify new cities in a technological consortium, in which a real estate company and National Centre of Excellence for Wood Industry are developing projects to boost the timber construction [65]. Although Brazil does not yet have current plans a wood city, the scenario is already promising due to affirmative housing policies based on timber building systems – Brazil recently implemented a national initiative of social houses built from light-woodframe system [66] and a regional program from Paraná state to provide modular houses for vulnerable people and communities in rural areas [67]. In 2025, a series of new light-woodframe housing developments is already being projected for south and south-east regions. Furthermore, bamboo is being studied in new regenerative urbanization plans in the United Kingdom, China, and Austria. While bamboo houses are popular in regions with bamboo forests, found in tropical and temperate nations, modern buildings shall require industrial manufactures of engineered bamboo products and plants to prefabricate buildings [43,68,69].

5. Challenges and actions towards a carbon-neutral urbanization

Any bioresource-based construction becomes a viable technology when it is developed using forest products exclusively collected from sustainable practices, as increased consumption will require careful planning to ensure high levels of sustainability [70]. The North America and Europe have experienced an increasing interest in urban wood as an alternative source for wood products (e.g., construction, furniture, decoration, utensils, etc.), creating opportunities for small sawmills. This way, some factors need to be assessed in future carbon-neutral plans.

5.1. Assertive codes and legislations

With potentially thousands of cubic meters of wood available within the built environment, regional circular economies can benefit from, and foster the use of wood in civil construction [71]. Wisconsin [72], Alaska [73], New Hampshire [74], and North Carolina [75,76] have passed or are considering legislation to allow small sawmills to certify wood for structural purposes, which can be a key to more efficiently using resources in the United States. Canada has a nationwide grading rule based on structural performance of lumber for construction [77]. Europe is revising timber grading codes to modernize construction regulations [78], and to open up the market for hardwoods [79]. The use of wood in more sustainable buildings is being considered by EU nations on new codes and legislations to reduce gas emissions by 55 % by 2030 [80]. This should encourage new fronts of study on unconventional bioresources to be industrially engineered for buildings.

Currently, a series of international and national publications are already officially established by recognized organizations. Wood materials for construction (e.g., parts, components, and elements) are formally regulated by recommendations and prescriptions contained in dozens of codes, of which address world and European coverages and national scopes, for example, in Canada, Ireland, England, Denmark, Australia, Brazil, Ecuador, New Zealand, and China [81]. According to this same study, timber construction codes to guide professionals and establish directrices are already available, for example, in the United States for heavy timber and plank-and-beam systems, in the United States, South Africa, England and Japan for modular buildings based on cross-laminated timber panels, and in the United States, Brazil, Australia and Denmark for light-woodframe building system. In contrast, these authors evaluated in this survey with 107 timber house producers from Brazil [81] that only 22 % of this sector has utilized standard codes, in which the priority challenge is to establish readable codes to support the design and manufacture of different timber construction systems.

5.2. Well-managed resources

The wood production has been reaching record levels in the last decade, whereas the world has yearly consumed about 4 billion cubic meters since 2018 – a number 13 % greater than 1990 – where 61 % of industrial roundwood is produced in Europe and North America and 39 % reflects the combined production from Asia, Africa and Central-and-South Americas [82].

To avoid the greater consumption of natural forests in response to the use of engineered wood and bamboo, about 150–300 Mha of new plantations will need to be continuously cultivated by 2100. It is possible to expand timber plantations without compromising food production, although strong governance and planning are needed so that the transition to biocities does not impede the protection of biodiversity [58,83]. The conjunction of planted and managed forests reinforces that sustainable forestry not only provides more wood production from unproductive and underutilized lands as they also offer climate benefits by reducing the pressure on natural forests under protection and replacement of carbon-intensive materials by renewable woods from these more sustainable sources. This way, the utilization of wood from plantations and managed forests is intensely aligned with global trends that aim to balance the triad of production, efficiency and mitigation.

Supplies must be rethought and improved. Subtropical and tropical regions (e.g., Africa, Asia, and Latin America) have the power to supply industries with bioresources collected in shorter cycles. A study [84] suggests that faster-growing wood and bamboo might be able to partially supply the demand for bio-based building materials. Developed nations have more difficulty in the large-scale supply due to slower planting cycles common to colder regions. Reforesting areas using public funding and tax reductions, especially for small farmers and forest producers, can become a boosting action for agroforestry supplies. The society needs to be educated regarding forest activities and the efficient use of bioresources (see Box 1). This educational process could take advantage a series of undergraduate and graduate courses on forestry and timber scopes available in all continents [85].

5.3. Resolution of challenges

As wood behaves differently in dry and humid climates, timber-derived solutions need to adapt efficiently their resources and projects to the local humidity, temperature, and environment. While timber buildings are usually designed for temperate to polar regions, tropical territories require a “tropicalization process[1]” to ensure more comfort to users and resist pathology and decay due to intense temperature and humidity (see Box 1). For this, stakeholders need to better understand and improve biobased building products with respect to the material behaviour and durability in the medium and long terms (including nails, dowels, screws, fasteners, brackets, plates, structural adhesives, etc.), development of greener resins and preservatives, behaviours between "stiffest" and "least stiff" parts, prevention of pathologies in times of more aggressive climates, climate challenges related to very different weather conditions between factories and building sites, and other challenges.

To achieve the proposed transition of the built environment, it is also important to overcome certain timber myths still present in the society, as addressed by a group of experts in Europe [86]. Thereby, available knowledge needs to be supplemented with future research to add arguments and complete gaps and challenges (see Box 1) in the discussion on the global uses of lignocellulosic-and-bioresource-based solutions in more sustainable building solutions. Sequentially, enhanced training needs to be efficiently developed and performed in product design and manufacturing, engineering, architecture, construction, structural detailing, urban planning, and other fields.

The lack of knowledge about mitigating actions regarding these pitfalls has a weakening effect on wood and bamboo uses in civil construction. Thus, we list possible responses and actions (Box 1).

Buildings designed under stringent projects, adequate selection of construction systems and techniques, proper sizing of construction parts, compliance with legal constraints (laws, urbanization and building codes, etc.) and location specificities (land, site, etc.), routine maintenance, and life cycle analyses become necessary parameters to efficiently utilize bioresources as leading building materials. The obstacles are indeed less complex to solve when compared to the irreversible environmental liabilities caused by mining and oil activities, high consumption of fossil fuels in the minerals conversion into products, and high carbon releases from these transformation industry activities.

Faced with these challenges on bioresources usage in construction (Box 1), the following issue is raised: given the advantages of wood and bamboo in construction, production, economic, social, health, and environmental terms, why are bioresources still underutilized for definitive purposes in urbanization? It is plausible that this answer could be found through other issues: on the harmful effects of fossil options necessary to industrialize mineral-based construction products, why are low and no-renovation resources so heavily used?

Insofar as bioresources became historic materials used in former cities and remaining secular towns and villages, more questions still demand assertive answers: Why do less developed regions fail to utilize wood and bamboo, since many countries of South America, Africa and Asia have long-standing forestry activities? Contrastingly, why are bioresource products once again assuming more prominent roles to make richer countries look greener? Would the “urban greenwashing[2]” be used by developed nations to conform them to the expectations of the United Nations for a greener future? Will a greener future be delayed by the inefficiency of nations and leaders in adapting and using sustainability-oriented policies? The lack of knowledge about positive contributions of bioresources in the mass production of sustainable solutions touches on some challenging factors (Box 2), which must be promptly realized, discussed, questioned and rethought from then on by global stakeholders, involving civil, business, political-governmental and non-governmental representations.

It is important that the societal perception be changed and that proper training is provided for stakeholders in the construction ecosystem. The International Society of Wood Science and Technology (SWST), International Academy of Wood Science (IAWS), TallWood Design Institute (TDI), Brazilian Institute of Woods and Timber Structures (IBRAMEM), Wood Campus portal, and other initiatives have worked hard to present wood and forest opportunities and promote timber products by educating people and encouraging global cleaner

[1] *Tropicalization process* can be understood as the strategy to adequate materials and buildings to sub-tropical and tropical regions, which present more aggressive levels in temperature and moisture.

[2] *Greenwashing* is a corporate term used to express the negative situation in which institutions and/or individuals declare the use and following of sustainable practices when they are not effectively use them.

Box 1
Challenges and responses for a greater use of timber and bamboo in construction

Challenges related to forest activities	Responses and actions
Fires in natural and planted forests	Maintain defensible spaces and fire-resistant zones in forests
Deforestation of native forests	Reduce wildlife degradation by stringent forestry monitoring
Illegal logging are forestry obstacles	Severely punish facing the illegal advances to natural forests
Native timber from obscure sources	Proliferate sustainable forestry and encourage material certification
Bamboo forest outside of tropical zones	Develop species adapted to temperate and continental zones
Pressure on woody forests	Encourage and expand short-cycle plantations for industry, preferably in arid, vacant, and unsuitable lands for crops
Challenges related to timber buildings	Responses and actions
Long-term durability	Design, construction, and maintenance plans with dried parts
Decay of structural parts	Ease maintenance and avoid flaws leading to physical-biological decay
Pest infestation	Keep parts in dry conditions and use naturally durable species
Moisture susceptibility	Design protected facades and insulate wet areas, and build dry
Acoustics	Insert elastomers and porous absorbers in walls and floors
Fire safety	Design structures with fire safety systems and firebreak parts
Toxicity	Use non-toxic and bio-based resins and pesticides
Sustainability	Create life-cycle and cost analyses considering distinct building systems

Box 2
Mounting calls and challenges to be answered to increase biocities and biodistricts

Steps needed to promote a more sustainable future based on bioresources
Promotion of bioresource products as green products produced from sustainable processes
Awareness of benefits of the use of bioresources as highly-renewable materials for industries
Awareness of performance of engineered bio-based products for industrialized buildings
Insertion of timber and bamboo building courses to update Engineering and Architecture syllabi
Promotion of Timber and Bioresource Engineering as courses driven by sustainable activities and solutions
Availability of modern Engineering and Technology careers driven by bioresources and their products
Consolidation of global public policy regarding the use of bioresources in construction
Incentives and financial supports for bioresource and climate sciences on construction and urbanization
Incentives on the proliferation of managed plantations as green suppliers for cleaner industries
Incentives to boost technologies and cleaner manufacturing practices for bio-based sectors
Challenges related to timber and bamboo
Historical cultural prejudgments about timber and bamboo buildings
Unfamiliarity with versatile applications and building systems from timber and bamboo
Unfamiliarity with better performances of engineered products compared to solid wood and bamboo
Limited trained workforce due to unfamiliarity with modern timber and bamboo industrialization careers
Challenges related to sectors and governments
Ineffective policies for cleaner industries
Limited availability of low-cost financing and insurance for timber buildings
Fallacious speeches of governments and leaders about environmental issues
Lobbies of the powerful industries of cement and metal sectors

industries.

The New European Bauhaus Academy Pioneer Hub for Sustainable Built Environments with Renewable Materials (NEBAP-HUB) has promoted courses for professionals, policymakers, investors, educators, and students about construction ecosystem in biobased building systems and materials, digital technologies, and circularity to boost construction decarbonization. This hub gathered institutions from around Europe to create the New European Bauhaus Academy [87], which will train and upskill millions of construction professionals, in line with the European ambition of the Green Deal, Climate Law, and the Renovation Wave strategy.

5.4. Clarification campaigns on decarbonization

Educational efforts affect not only adults but also new generations. In a recent study [88], 51 % of millennial people understand lumber as a wood product, while 75 % are unaware of cross-laminated timber and 54 % do not feel it is a safe product for taller buildings. Despite millennials' positive perceptions on wood, some views need to be clarified regarding the manufactured solutions and durable uses in construction.

Younger generations often have difficulties associating bioresource-based products with the high-tech world they live in. A lot of advanced technology and sustainability are used for the design and manufacturing of modern timber buildings and, consequently, future biodistricts and biocities. Primary activities such as logging and sawmilling are possibly more frequent in the thoughts of teenagers and young adults, implying a more distorted view that wood would be exclusively linked to old-fashioned careers. This is despite the fact that wood construction increasingly involves industrial prefabrication, modulation, automation, and robotics.

A greater elucidation of the advanced stages of the forest and wood industry is essential to attract and train more people (Box 2), insofar as bioresources are in the spotlight as highly renewable sources for greener products. As the next generations will be the beneficiaries of biocities and biodistricts, it is of paramount importance to train them about healthier life prospects that can be derived from sustainable practices, clean activities, and green solutions oriented to the use of renewable bioresources from plantations. People from generations Y and Z need to be better informed about the versatile possibilities of wood and bamboo in industrialized products, especially for bio-urbanization in a technologically advancing world. Children and teenagers from Generation Alpha need to be taught about the multiple options and benefits of consuming natural resources from renewable sources for a better well-being.

Corrective actions and global articulations are needed to mitigate these issues and convert difficulties into affirmative responses of a more environmentally engaged society (see Box 2). This pathway could be inspired by Mata et al. [9], that "in all, further forceful policy actions, tailored to heterogeneous contexts, solutions, and target groups, would be required for the establishment of low-carbon buildings worldwide". Initiatives are emerging all over the world, and a blueprint for a global policy was proposed under construction circularity [89].

Greater clarity about sustainability and environmental advantages of industrialized solutions must be provided to the society. As the construction sector has introduced prefabrication and automation to produce industrialized solutions on large scales, Wimmers [37] stated that more benefits are obtained if renewable materials are the major components. Wood-based additive manufacturing emerges as further promising technology for increasing the sustainability in civil construction [90].

In parallel, the integration of renewable energy sources into energy systems can improve performance, being more efficient in co-generation and stability [91]. In turn, more accessible information that clarifies carbon footprints, energy usage, and lifecycles become essential to establish practical sustainable consumption, sharing the environmental benefits of products from renewable sources and clean processing [48]. Given the neutralization reached using bamboo and wood in greener buildings, as verified by Carcassi et al. [7], reduced activities and impacts, material rationalization, low-carbon materials, renewable energies, and negative emission technologies can boost strategies on the pathway to adjust expectations and meet targets for net-zero emissions by 2050 [3]. A systemic transformation becomes a priority, as decarbonization must consider regional urban landscapes and extend to key transboundary supply chains [92]. It is worth highlighting the need for in-depth studies blending carbon sink and lifecycle potential of bioresources in their engineered products and building systems, considering involved challenges and analysing global performances for cities at a large scale.

6. Final considerations and long-term environmental and societal commitments

In the future, it is practically certain that wood and bamboo will become increasingly used and valued around the world – as they had previously been used in the edification of urban centres as the list raised by this review (Suppl. Tables 1 and 2) –, not only with respect to environmental and social contexts but also in terms of production and economic scopes. More generally, bio-urbanization driven by renewable natural resources will represent a disruptive innovation of the future greener cities.

Strong efforts will be necessary to support the proliferation of bio-based districts and cities, including the resolution of barriers and gains with opportunities – as the challenges and actions raised by this review (Boxes 1 and 2) – and massive campaigns to clarify questions for these and future generations regarding the multiple vocations, uses and benefits of the application of wood and bamboo for durable purposes. However, studies warn that the bioresource supplies must be aligned with future industry demands, which require the need for diversifying bio-based materials [93], especially through fast-growing species [84, 94,95].

Well-managed wood and bamboo resources will become increasingly common in our daily lives, as they will have the ability to be converted into sustainable construction solutions – e.g., from single-family and tiny houses to tall and large apartment towers in housing, sheds and skyscrapers in commerce, and platforms and bridges in infrastructure ends. In addition, bioresources can be used in more components necessary for the functioning of "biocities", including living biomass for gardening through trees and plants, dead biomass for crafts and adsorbent filters, and biomass waste for solid and liquid fuels. The authors of this study are optimistic that the future proliferation of "biodistricts" and "biocities" built from innovative buildings with decarbonization and biophilia powers in synergy with more environmentally friendly habits and good practices may provide a healthier future, transforming traditionally polluting urban centres into greener cities driven by sustainable and bioeconomy. For this path, we strongly recommend the continuity of global discussions to produce more affirmative and representative policy involving different stakeholders (e.g., developers, professionals, policymakers, investors, academics, interested people, etc.) and give due priority on further research investigations to answer challenges raised in Boxes 1 and 2 and guide researchers to reach and go beyond the expected actions.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.rser.2025.116257.

Data availability

No data was used for the research described in the article.

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