



REPORT

BIOMATERIALS SUPPORTING THE TRANSITION TO A CIRCULAR BUILT ENVIRONMENT IN THE GLOBAL SOUTH



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EXECUTIVE SUMMARY

BIOMATERIALS OFFER A KEY OPPORTUNITY TO MOVE TOWARDS DECARBONIZING BUILDINGS AND CONSTRUCTION

Achieving the goals of the Paris Agreement relies, among others, on ambitious commitments by policymakers to reduce greenhouse gas emissions associated with the built environment. Factors that determine emissions related to the buildings sector include the quantity of resources used in the construction and operation phases, which materials are used, how these materials are sourced, and how they are produced and used. The production and use of construction materials – particularly energy-intensive, mineral-based construction materials – has significant implications for human-induced climate change.

According to the International Resource Panel (IRP 2020), the production of materials in the global economy contributed 11 gigatons of carbon dioxide equivalent, or 23 per cent of total greenhouse gas emissions, in 2015. Of that share, 32 per cent was for producing iron and steel, 25 per cent for cement, lime and plaster, 13 per cent for rubber and plastics, and 13 per cent for other non-metallic minerals. Such material production fails to close the loop on waste generation, as it is typically associated with a linear process that relies heavily on the energy-intensive extraction, manufacturing and transport of non-renewable, mineral-based resources.

Biomaterials offer significant opportunities for reducing emissions associated with the life cycle of building materials, from the sourcing and production stages to use, consumption and disposal. Biomaterials do not rely on extractive mineral-based processes but instead are derived from bio-based renewable resources, and many are bio-degradable at the end of their life cycle. However, the production and use

of biomaterials and bio-based materials must be governed by robust sustainability criteria to ensure that unsustainable practices and environmental impacts are avoided, from deforestation and land-use change to loss of biodiversity.

Rising demand for construction materials in the rapidly urbanizing Global South is a key driver for low-carbon building materials, providing opportunities for a local circular economy approach and in Covid-19 recovery plans.

By the year 2050, 68 per cent of the world's population is projected to live in urban areas. As much as 90 per cent of the increase in the urban population is expected to occur in Asia and Africa, where an estimated 300 million additional houses will be needed by 2030. To achieve targets such as United Nations Sustainable Development Goal (SDG) 11, which calls for the provision of decent and affordable housing for all, the demand for green construction materials and practices is pressing, especially in the face of exacerbating environmental impacts associated with current material production practices. A circular economy approach provides significant opportunities to reduce the greenhouse gas emissions associated with construction materials. Biomaterials offer one path towards circular production of building materials.

The use of bio-based agricultural by-products – such as rice, straw, corn and coconut husk – as the raw materials for producing construction materials aims to tackle the challenge of agricultural waste while creating new practices of circular production of building materials. A circular approach to bio-based material production has the potential to generate new industries and entrepreneurship that are “local” or “location-specific,” including opportunities for job creation and technological innovation. These would take effect at the local scale, supporting local economies and societies. The opportunities are especially relevant in the context of Covid-19, where global supply chains have faced significant disruptions and logistical challenges.



A bio-based economy can engage the material production and construction sectors at a local scale, thereby assisting in post-Covid recovery plans.

Biomaterials and their performance characteristics offer new opportunities for climate-responsive, passive-built environmental design. Many vernacular architectural precedents exist that demonstrate the use of locally sourced bio-based materials – which are typically in plentiful supply – for reducing energy demand and the embodied energy and carbon of buildings, as well as promoting the thermal comfort of occupants through enhanced temperature and humidity control.

POLICY INTERVENTION IS REQUIRED TO ENABLE THE SUSTAINABLE DEVELOPMENT OF BIOMATERIALS

Key policy considerations and potential policy enablers to incentivize the implementation of bio-based construction materials are considered in this report and mapped to the UN SDGs. Overall, bio-based materials have the potential to directly contribute to 10 of the 17 SDGs. Beneficial policies may facilitate the establishment of local biomaterial manufacturing industries while ensuring sustainable land-use practices and the protection and conservation of biodiversity in the scaling-up of biomaterials production.

Enacting performance-based building standards and regulation reform, such as the establishment and/or revision of building codes to focus on performance rather than prescriptive standards, would enable the use of alternative materials. Such measures would also ensure the use of construction materials that do not negatively impact human and environmental health. Policy considerations could encourage, for example, the use of bio-based resins as an alternative

to using toxic materials in construction that emit volatile organic compounds and that can alter the indoor air chemistry.

Among the economic incentives that policymakers could consider are those that would ensure that economic and market settings promote new and innovative bio-based companies. Such policies would help such companies to expand and support local economies while also ensuring that funding mechanisms are in place to advance research and development in the area of bio-based materials. Other key policies may include the promotion of green public procurement to encourage more life-cycle thinking in building design, as well as training, education and research towards knowledge exchange on the construction practices and skills needed to use bio-based materials.

Socio-cultural factors and communication are also important policy considerations to address, especially given existing perceptions that associate local biomaterials and vernacular design with undesirable or old-fashioned aesthetics rather than a contemporary lifestyle. Addressing consumer preferences and behaviour is a key consideration; this may be supported through marketing and awareness campaigns to make bio-based materials more desirable and mainstream and to lift remaining doubts about their properties, durability, life spans and health benefits. Promoting solutions that facilitate refurbishment and that promote heritage buildings may also enhance socio-cultural perceptions of bio-based materials.



INTRODUCTION

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TRANSITIONING FROM A FOSSIL-BASED TO A BIO-BASED ECONOMY

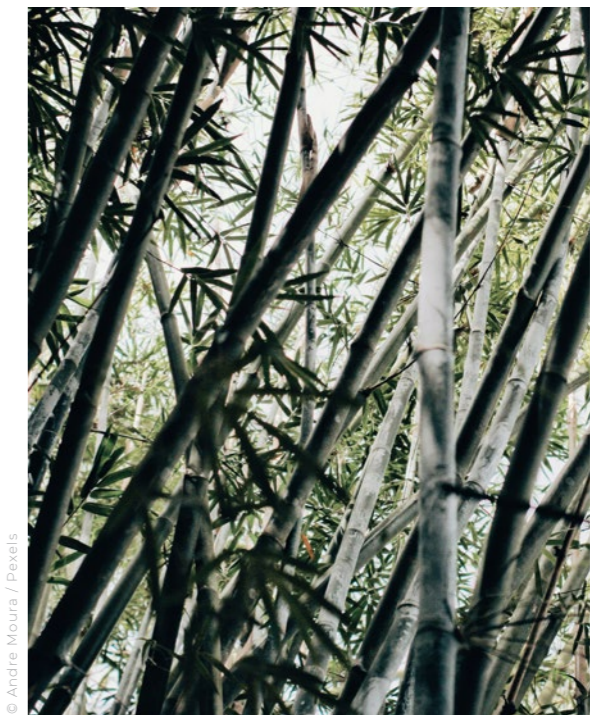
The global societal challenge of moving to a more sustainable economy involves shifting away from a fossil-based, non-renewable, linear extractive economy. Such a transition from a fossil-based to a bio-based economy has the potential to answer the demands of rapid urbanization while reducing the carbon footprint of cities and infrastructure, and is therefore critical to meeting the goals of the Paris Agreement and the 2030 Agenda for Sustainable Development. However, a transition to a bio-based economy must be grounded by sustainable criteria to prevent cascading environmental impacts from deforestation, harmful land-use change and the loss of biodiversity.

Proceeding in a sustainable way, a bio-based economy can become one of the possible pathways towards circularity in the buildings sector. The world has continued to use natural resources unsustainably (Organisation for Economic Co-operation and Development [OECD] 2019; IRP 2020; United Nations Economic and Social Council 2020). The Covid-19 pandemic offers an opportunity to develop recovery plans that build a more sustainable future. A bio-based economy, where construction materials are produced from renewable biomass, can engage construction sectors at a local scale, transitioning away from global supply chains and assisting in post-Covid recovery.

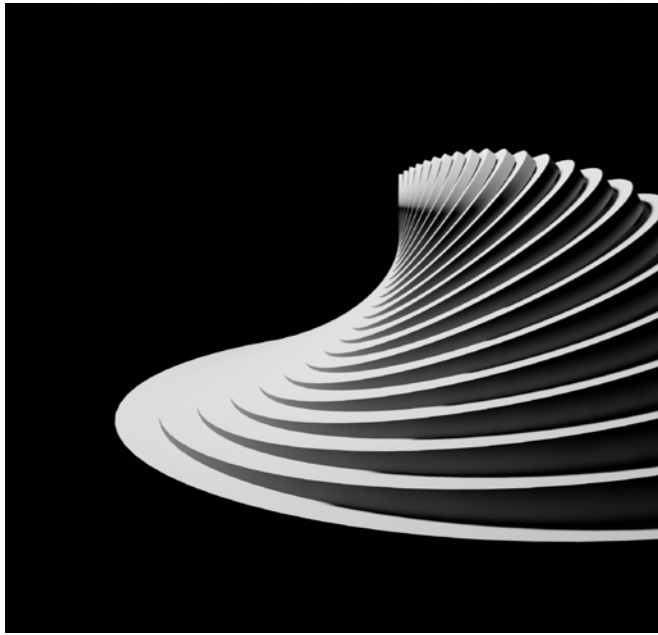
How we produce materials can greatly impact greenhouse gas emissions, in addition to having impacts on ecosystems and pollution. A recent International Resource Panel report (IRP 2020) emphasizes the strong interrelationship between the production and use of construction materials and human-caused climate change. It highlights how the production of energy-intensive, mineral-based construction materials leads to greenhouse gas emissions. However, efforts within the buildings sector to mitigate emissions and to adapt to climate change will still require the production and use of materials. Therefore, factors that determine greenhouse gas emissions include: 1) which materials

are used, 2) how these materials are sourced and 3) how they are produced and used. This report introduces construction biomaterials and bio-based materials that do not rely on extractive processes but rather on bio-based renewable resources, offering a low-carbon alternative for decarbonizing buildings and construction.

In order to achieve transformative environmental effects, several material manufacturing and design industries, construction sector industries and policymakers recognize the need to make a bio-based economy viable and sustainable at a large scale (Hill, Dibdiakova and Zukowska 2019). Policymaking in particular will play a key role in catalyzing such transformation by enabling the manufacturers of new bio-based and sustainable building products to successfully and competitively industrialize their products at scale. Policies are also crucial in subsequently enabling and incentivizing the use of such products in the construction industry.



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A bio-based economy has the potential to generate new industries and employment. Given that biomaterials for construction are “local” or “context-specific,” opportunities for job creation and technological innovation would take effect at the local scale, supporting local economies and societies (Mussatto 2017). These promising opportunities are especially relevant for Covid-19 recovery plans. Bio-based materials are also linked to potential health benefits, such as the use of green chemistry and green engineering principles in the design of, for example, bio-based resins for wood treatment to offer an alternative to toxic materials, such as some synthetic resins that may release volatile organic compounds; this would contribute to healthier indoor air conditions, including better air quality as well as temperature and humidity control (Zimmerman *et al.* 2020).

This report is targeted at policymakers, government decision makers, building sector stakeholders, research institutes and community organizations. It focuses primarily on the Global South, where growing urbanization is set to continue – mostly in Asia and Africa (United Nations 2019) – and with it, increased demand for housing and materials. The report addresses the potential for biomaterials to meet rising housing demands while encouraging local employment and industry.

The rest of section 1 outlines the current growing demand for construction materials in the face of rapid urbanization, questions how circular economy strategies can help in providing low-carbon bio-based construction materials, and highlights the social, economic and environmental benefits of using bio-based materials in construction (ranging from enhanced human health and well-being to the recovery and advancement of traditional building materials and

Section 2 highlights the solutions that bio-based materials can offer, outlining high-performance and low-embodied-carbon priorities for climate-specific building design. The section also investigates the challenges that biomaterials must overcome to be widespread and competitive in the construction market. These challenges are social (relating to consumer preferences and behaviour), economic (in terms of establishing competitiveness and economies of scale) as well as regulatory (in terms of limitations of material certifications, regulations and building codes).

Section 3 introduces three case studies: 1) the Ecological Pavilion, an exhibit into the possibilities and cutting-edge developments in biomaterials, 2) the ISOBIO project, which investigates a strategy to allow for the successful scale-up of biomaterials, and 3) an exploration of the work of governments in supporting bio-based materials, with a focus on initiatives surrounding low-carbon concrete.

Section 4 highlights key enablers and opportunities for policy considerations to support an environment where the widespread adoption of biomaterials in the construction marketplace may be realized. The key enablers are mapped to associated United Nations Sustainable Development Goals (SDGs).

CURRENT GLOBAL CONTEXT AND THE GROWING DEMAND FOR CONSTRUCTION MATERIALS

By the year 2050, 68 per cent of the world's population is projected to live in urban areas. As much as 90 per cent of that increase is expected to occur in Asia and Africa (UN 2019). In the face of rapid urbanization, the World Bank estimates that 300 million additional houses will be needed by 2030, primarily in emerging economies (World Bank 2016). The provision of decent and affordable housing, as targeted in SDG 11, places increased demand on construction materials. Such demand, coupled with increased construction, could greatly exacerbate environmental impacts, particularly if current material production practices continue.

According to the International Resource Panel (IRP 2020), the production of materials in the global economy contributed 11 gigatons of carbon dioxide equivalent, or 23 per cent of total greenhouse gas emissions, in 2015. Of that share, 32 per cent was for producing iron and steel, 25 per cent for cement, lime and plaster, 13 per cent for rubber and plastics, and 13 per cent for other non-metallic minerals. Such material production fails to close the loop on waste generation, as it is typically associated with a linear process that relies heavily on the energy-intensive extraction, manufacturing and transport of non-renewable, mineral-based resources.

A shift away from traditional mineral-based, energy-intensive construction materials towards bio-based materials would involve eliminating virgin material extractive processes and, in many cases, converting waste by-products to new construction materials – thus closing the loop at the material's end-of-life. Hence, biomaterials are good examples of applying a circular economy approach to the production of construction materials. The next section introduces the concept of the circular economy and highlights the potential for biomaterial life cycles to forge a new circular economy in the construction industry.



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BIOMATERIALS: ONE PATH TOWARDS THE CIRCULAR PRODUCTION OF BUILDING MATERIALS

Failing to fundamentally challenge mainstream approaches related to the unsustainable production and consumption of construction material supply chains hampers the capability to foster systemic change. The key to the circular economy is that it takes a systemic approach in aiming to redesign an economy. The circular economy can be defined as a process to improve material efficiency, primarily by closing the resource loop and reducing material waste at the end-of-life of a material.

Achieving circularity involves following a set of principles. According to the Ellen MacArthur Foundation (2020), the first principle is to “design out waste and pollution,” the second is to “keep materials and products in use,” and the third is to “regenerate natural systems.” Haas *et al.* (2015) note that implementing these three basic principles across the economy implies an extensive overhaul to the basic structure of industrial systems.

Traditional material production practices are associated with the extraction of raw materials and with energy-intensive processes that contribute to global greenhouse gas emissions. According to the OECD (2019), global materials use is projected to more than double from 79 gigatons in 2011 to 167 gigatons in 2060. More than half of the total materials currently in use are non-metallic minerals used in construction, such as sand, gravel and limestone. The global extraction and production of construction materials, such as metals and concrete, results in a wide range of environmental impacts¹. Iron and steel have the highest absolute environmental impacts due to their large volume of use; concrete has smaller impacts per kilogram, although it is also used in large volumes, making it responsible for 9 per cent of total greenhouse gas emissions (OECD 2019).



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¹ Environmental impacts from the traditional construction material production process include acidification, climate change, cumulative energy demand, eutrophication, human toxicity, land use, ozone layer depletion, photochemical oxidation, and aquatic and terrestrial ecotoxicity (OECD 2019).

From a circular economy perspective, promising research and initiatives demonstrate that construction, renovation and demolition residues, which include materials that have already been extracted and used in a building, can be re-used and recycled, extending their life span. In addition to this circular approach to building materials, biomaterials offer an alternative circular approach. Many biomaterials “design out” waste – for example, through the use of post-agricultural waste materials such as rice, straw, corn and coconut husk – potentially providing disruptive new solutions to the need for immediately available building materials. Other bio-based materials include sheep wool and recycled textiles (for insulation), wood wool, hemp and nature-based materials, such as the use of linseed oil (the oil in flaxseed) in the production of traditional linoleum flooring.

A series of reports from the United Nations One Planet Network Sustainable Buildings and Construction programme addresses the current state of play with regard to circularity in the built environment in seven geographic regions: Africa, Asia, Europe, Gulf Cooperation Council countries, Latin America and the Caribbean, North America and Oceania (Al-Alawi *et al.* 2020; Gibberd 2020; Iyer-Raniga 2020; Keena and Dyson 2020; Moreno 2020; Niazi, Singh and Sen 2020; Westerholm 2020). In addition to the seven regional outlooks, a global report summarizes and compares the state of play regarding circularity in different regions (Iyer-Raniga and Huovila 2020). In the context of this work, the reports on the regions of Africa, Asia, and Latin America and the Caribbean are especially relevant as they highlight the state of play in the Global South. In particular, they point to the potential for using agricultural by-products as source materials for producing new building materials as well as the potential for hybrid construction materials that use both bio-based and mineral-based materials.

For example, the report for Latin America and the Caribbean indicates the potential to use husks and

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fibre from industrial agriculture processes to facilitate the production of new construction materials, such as using hemp shives to make pre-cast concrete blocks, i.e., “hempcrete” (Moreno 2020). The report for Africa outlines the potential to use local bio-based materials, supported through incentives, to enable local manufacturing entrepreneurship of bio-based construction materials. It highlights the need to promote collaboration between local industries and agriculture to develop grown building products and suggests schemes to enhance local capacity. These reports outline barriers and opportunities towards achieving greater levels of circular economy approaches within the building sector in the Global South and also address how these circular practices can contribute directly and indirectly to the UN SDGs.

Biomaterials are typically local or “climate specific,” offering appropriate performance characteristics in response to passive design strategies, while providing additional income streams and employment to local economies. They eliminate the need for mining of construction minerals, thereby reducing extractive processes and offering an alternative that is typically biodegradable at the end-of-life, helping to regenerate natural systems.

Figure 1a looks at the embodied energy and embodied carbon associated with a selection of construction materials. It is based on data from a number of sources, including the Inventory of Carbon and Energy databases (Hammond and Jones 2008; Asif 2009; Hammond and Jones 2011; Hammond and Jones 2019). It is worth noting that many factors affect the overall embodied energy and embodied carbon of materials, including where raw materials are sourced and the methods of manufacturing used.

An additional caveat is that the data illustrated in Figure 1a are on a per unit weight basis, and therefore the embodied energy and embodied carbon values will vary substantially based on the amount of material used. To highlight this point, Figure 1b provides a comparison of the embodied carbon and carbon storage associated with the use of five different materials for the same building (i.e., the same floor area). The data are from a life-cycle assessment study by Takano, Hughes and Winter (2014), where a three-storey residential building with five dwellings was considered. The building had a gross floor area of 1,243 square metres (m²) and a heat floor area of 986 m², and was designed for the climate of Helsinki, Finland.

A variety of frame building materials were analysed, five of which are shown in Figure 1b: light-weight timber panel, cross-laminated timber, reinforced concrete panel, brick and light gauge steel. Among the indicators considered were embodied greenhouse gas emissions (i.e., global warming potential) and carbon storage. Carbon storage was indicated as a negative value because it represents the carbon captured in the materials. Because the study analysed the whole building, all of the options had an element of timber in the building; hence the five different building materials shown in Figure 1b all have an element of carbon storage. The timber frame options had the highest levels of carbon storage, thus

yielding negative global warming potential impacts for the building (Takano, Hughes and Winter 2014; Hill and Dibdiakova 2016).

The embodied energy and carbon data in Figure 1a, and the environmental impact data in Figure 1b, are provided merely as a guide for the reader. Further information on the embodied energy and embodied carbon of construction materials is discussed in depth elsewhere and can be accessed via the sources referenced.



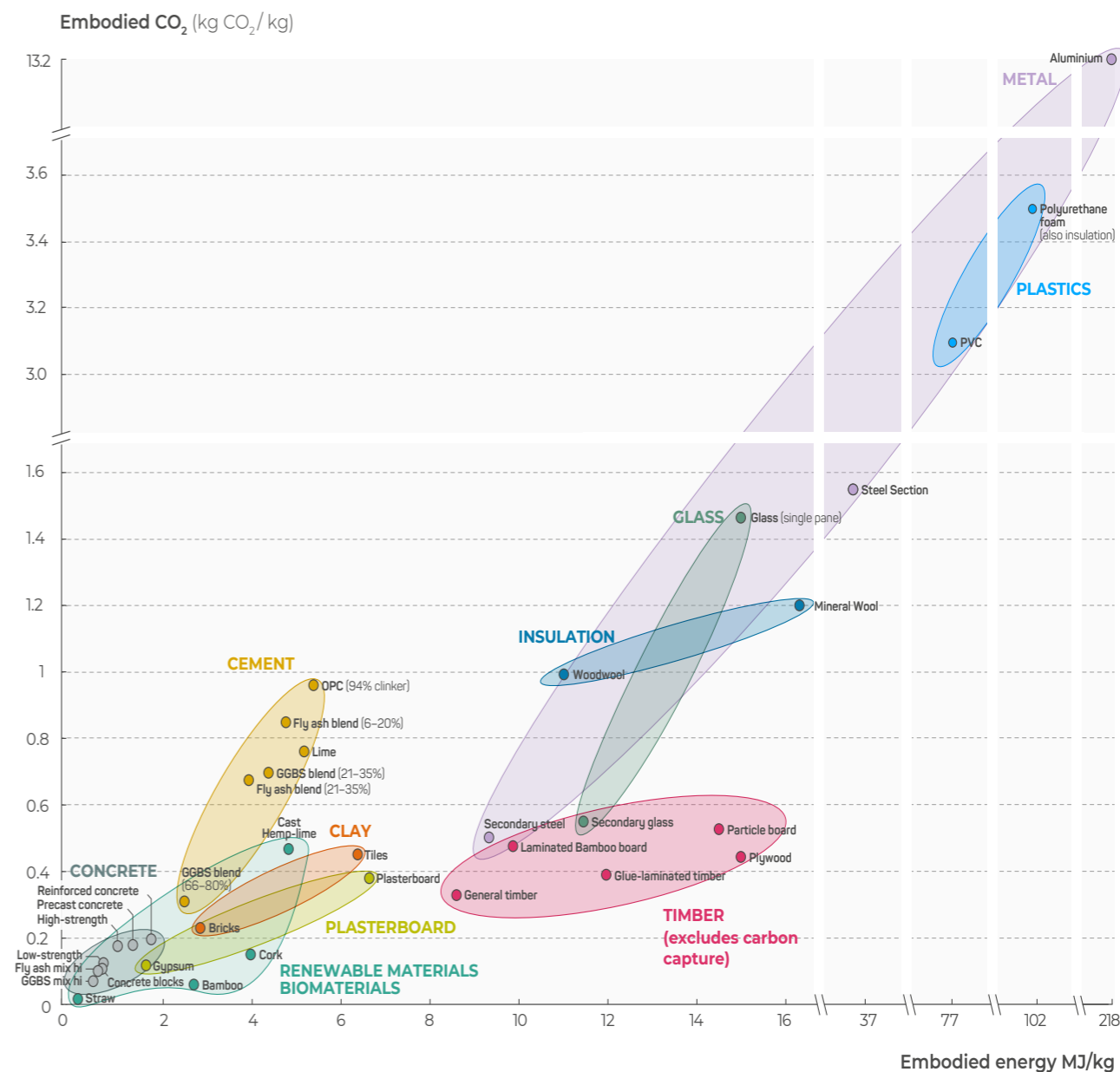
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FIG. 1A

Embodied energy and embodied carbon of a selection of common building materials, including some biomaterials

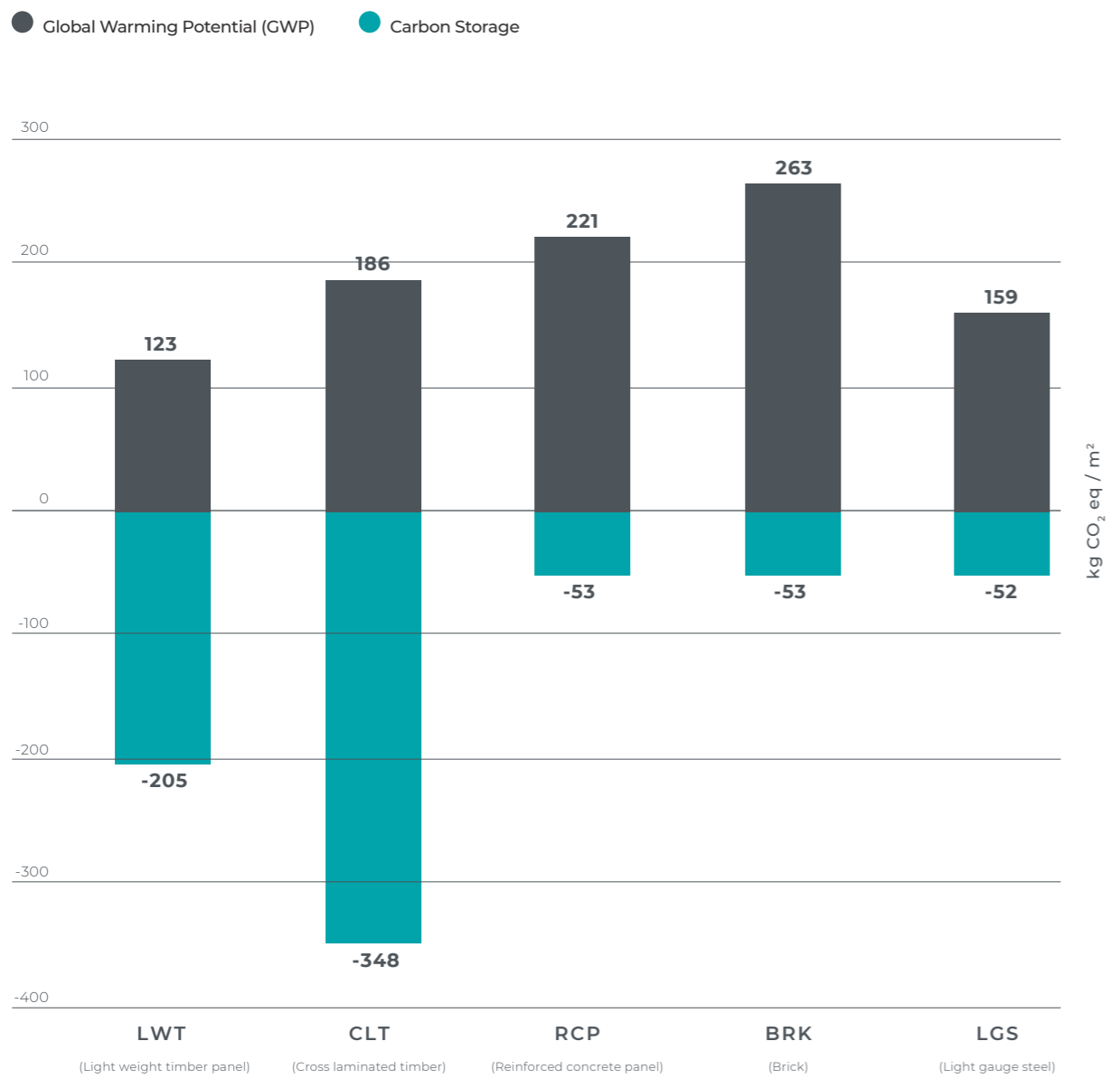


Note: The data provided are on a per unit weight basis; therefore, the embodied energy and embodied carbon values will vary substantially based on the amount of material used. For example, on a per unit weight basis the carbon emissions from concrete are significantly lower than those from aluminium; however, due to the quantities of cement used in the construction industry its production currently ranks third in anthropogenic CO₂ production (Lehne and Preston 2018; OECD 2019).

Source: Redrawn and modified from Lehne and Preston 2018. Data are from the Inventory of Carbon and Energy databases (Hammond and Jones 2008; Hammond and Jones 2011; Hammond and Jones 2019) and from literature sources (Yu, Tan and Ruan 2011; Lawrence 2015).

USING BIOMATERIALS TO PROMOTE A CIRCULAR APPROACH TO THE MANUFACTURING, FABRICATION AND CONSTRUCTION OF BUILDINGS

FIG. 1B
Environmental impact data for the same building, but with five different frame building materials



Note: The functional unit is net heated floor area.

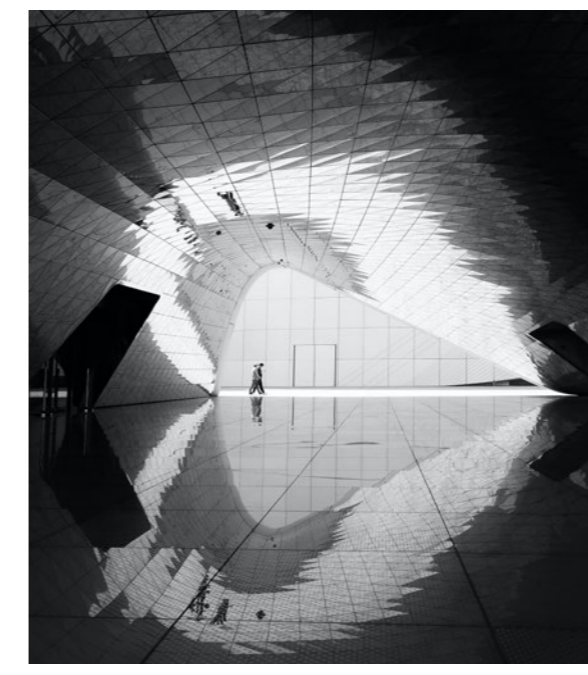
Source: Takano, Hughes and Winter 2014.

During the construction phase, biomaterials are compatible with innovation and cutting-edge construction practices. Aspects of the construction industry are transitioning towards prefabrication, modular construction, and other construction design for manufacturing and assembly techniques. These techniques facilitate the prefabrication of various scales of bio-based building components, such as biomaterial panels that are manufactured within a controlled environment and then transported to the building site for quick assembly. This reduces overall construction time and facilitates clean, healthy and efficient construction sites.

Such thinking can enable a circular economy within the building sector by: 1) radically re-thinking construction practices, 2) minimizing and controlling the quantity of material used and its associated waste, and 3) addressing a material's end-of-life during the early design phases, with design for disassembly.



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Three-dimensional (3-D) printing is also an innovative construction activity that is compatible with bio-based plastics and ceramics, as well as hybrids of bio-based plastics with paper, ceramics and agricultural waste by-product fibres such as bamboo (van Wijk and van Wijk 2015). 3-D printing allows for control over the quantity of material used, thereby limiting material waste. A case study of a 3-D printed pavilion using post-agricultural bamboo is described in section 3.1.




SIGNIFICANCE AND SCOPE OF THIS WORK

Despite the many challenges in transitioning to the use of biomaterials in construction, as outlined in the previous sections (and discussed in depth in sections 2.2 and 2.3), biomaterials also present key opportunities for the built environment. From the standpoints of the

environment, economy, society, and human health and well-being, biomaterials offer a holistic approach where the potential to reduce multiple impacts is evident at each phase of the building life cycle. Table 1 describes these multifaceted benefits.

TABLE 1

The multiple environmental, economic, social and human health benefits offered by biomaterials

BENEFITS	DESCRIPTION
ENVIRONMENTAL BENEFITS	
 MATERIAL SOURCING PHASE	Biomaterials reduce the need to extract minerals and other major resources that traditionally provide the raw inputs for construction materials. Instead, biomaterials use local, bio-based renewable materials as primary resources. Certain bio-based materials (such as hemp) have the potential to sequester CO ₂ emissions while growing and to fertilize fields for agriculture.
 MANUFACTURING PHASE	The manufacturing of biomaterials promotes low-energy and low-carbon practices during production. This avoids the kind of energy- and/or carbon-intensive manufacturing and production necessary to make steel, aluminium, traditional concrete and glass. Biomaterials (including the use of bio-resins) promote clean, non-toxic manufacturing.
 TRANSPORT PHASE	Biomaterials greatly reduce environmental impacts associated with transport by relying on local, climate-specific production and supply. Transport involves the delivery of source materials to local manufacturing facilities, and subsequently the transport of bio-based materials to local construction sites. Using locally sourced biomaterials supports low embodied energy and low embodied carbon design.

BUILDING LIFE-CYCLE PHASES



CONSTRUCTION OR FABRICATION PHASE

As discussed in Section 1.3, biomaterials are compatible with innovative and productive methods of designing for fabrication off-site with final assembly on-site. Non-traditional construction practices, including prefabrication, modular construction, design for manufacturing and assembly techniques, as well as 3-D printing, are viable alternatives. Biomaterials can offer many environmental benefits, including reducing material use and associated waste, considering end-of-life disassembly during the design and fabrication phases as well as the ability to design environmentally friendly approaches with more accuracy within a controlled working environment.



END-OF-LIFE PHASE

By diverting waste from waste streams to become resources in the production of construction materials, biomaterials support a circular economy – e.g., the use of agricultural waste byproducts. Biomaterials are typically biodegradable at the end of their life.

ECONOMIC BENEFITS



LOCAL ECONOMIES

Biomaterials production can support local economies at each phase in the construction material life cycle – from initial bio-based raw material sourcing, to production and manufacturing, to on-site assembly, to end-of-life considerations.



JOB CREATION, SKILLS DEVELOPMENT AND SUPPORT TO ENTERPRISES

Biomaterials production can support local economies and offer economic opportunities at each phase in the biomaterial production life cycle (from initial bio-based raw material sourcing, to production and manufacturing, to on-site assembly, to end-of-life activities). These opportunities include job creation at each phase, skills training and knowledge sharing, and supporting micro, small and medium enterprises.



ECONOMIC RESILIENCE

Diversifying building materials can ultimately support the resilience of the construction industry. It offers a buffer against price inflation that may arise due to scarcity of construction minerals such as sand for concrete and glass production or other raw materials for the production of metals.

BENEFITS

DESCRIPTION

SOCIAL BENEFITS



RECOVERING TRADITIONAL METHODS AND CULTURAL IDENTITY

Biomaterials can help maintain a local culture and identity through the rediscovery of traditional and vernacular building methods and materials. Innovation in materials and methods can help enable with the recovery and enhancement of traditional designs and construction techniques.

HEALTH AND WELL-BEING BENEFITS



HUMAN COMFORT

Biomaterials contribute to occupants' comfort with healthier indoor conditions related to air quality, temperature control and humidity regulation.



GOOD INDOOR AIR QUALITY

Biomaterials, unlike certain synthetic products, do not off-gas volatile organic compounds, which can negatively impact human health and well-being by altering the indoor air chemistry (Katsoyiannis, Leva and Kotzias 2008).



NON-TOXIC MATERIALS

Bio-resins, such as mycelium, used in biomaterials assembly and production offer a substitute to synthetic glues and resins that are associated with volatile organic compounds and other harmful toxic chemicals. This applies to the health of both the material manufacturers and the building occupants.



HUMAN SAFETY AND FIRE RESISTANCE

Many biomaterials can be very predictable in their fire resistance properties. For example, wood burns at 4 centimetres per hour. The fact that it does not melt like steel and does not produce toxic fumes means that fire fighters know how to handle it.

Given the potential of biomaterials, why are they not ubiquitous in the construction industry? Section 2 explores a range of available biomaterials, considering both different climate zones and their bioclimatic design priorities. The section also addresses the key challenges with making biomaterials a strong competitor in the construction material market.



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BIOMATERIALS OFFER NEW OPPORTUNITIES FOR CLIMATE-RESPONSIVE, SUSTAINABLE DESIGN IN THE BUILT ENVIRONMENT

CHARACTERIZING BIOMATERIALS IN TERMS OF CLIMATE CLASSIFICATIONS, BIOCLIMATIC DESIGN PRIORITIES AND BUILDING APPLICATIONS

Bioclimatic design involves creating buildings that respond to the climate in which they are situated, thereby providing comfortable interior conditions (in terms of temperature and humidity), or “thermal comfort” to the occupants. Such a design approach results in more sustainable buildings, and it also promotes the use of biomaterials.

Bioclimatic design builds on vernacular and traditional architectures where it is common to select materials driven by local, regional and environmental considerations in order to meet building performance demands. Traditional construction materials and practices are typically characterized by achieving circular material life cycles with low emissions, low energy intensity and low embodied energy associated with their production. They demonstrate high-performance characteristics during the operational phase of the building's life cycle and are able to be recycled or reused, or to biodegrade, at the end-of-life.

In order to achieve bioclimatic buildings, materials are just one of many factors. A building's orientation, size and massing, as well as the location of openings, are among numerous other factors that need to be considered and are outside the scope of this work. However, materials play a key role in sustainable built environments². As discussed earlier, the material that is chosen can have very different environmental impacts depending on its overall life cycle and embodied energy³.

Table 2 characterizes biomaterials in terms of climate classifications, bioclimatic design priorities and building applications. For climate classification, the Köppen-Geiger approach is used (Beck *et al.* 2018). Köppen-Geiger has five primary climate groups: A (tropical), B (dry), C (temperate), D (continental) and E (polar), as shown in Figure 2. Table 2 outlines the three Köppen-Geiger climate classifications that are most prevalent in the Global South (colour-coded by climate group). These are: A (tropical) and B (dry), with a smaller number of countries falling into group C (temperate).

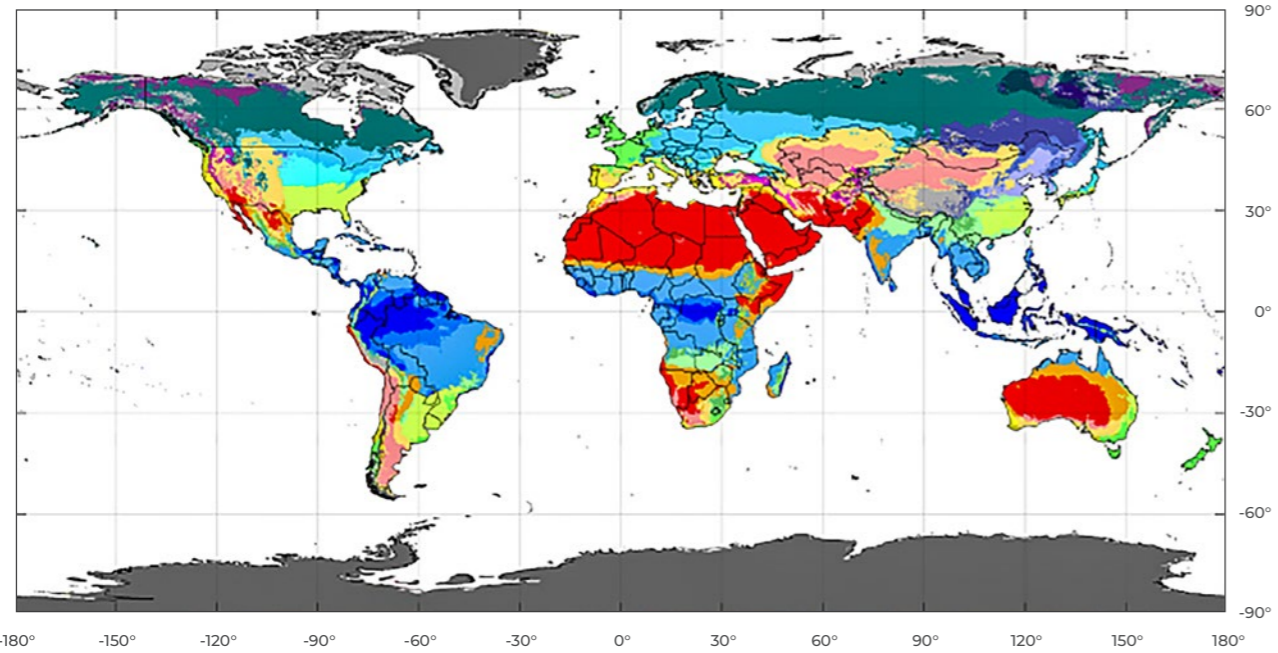
For each of the main climate groups, additional sub-groups have been emphasized. These include a desert climate (BWh), characterized by hot arid weather conditions; a tropical wet and dry climate (Aw/As), characterized by a dry season and a wet season; and a hot humid subtropical climate (Cfa/Cwa) characterized as having hot humid summers and dry mild winters. For each climate type, bioclimatic building priorities are outlined.



- 2 Materials play a key role in sustainable built environments. For example, in terms of the building performance the energy transferred at the boundary of the building is a function of the materiality of the façade, roof and floor. The rate of heat flow through various construction assemblies, including time lag as well as the energy storage capacity of the building, are all governed by the materials used.
- 3 Building materials that are designed to have low energy and low emissions in their initial creation, and to support many life cycles, typically have lower embodied energy and better material life cycles than those that have a single life-cycle use and are very energy and material intensive in their production.

FIG. 2

Map of Köppen-Geiger climate classifications, with a focus on groups A (tropical), B (dry) and C (temperate)



A TROPICAL			B DRY			C TEMPERATE					
Af	BWh	Csa	Cwa	Cfa	Dsa	Dwa	Dfa	ET			
Am	BWk	Csb	Cwb	Cfb	Dsb	Dwb	Dfb	EF			
Aw	BSh	Csc	Cwc	Cfc	Dsc	Dwc	Dfc				
	BSk				Dsd	Dwd	Dfd				

Source: Modified from Beck et al. 2018.

2.1.1

GROUP A: TROPICAL – FROM TROPICAL RAINFORESTS TO TROPICAL WET AND DRY CLIMATES

The focus of Group A is primarily on those climates characterized by distinct wet and dry seasons, with most of the precipitation occurring in the high sun, i.e., the hottest and wettest season. In hot-humid

zones, where the daily temperature fluctuation is small and relative humidity is high, from a bioclimatic viewpoint the form and construction of the building should be as open and as lightweight as possible to induce natural ventilation. At the same time, shade and sun protection are essential and should be provided. Table 2 outlines the bioclimatic design priorities and the bio-based material selection criteria for this climate type.

In terms of lightweight construction, wood and other natural materials fare well. Biomaterials such as bamboo and various agro-waste combinations (coconut, straw, rice, etc.) are all materials that work well in humid conditions and are native to this climate type. Such materials, when used for lightweight construction, have low thermal capacity and thus hold little heat, keeping the building cool, especially at night. Traditionally, thatched or attap (a tropical palm) roofing made from natural materials was used for its low thermal capacity and thermal insulation qualities, keeping the interior temperature cool. Even today in tropical climates, traditional construction materials are readily employed, which is advantageous for many reasons.

These traditional materials, being climate-specific, are typically in plentiful supply and are sourced locally, which generally results in low environmental impacts due to low embodied energy and carbon in their production. Typically, they can be recycled or are biodegradable at the end-of-life. Skilled labour in the region is often available, given the tradition of constructing and maintaining buildings with these materials. Skills that have been lost can also be revived through local trainings and the promotion of traditional techniques and new innovations, supported by organizations such as the International Labour Organization (ITC-ILO 2019). Many of the materials found locally in tropical climates, such as coconut coir, rice husk and cork – i.e., the natural fibres – have desiccant properties that can be taken advantage of in building design to extract moisture from the interior air. This is particularly important in tropical climates where there is danger of mold, rotting and insects when using biomaterials, especially for insulation.

The literature shows that biomaterial composite building panels exist that demonstrate low thermal conductivity and excellent hygric behaviour⁴ and moisture-buffering performance. These include, for example, hemp-straw composites (Maalouf et al. 2015; Collet, Prétot and Lanos 2017) and coconut-fibreboard panels (Lokko 2016). Hence, new innovations in biomaterials that recover and enhance traditional building practices through innovation should be encouraged. The locations of tropical climate types are represented in Figure 2 by Af, Am and Aw, as illustrated in the dark blue tones.

2.1.2

GROUP B: DRY – FROM DESERT CLIMATES TO SEMI-ARID CLIMATES

The key bioclimatic priorities in a hot, arid climate involve: 1) mitigating high interior temperatures in the hottest months, 2) protecting against the sun in the hottest months, 3) employing evaporative cooling to provide thermal comfort and 4) using thermal mass to reduce day-to-night (diurnal) temperature fluctuations, as summarized in Table 2. To achieve thermal mass, materials properties must include high specific heat capacity⁵ and high density. Therefore, heavy materials are typically used for wall construction, as they allow for a slow movement of energy transfer through the wall (i.e., increased time lag) by absorbing thermal energy when the temperatures outside are hotter, thereby keeping the indoor space cool. At night, when temperatures drop, the wall re-radiates the thermal energy back outside.

⁴ Hydric behaviour and moisture-buffering performance involves understanding the material's behaviour with regard to humidity, i.e. the ability for the material to moderate changes in humid climates by absorbing and desorbing water vapour from the indoor air.

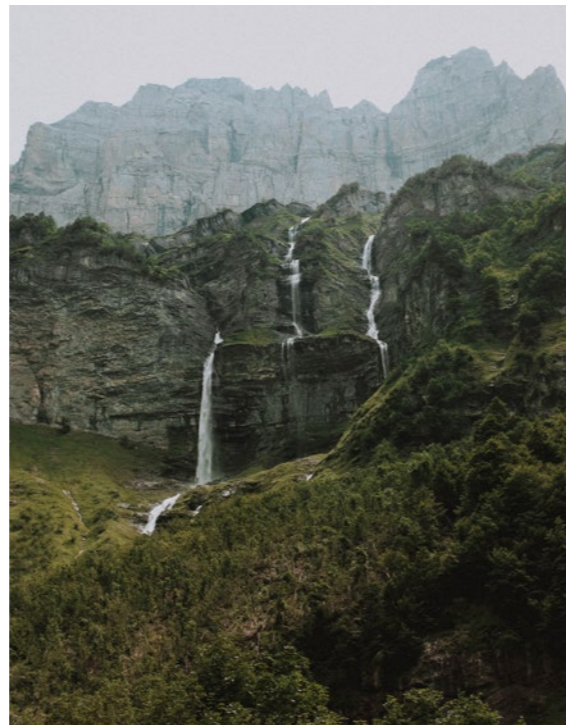
⁵ Heat capacity of a material refers to the amount of heat required to change the temperature of that material by one thermal unit (e.g., 1 degree Celsius). The heat capacity of different materials varies greatly; however, heavier materials typically have a higher heat capacity.

Traditionally, adobe and rammed earth were used to construct massive walls to achieve thermal comfort. There are also possibilities of having massive structures for thermal mass that act as furniture or storage spaces within a building. Bio-based concrete and clay or adobe bricks are other biomaterials that could be used. The South African government in its handbook on green materials highlights a clay brick used in the country for its thermal mass properties, low embodied energy and use of local content (GreenCape 2014).

Roofs also play an important role in mitigating solar heat gain in a hot, arid climate. Light-coloured roofs reflect heat, keeping the interior cool, as compared to dark-coloured roofs that absorb heat and have the reverse effect indoors. Green roofs covered with vegetation convert solar energy into chemical energy via photosynthesis, and in doing so they keep the roof and building cool.

An alternative strategy to thermal mass is night-flush cooling. This passive cooling strategy involves insulating the mass of the building exterior. During the day, the building is kept closed, allowing the mass to act as a heat sink to keep the interior temperature cool; at night, the building is opened to enable the use of night ventilation to cool the mass of the building.

In terms of location, desert climates to semi-arid climates are represented by the red, pink and orange zones in Figure 2.



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2.1.3

GROUP C: TEMPERATE – FROM HOT, HUMID, SUBTROPICAL CLIMATES TO OCEANIC

Table 2 outlines the bioclimatic priorities for the temperate zone – with hot, humid summers and dry, mild winters – focusing primarily on the climate types of countries in the Global South⁶. These climate types are similar to the “tropical wet and dry climate” (Aw/As) types in terms of materials and construction practices that help to control for high humidity. Hence, many of the same principles apply as outlined in tropical climates above. The weather is typically favourable in these climates, so opening up the building is a strategy that is very effective in controlling humidity and is easy to achieve.

In terms of location, humid subtropical climates are represented by the Cfa and Cwa green portions of Figure 2.

⁶ Countries in the Global South that fall under the “temperate” climate zone are identified. The most relevant characterization is “hot humid subtropical climate,” as opposed to “Mediterranean” and “oceanic,” which also fall under the temperate climate group but are not relevant to the Global South countries.

TABLE 2

Summary of the bioclimatic design priorities, bio-based material selection criteria and building application options for the three climate classifications most prevalent in the Global South

BIOClimatic DESIGN PRIORITIES	BIO-BASED MATERIAL SELECTION CRITERIA AND BUILDING APPLICATION
A TROPICAL – TROPICAL WET AND DRY CLIMATE (AW/AS) (DRY SEASON, WET SEASON)	
PERFORMANCE	
<ul style="list-style-type: none"> Minimize discomfort at night due to high temperatures and high humidity. Induce natural ventilation (night ventilation). Use lightweight, open construction that is elevated off the ground to induce natural ventilation. Provide shade and sun protection. 	<ul style="list-style-type: none"> Choose biomaterials such as bamboo and various agro-waste combinations (coconut, straw, rice, etc.), which work well in humid conditions due to their low thermal capacity. Use thatched or attap (a tropical palm) roofing made from biomaterials (leaves, grasses, straw, water reed, sedge, rushes, heather, palm branches), which have good thermal insulation qualities and are water resistant, protecting from heavy rainfall. Prioritize materials with low thermal conductivity and excellent hygric (moisture-buffering) performance, such as hemp-straw composites and coconut-fibreboard panels. Materials with desiccation properties will help extract excess moisture from the interior air. To achieve lightweight construction, choose low-energy structural systems such as load-bearing timber (e.g., bamboo) as an alternative to steel frames. Aim to minimize the quantity of the resource used; fewer materials means more open, breathable spaces.
LIFE-CYCLE APPROACH	
<ul style="list-style-type: none"> Reduce energy consumption / reduce embodied energy and embodied carbon – i.e., promote a life-cycle approach. 	<ul style="list-style-type: none"> Use local, renewable, and readily available biomaterials, such as wood from sustainably managed local forests and construction materials from local agricultural by-products. Select materials with low embodied energy and low energy construction systems; for example, use domestic, certified timber in place of concrete. Aim to use durable materials, especially for structural components, facilitating long-term use and thus sustainable material life cycles. Consider the end-of-life of the material, including its potential for reuse and recycling; for example, composites are more difficult to separate and to recycle than solid wood, blocks or stone.
APPLICATION OPTIONS	
	<ul style="list-style-type: none"> Structural system – lightweight construction Walling – cladding, wall rendering, interior finish Flooring Roofing – thatch, attap

B

DRY – DESERT CLIMATE (BWh) (HOT, ARID CLIMATE)

PERFORMANCE

- Keep hot temperatures out of the interior during the hottest months.
- Protect from the sun during the hottest months.
- Use evaporative cooling during the hottest months.
- Use thermal mass to reduce day-to-night temperature swings during the hottest months.
- Use night-flush cooling. This involves insulating the buildings mass on the outside to keep the interior temperature cool during the day and opening the building at night, using night ventilation to cool the mass of the building.
- Achieve **thermal mass** through the use of adobe, rammed earth, low-carbon concrete, clay and/or adobe bricks.
- Achieve **night-flush cooling** by using biomaterials for insulation, such as sheep wool on the outside of the building mass.
- Prioritize materials of **lighter colour**, as these will reflect rather than retain heat, keeping the interior environment cooler
- Choose light-coloured or vegetative green roofs to help **mitigate solar heat gain**.

LIFE-CYCLE APPROACH

- Reduce energy consumption / reduce embodied energy and embodied carbon – i.e., promote a life-cycle approach.
- Minimize **the quantity of the resource used**, especially during the construction process; for example, work to reduce the construction and demolition waste from materials that have higher embodied energy, such as low-carbon concrete.
- Use **durable materials**, especially for thermal mass and structural components, facilitating long-term use and a reduction in maintenance, renovation and refurbishment costs during the lifetime of the building.
- Consider the **end-of-life** of the material, including its potential for reuse and recycling; for example, composites are more difficult to separate and to recycle than solid wood, blocks or stone.

APPLICATION OPTIONS

- Exterior walls and interior floors can be used to achieve thermal mass
- Roofs – light-coloured or green roofs

C

TEMPERATE – HOT HUMID SUBTROPICAL CLIMATE (Cfa/Cwa) (HOT HUMID SUMMERS, DRY MILD WINTERS)

PERFORMANCE

- Open the building to the outdoors, since temperatures are comfortable much of the year.
- Allow natural ventilation to both cool and remove excess moisture in the hottest months.
- Protect from the sun during the hottest months.
- Avoid creating additional humidity during the summer.
- If humidity is mild and there is a high diurnal temperature swing, night-flush cooling (see “**B: Dry - Desert Climate**” above) may be effective in some temperate climates.
- See “**A: Tropical - Wet and Dry Climate**” above



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CHALLENGES REGARDING THE PROMINENCE OF ENERGY-INTENSIVE, MINERAL-BASED CONSTRUCTION MATERIALS: A HISTORICAL PERSPECTIVE

Despite the potential benefits offered by the use of biomaterials, there are still significant technological, socio-economic and regulatory challenges to overcome in the delivery of more readily available and more sustainable bio-based construction material cycles that are able to compete with, or even supersede, existing optimized petrochemical, steel and concrete production chains (Mussatto 2017). The prominence of mineral-based, energy-intensive construction materials in many existing and new building typologies is still evident. This section looks at the historical context and current social influences that have led to such material use. Section 2.3 then highlights the challenges that biomaterials production needs to overcome in order to be more readily available and ubiquitous in the construction marketplace.

From a historical viewpoint, the industrial revolution in Europe and North America resulted in a shift away from traditional and bioclimatic design and the reliance on locally sourced materials. This shift became particularly apparent after World War II, with the “modernism” movement of the mid-1900s. Modernism had many influences and was associated with diverse technological innovations. The ones most relevant to this report include structural innovations in steel, reinforced concrete, and glass, and innovations in material mass production, coupled with Willis Carrier’s invention of the first air conditioning system.

During this time, inspired by such technological innovations, the first high-rise steel and glass buildings with mechanical cooling and humidity control were built. They relied heavily on fossil fuel-based energy

consumption for space conditioning yet provided a new paradigm for occupant thermal comfort. Evolved forms of such buildings are commonplace today in most cities around the world. These buildings are internally dominated, meaning that most of the loads come from heat gains within the building, i.e., from people, equipment, lighting, etc. Often the buildings are cooled year-round regardless of the climate type.

In other words, such buildings can ignore the outside environment and use mechanical systems to maintain a constant temperature indoors. Although extremely innovative for its time and to this day associated with modern, contemporary living, such an approach to conditioning a building’s interior environment with little concern for the exterior environment, coupled with the use of glass, steel, and concrete, has resulted in a building type that is “context-less,” being the same globally. Many such buildings have in turn contributed to catastrophic environmental impacts and challenges.

In hot-arid and hot-humid climates, the operational energy for buildings of this type is very high. This is because the construction materials and assemblies being used are not climate responsive in their design, hence they rely on mechanical air conditioning and ventilation to keep interior environments cool. In terms of material sourcing and production, these buildings are typically associated with the importation of materials such as steel or glass from global supply chains. This in turn tends to result in a building with high embodied energy and associated carbon emissions. At the end-of-life, these materials are often difficult to reuse and dispose of, and their demolition contributes to greenhouse gas emissions.

THE CHALLENGES IN MAKING BIOMATERIALS MORE READILY AVAILABLE

There are social, economic and environmental considerations with moving away from the use of energy-intensive, mineral-based materials and technologies and towards a biomaterials approach. From a socio-cultural perspective, materials such as steel, concrete and glass have been linked with certain societal and aesthetic choices, including their association with progressive and contemporary lifestyles, which need to be re-questioned. From an economic standpoint, such materials are associated with established supply chains that have demonstrated affordable and reliable economies of scale for the construction process.

In addition, these materials have met certain structural and regulatory standards and adhere to building codes. These regulatory standards are primarily for safety and performance measures. More recently, integrated environmental performance is being addressed. However, from an environmental standpoint, many of these materials are associated with linear, material throughput economies that have negative impacts on the environment from both their production process and their end-of-life design. Yet many manufacturers of these materials are engaging in circular thinking to revisit their supply chains; for example, low-carbon concrete as discussed in section 3.3. For biomaterials to compete strongly in the construction materials marketplace, social, cultural, economic and regulatory limitations need to be overcome.

Policymaking is key in helping to overcome these limitations. Government incentives can encourage both the manufacturing as well as the widespread adoption of new bio-based and sustainable building products. Policies enable transformation by regulating the government approval process for materials before they enter the marketplace. For instance, new materials must meet recognized material standards and certification regarding their composition and properties, and must also comply with building codes.

Material standards are often defined by government non-regulatory bodies, such as the National Institute of Standards and Technology (NIST) in the United States, while building codes are developed at the international, national and/or local levels through a legislative and public policy process. For example, the International Building Code (IBC) is a model building code developed by the International Code Council (ICC) that has been adopted in the United States and is also used by other countries globally. Other examples of regulation include the labelling of materials at different phases of their development, such as the experimental label ATEX as part of the European directive to protect people working in potentially explosive environments.

From a socio-cultural perspective, specific messaging needs to be developed to convey the notion that low-tech and vernacular traditional building techniques are desirable and innovative. Such techniques can represent our future built environments, pioneered by countries of the Global South that will pave the way. Another policy consideration is the scale-up of biomaterials and its potential implications. If biomaterials are to become a significant source of materials use in the construction sector, this implies an increase in the volume of materials and resources sourced from the cultivation of land.

In an attempt to promote environmental health and to prevent unanticipated environmental impacts, at least two primary issues must be considered: firstly, avoiding the infringement of land marked for food production and, secondly, preventing the exploitation of land, which has the potential to lead to land degradation and the loss of soil nutrients. Hence, a promising circular economy approach involves sourcing the raw materials for construction materials from agricultural waste by-products or from plants that help regenerate soils between cultures. Section 3 explores three different case studies, the first of which introduces a number of construction materials made from post-agricultural waste.

CASE STUDIES



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CASE STUDY 1: ECOLOGICAL PAVILION FOR A CIRCULAR MATERIAL ECONOMY

3.1.1

INTRODUCTION

This case study outlines a demonstration and exhibition of the possibilities in biomaterials and innovative sustainable construction systems. Carried out by Yale University's Center for Ecosystems in Architecture (Yale CEA) in collaboration with UN Environment, the Ecological Pavilion for a circular material economy was presented at the Fourth Session of the UN Environment Assembly in Nairobi, Kenya in March 2019.

The goal of the exhibition was to demonstrate future endogenous building materials, systems and environmental strategies for addressing the global environmental and human crisis associated with housing insecurity (Dyson and Keena *et al.* 2020). This exhibition highlighted that locally available raw materials offer potential local solutions for creative and innovative new construction materials

as well as a new type of “neo-vernacular” design. Hence, it worked on changing social perceptions, demonstrating that the use of local bio-based construction materials can be innovative, new and desirable.

The exhibition was housed in a unique pavilion and was entirely 3-D-printed and made of biodegradable bamboo, designed by the internationally renowned US firm SHoP Architects (Figure 3). The featured systems showcased construction materials made from post-agricultural waste – such as coconut, bamboo, rice, corn and mycelia – and highlighted a number of innovative companies that have developed these construction technologies. The exhibit also featured modules, components and small-scale demonstrations for energy systems, water purification systems and sensors to monitor the environmental conditions of the structure. The focus of this case study is on the bio-based post-agricultural waste materials and sustainable construction practices showcased.



FIG. 3
Largest 3-D-printed structure made of biodegradable bamboo, displayed at the Ecological Pavilion

Note: The structure was co-designed by SHoP Architects and Branch Technology and was fabricated at Oak Ridge National Laboratory, United States.

Source: Yale CEA 2019

3.1.2

LIFE CYCLES OF ENERGY- AND CARBON-INTENSIVE MATERIALS

In considering the human activities required to construct our urban environments, and the work of global ecological systems in sustaining such development, many ubiquitous construction materials have detrimental environmental impacts. Producing commonplace construction materials such as steel, concrete and glass typically requires the use of non-renewable energy to acquire the raw materials as well as to process, manufacture and ultimately transport the materials to a construction site.

The acquisition of raw materials typically involves mining. Using mined and quarried materials has consequences for global ecological systems. The mined and quarried materials used to produce common construction materials – for example, the minerals, sand, gravel, crushed stone, cement, etc. used to make steel, aluminum, concrete, glass, etc. – are non-renewable resources that rely on long-term natural ecological products and services, such as natural sedimentary cycles, for their formation. These cycles can take anywhere from thousands to millions of years (Keena and Dyson 2017).

Considering both the biological inputs⁷ and the required human activities, it is clear that producing common construction materials relies on and depletes non-renewable mineral resources. Humans depend on global ecological systems not only for raw materials but also for other ecosystem services such as dilution of the air pollution often associated with the manufacturing and production of construction materials.

For example, the production of cement, one of the key ingredients in concrete, emits large amounts of CO₂; hence concrete manufacture relies heavily on the surrounding environment to absorb and mitigate pollution caused by its CO₂ emissions. In contrast, bio-renewable materials such as timber and agricultural by-products have low-carbon production processes as well as the potential to sequester CO₂ during their lifetime. Thus, from a life-cycle perspective many biomaterials are carbon neutral or carbon negative. The Ecological Pavilion exhibition examined a range of bio-renewable construction material alternatives.

3.1.3

THE NEXUS BETWEEN TACKLING THE CHALLENGE OF WASTE IN AGRICULTURE AND CREATING CIRCULAR MATERIAL PRODUCTION: BIO-BASED POST-AGRICULTURAL WASTE MATERIALS

In many countries, getting rid of agricultural waste is a significant challenge. Turning this waste into building materials can resolve this issue for the agricultural industry and can also positively impact the environment by providing a clean construction material. The Ecological Pavilion exhibition featured local or “climate-specific” bio-based post-agricultural waste materials – such as bamboo, rice, straw, corn, mycelium and coconut husk – and demonstrated the potential and viability of these renewable by-products as next-generation building materials. The following sub-sections provide details on how several of these materials are used in construction.

⁷ Biological inputs refer to those inputs that come from global ecological systems, such as minerals, renewable and non-renewable materials and sources of energy, water, air, etc. These are inputs that humans rely on in order to support human activities.

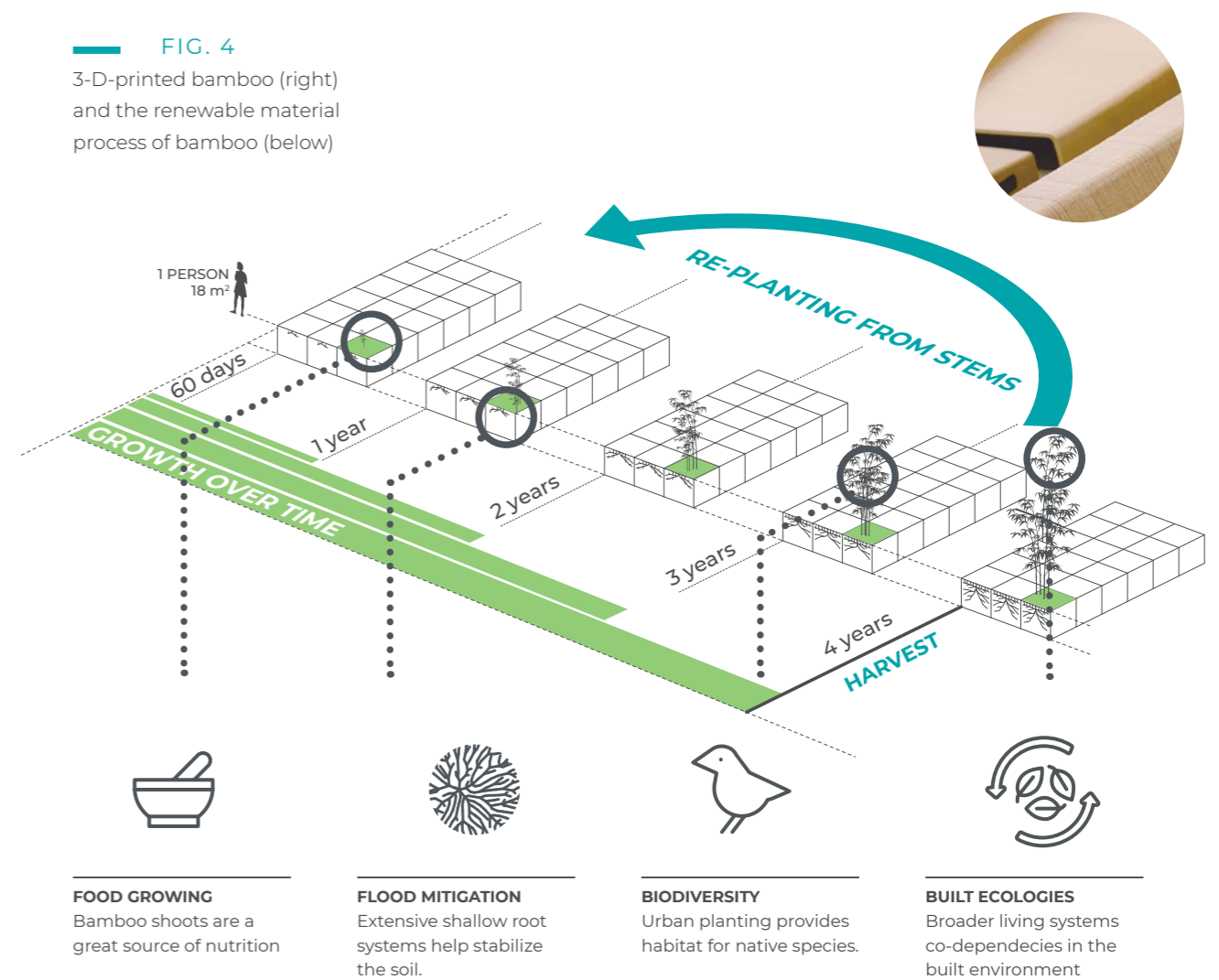


BAMBOO

Bamboo filament is a biodegradable material capable of enormous output sizes that has the properties of wood – i.e., the same sound, smell, and touch, with wood’s recyclable characteristics. It can be used for many construction applications such as structural walls, non-load-bearing walls, roofing, interior panels and flooring. Bamboo has additional structural benefits and is often used in seismic zones due to its excellent flexibility and resilience. Researchers at Oak Ridge National Laboratory in the United States used bamboo fibre in 3-D printing experiments to determine whether bio-based feedstock materials are feasible in additive manufacturing. The research highlighted the use of polylactic acid (PLA), sometimes referred to as a bioplastic, since it is a biodegradable, thermoplastic polyester. The result is a printed product that has similar properties to wood, as illustrated in Figure 4.

FIG. 4

3-D-printed bamboo (right) and the renewable material process of bamboo (below)



Source: Yale CEA 2019



MYCELIUM

Mycelium, the root structure of mushrooms, is used in bio-fabrication to grow advanced biomaterials and bio-resins. It is durable and biodegradable and forms a vegan composite. Mycelium biomaterials from the New York-based bio-tech company Ecovative also formed part of the Ecological Pavilion exhibit (Ecovative Design 2018). The rise of rapid consumerism has contributed to numerous environmental and health problems, with issues ranging from the buildup of ocean plastics and toxins to harmful industrial farming methods developed to feed an ever-growing population – all at the cost of our natural ecosystems. Using mycelium-based inputs, Ecovative is collaborating with companies to address some of these challenges by creating alternative meat products, biodegradable packaging materials, animal-free leather and more, as illustrated in Figure 5.

For construction applications, mycelium is used as a bio-resin to bind biomaterial fibres, many from recycled products, to create fibreboard panels. It can also be used as insulation given its advantageous acoustic, insulative and hydrophobic properties. Mycelium materials are competitive with synthetic foams. Ecovative platforms consist of original MycoComposite material (a mixture of hemp and mycelium) and newer MycoFlex material that consists of pure mycelium; these can be used for interior wall covering such as wall boards and panels and drywall partitioning, as an alternative to fibreboards and gypsum boards.

FIG. 5
Mycelium products by Ecovative used in construction (left) and for packaging (top-right); detailed view (bottom-right)



Source: Ecovative 2019



STRAW AND RICE

Straw panels are based on a technology that combines heat and compression in a dry extrusion process allowing the natural adhesives contained within agricultural fibres to bind the fibres to form a continuous high-quality strawboard panel. High-strength recycled paper is used to seal the strawboard panels and to give a finish-ready surface. These panels were demonstrated at the Ecological Pavilion by Strawtec Building Solutions of Kigali, Rwanda (Strawtec 2019).

Straw panels can be used for drywall partitioning as a single- or double-layer wall with fibre cement board. Straw panel wall systems can also be used as a partition in wet areas (such as bathrooms), where a single-layer straw panel wall is clad with wall tiles. In exterior load-bearing wall assemblies (such as light steel frame walls), straw panel walls can be used as the interior lining. The University of Rwanda School of Architecture showcased the use of straw and rice panels in a pavilion built for the Venice Biennale 2010, as illustrated in Figure 6.

Another use of straw is in straw bales, which fare competitively in price when used for insulation. However, given that a 60-centimetre width is typically needed for effective insulation, straw bales can consume space in the overall wall assembly.

FIG. 6
Straw and rice panels used on the roof of a temporary pavilion representing the University of Rwanda School of Architecture at the Venice Biennale 2010 (right); sample of a Strawtec panel (left)



Source: University of Rwanda 2019; Strawtec 2019



COCONUT FIBREBOARD

The Ecological Pavilion exhibit also demonstrated upcycled agrowaste derivatives and emerging bio-adhesives for intrinsic evaporative cooling and dehumidification in the built environment. The coconut fibreboard panel system on exhibit, as illustrated in Figure 7, was developed by Willow Technologies Ltd. (formerly AMBIS Technologies), where the coconut panels are produced in association with the Center for Architecture, Science and Ecology (CASE) at Rensselaer Polytechnic Institute in New York. Leveraging renewable agrowaste resources as an alternative material feedstock for the buildings sector can play a pivotal role in “closing” material life-cycle gaps between interdependent sectors of the African and global economies.

In advancing the replacement of synthetic petrochemical-based binders in the building materials industry, the use of emerging bio-binders in the production of a range of low- to high-density agrowaste-based materials has demonstrated composite advantages for improving air quality and energy use throughout the building life cycle. The hygric and thermal performance has shown potential for such materials to be used effectively as intrinsic evaporative cooling material systems and humidity-buffering technologies. While the mechanical strength of pressed coconut fibreboards is competitive with reconstituted wood material technologies on the market today, this modular prototype investigates the development of three-dimensional fibreboard panels that open up the potential for acoustic and indoor air quality applications (Lokko 2016; Lokko *et al.* 2016; Lokko and Rempel 2018) particularly as alternative drywall partitioning.

FIG. 7
Structural wall made of coconut agricultural waste by-product by Willow Technologies Ltd. (formerly AMBIS Technologies) at the Ecological Pavilion



Note: Pictured in the photo are UN Deputy Secretary-General Amina Mohammed, UN Environment Executive Director Inger Andersen and Yale CEA Director Anna Dyson.

Source: Yale CEA 2019



SUSTAINABLE CONSTRUCTION PRACTICES:

The Ecological Pavilion exhibit recognized the critical role that urban development plays in creating a more sustainable global future, particularly in cities and countries that are experiencing rapid urbanization. To provide high-quality housing to developing communities, the exhibition addressed prefabrication and modular approaches. This involves manufacturing the materials at an off-site production facility and then transporting them to the building site, arriving as a compact container. The manufacturing of the Ecological Living exhibit included the adaption of two industrial robots by Branch Technology, using a proprietary method called Cellular Fabrication™ to bring 3-D printing out of the realm of prototyping and table-top production and into broader use as a full-scale, practical means of construction.

The exhibit questioned whether solar technology could be used to drive such advanced manufacturing (Figure 8). The large-scale form was printed in parts for easy transport and on-site assembly. By taking a manufacturing approach to construction, the Ecological Pavilion can easily be relocated by repacking it into its original shipping volume and transporting it to a new location. Figure 9 illustrates the modular on-site assembly and shows how the Ecological Pavilion was relocated to the University of Nairobi in Kenya.

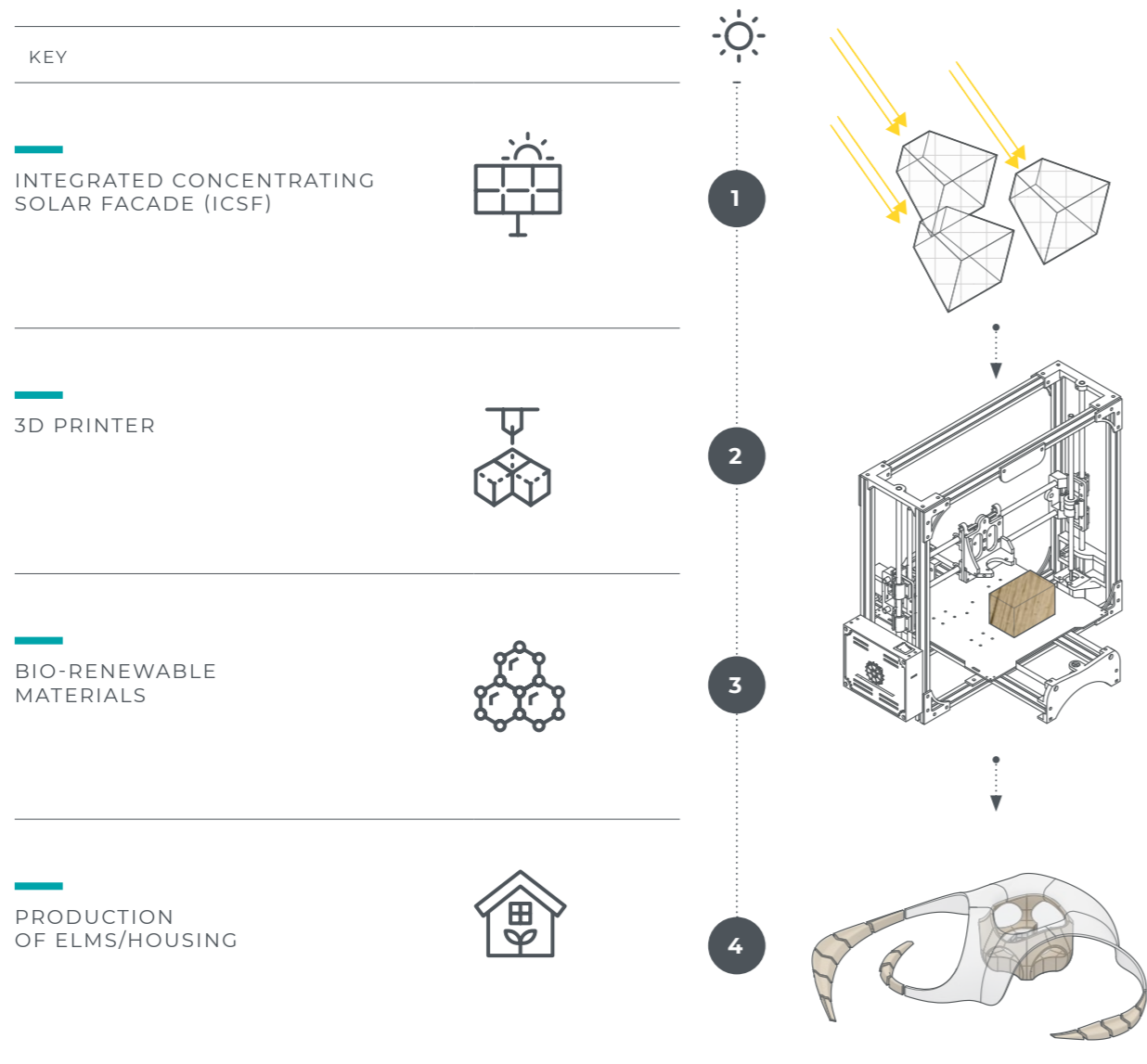
FIG. 8
Solar energy coupled with advanced manufacturing: Using solar energy to fuel manufacturing of bio-renewable materials



Source: Yale CEA 2019

(FIG. 8)

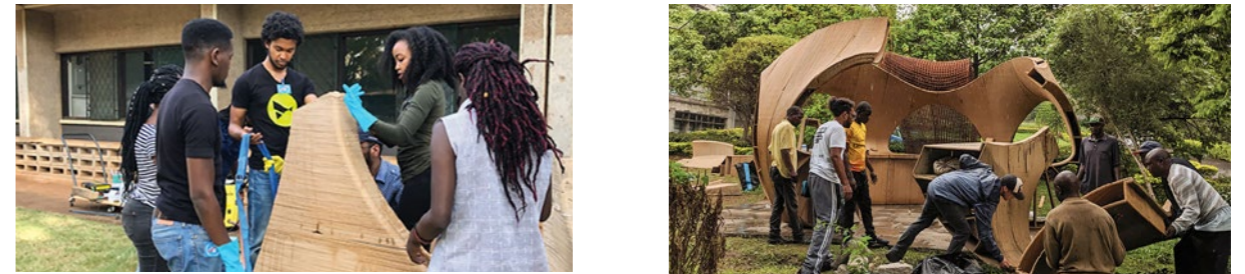
Solar energy coupled with advanced manufacturing: Using solar energy to fuel manufacturing of bio-renewable materials



Source: Yale CEA 2019

FIG. 9

The Ecological Pavilion demonstrating modular construction as an important concept to consider in sustainable construction practices



The Ecological Pavilion addressed innovations in biomaterials for construction and sustainable practices for advancing traditional non-ecological construction processes. The next case study looks at biomaterial building products and a strategy for scaling up their development.

Note: The photos (bottom) show the Ecological Pavilion being assembled at the UN Headquarters in Nairobi by Yale CEA team members and collaborators from the University of Nairobi, University of Rwanda, Kenyatta University and Kenya Forestry Research Institute (KEFRI). The modular construction facilitated an easy relocation from the UN headquarters in Nairobi to its current home at the University of Nairobi, Kenya (top).

Source: Yale CEA 2019

CASE STUDY 2: MOVING TO SCALE-UP STRATEGY WITH THE ISOBIO PROJECT

3.2.1

THE ROLE AND ORGANIZATIONAL STRUCTURE OF DEMONSTRATION PROJECTS

The second case study can be characterized as a “demonstration project.” Many studies have acknowledged the benefits of such projects. For example, Meadowcroft (2009) explains that demonstration projects showcase novel practices and technologies in order to initiate change and learn the potential and limitations of different methods. He calls this “learning-by-doing” and stresses the need to link technology and social innovation in order for society to embrace a path towards sustainable development.

Bossink (2017) note that the organizational structure of demonstration projects differs on a case-by-case basis, but many common characteristics exist. All projects have a physical location, which initially tends to be a laboratory or some controlled environment in a university, where the project takes the shape of a prototype or demonstration mock-up. At this initial stage, the work is typically led by a university research group, with public funding organizations or private firms acting as partners. These prototype demonstrations are typically followed by a collaboration with industrial partners and a national or regional funding organization in order to test the demonstration in a real-world environment. The final stage is typically a market demonstration project carried out by private actors in order to prepare the technology for commercialization and the development of market niches.

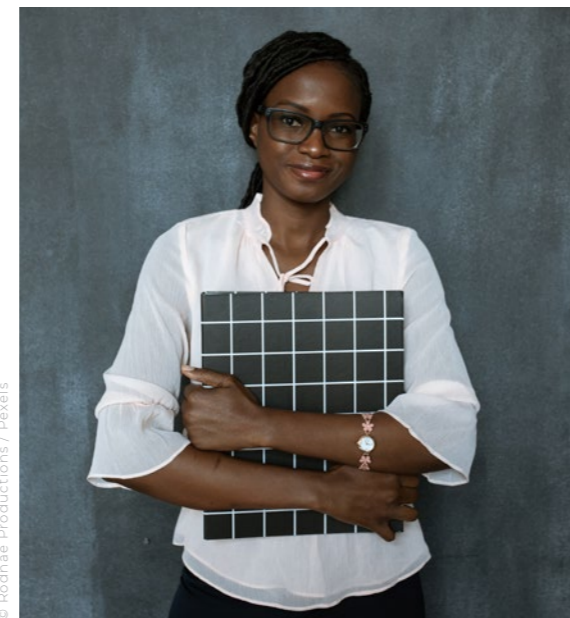
The organizational learning of each stage in demonstration projects is key in order to transfer knowledge on how the new sustainable construction technology functions and to demonstrate its successful application. The literature outlines how demonstration projects with such organizational form have the capacity to accelerate the technical

and socio-economic knowledge needed to facilitate the scale-up and large-scale adoption of sustainable technologies (Broto and Bulkeley 2013; Zeng *et al.* 2014; Bossink 2017). The case study highlighted here outlines the ISOBIO project, which can be characterized as a demonstration project.

3.2.2

AN INTRODUCTION TO THE ISOBIO PROJECT

The ISOBIO project, which ran from 2015 to 2019, was a multidisciplinary consortium representing 11 partners from academia and industry across 6 European countries. It was supported by the European Union’s Horizon 2020 programme, within the “Materials for Building Envelopes” call for Energy Efficient Buildings. The project provides an innovative example of how biomaterials for construction can be produced at scale for mainstream consumption. The materials developed through ISOBIO consist of insulation materials, hydrothermal and moisture-buffering materials, binders, sol-gel and resins (ISOBIO 2019).



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The ISOBIO project outlined the following opportunities related to the use bio-based materials in contemporary construction (ISOBIO 2019):

- Reduced greenhouse gas emissions
- Lower embodied carbon
- Better environmental performance
- Healthier buildings
- Resource efficiency (renewable; reduced waste)
- New markets (agriculture).

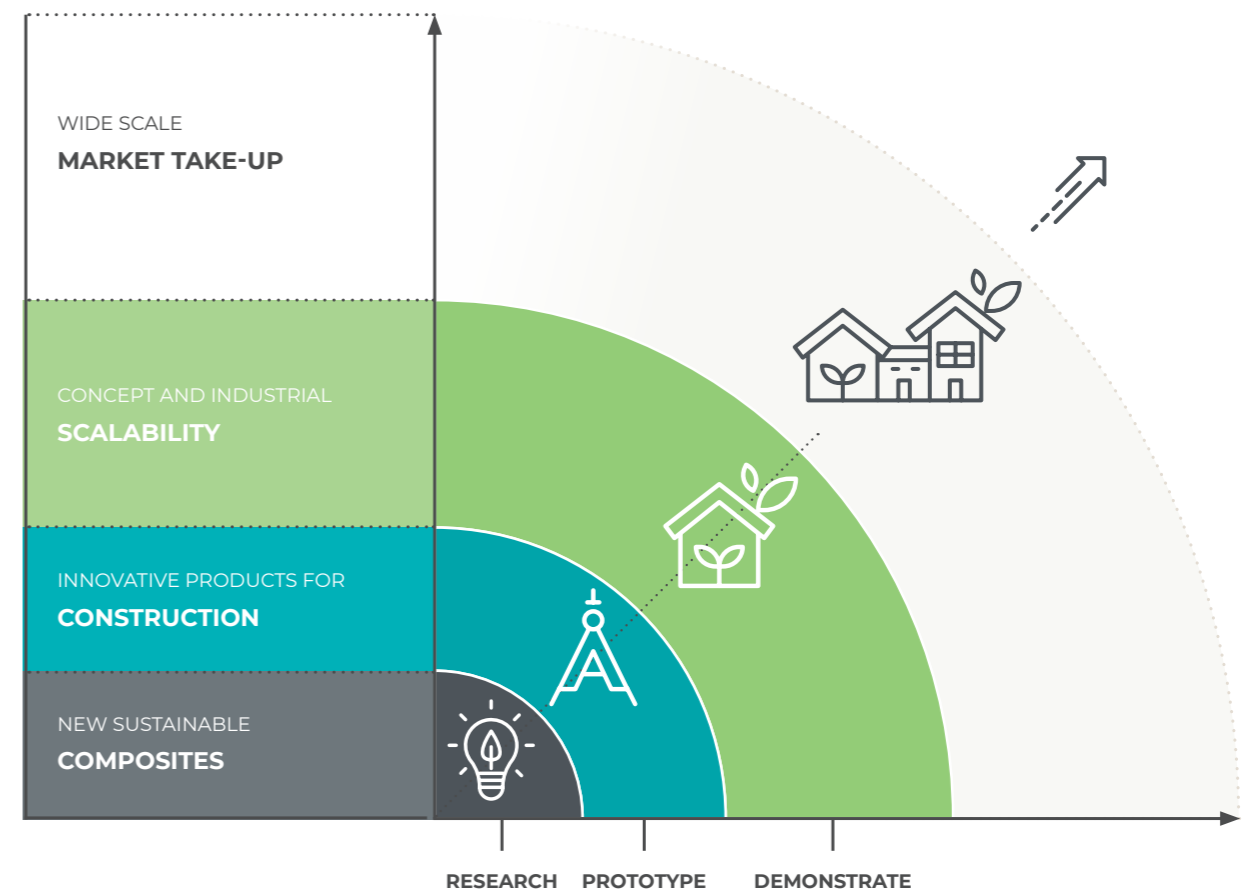
To achieve wide-scale market acceptance, the project outlined the following strategy, as illustrated in Figure 10:

- Research: New sustainable composites
- Prototype: Innovative products for construction
- Demonstrate: Concept and industrial scalability
- Scale up: Wide-scale market uptake.

The following case study analyses each of these stages.

FIG. 10

Diagram of the ISOBIO project’s proposed strategy to move bio-based construction materials into the mainstream



Source: ISOBIO 2019

3.2.3

RESEARCH: PRE-TREATING BIO-BASED AGGREGATES TO ACHIEVE MOISTURE-BUFFERING AND WATER-REPELLING PROPERTIES IN THE DEVELOPMENT OF A HIGH-PERFORMANCE AND LOW-EMBODIED-ENERGY COMPOSITE

The research phase of the ISOBIO project involved scientific investigations into advancing the state-of-the-art in bio-based insulation materials, hygrothermal and moisture-buffering materials, binders, sol-gel and resins. Through agglomerating existing technologies, pre-treated bio-based aggregates and binders were combined to form the ISOBIO composite panels. Research in nanomaterials allowed for the use of a silica nanoparticle treatment to improve the water- and fire-resistant properties of ISOBIO's biomaterial products (Collet, Prétot and Lanos 2017). Testing of the treatment demonstrated its ability to delay mold growth, and, given its quicker drying time at lower curing temperatures, also reduced energy consumption in its production.

The research phase took place primarily across the academic partners of the multidisciplinary consortium. The ISOBIO project was part of the Advanced Materials and Nanotechnology Cluster (AMANAC). Collet, Prétot and Lanos (2017) carried out a feasibility study to explore the use of wheat straw as a gluing material and numerous hemp-to-wheat straw ratios. From this study, three hemp-straw composites were chosen, and their thermal and hygric⁸ properties were characterized. The key findings showed that the composites had low thermal conductivity⁹ (0.071 to 0.076 Watts per metre-Kelvin) and expressed excellent hygric regulating behaviour (moisture buffer value > 2 W/m².% relative humidity) (Collet, Prétot and Lanos 2017).

⁸ Hydric (and moisture-buffering) properties involve the behaviour and ability for the material to moderate changes in relative humidity by absorbing and desorbing water vapour from the indoor surrounding air.

⁹ Thermal conductivity defines the rate at which heat passes through a material. It is a measure of the ability of a material to conduct heat. Materials of low thermal conductivity are good insulators and are used for thermal insulation.

3.2.4

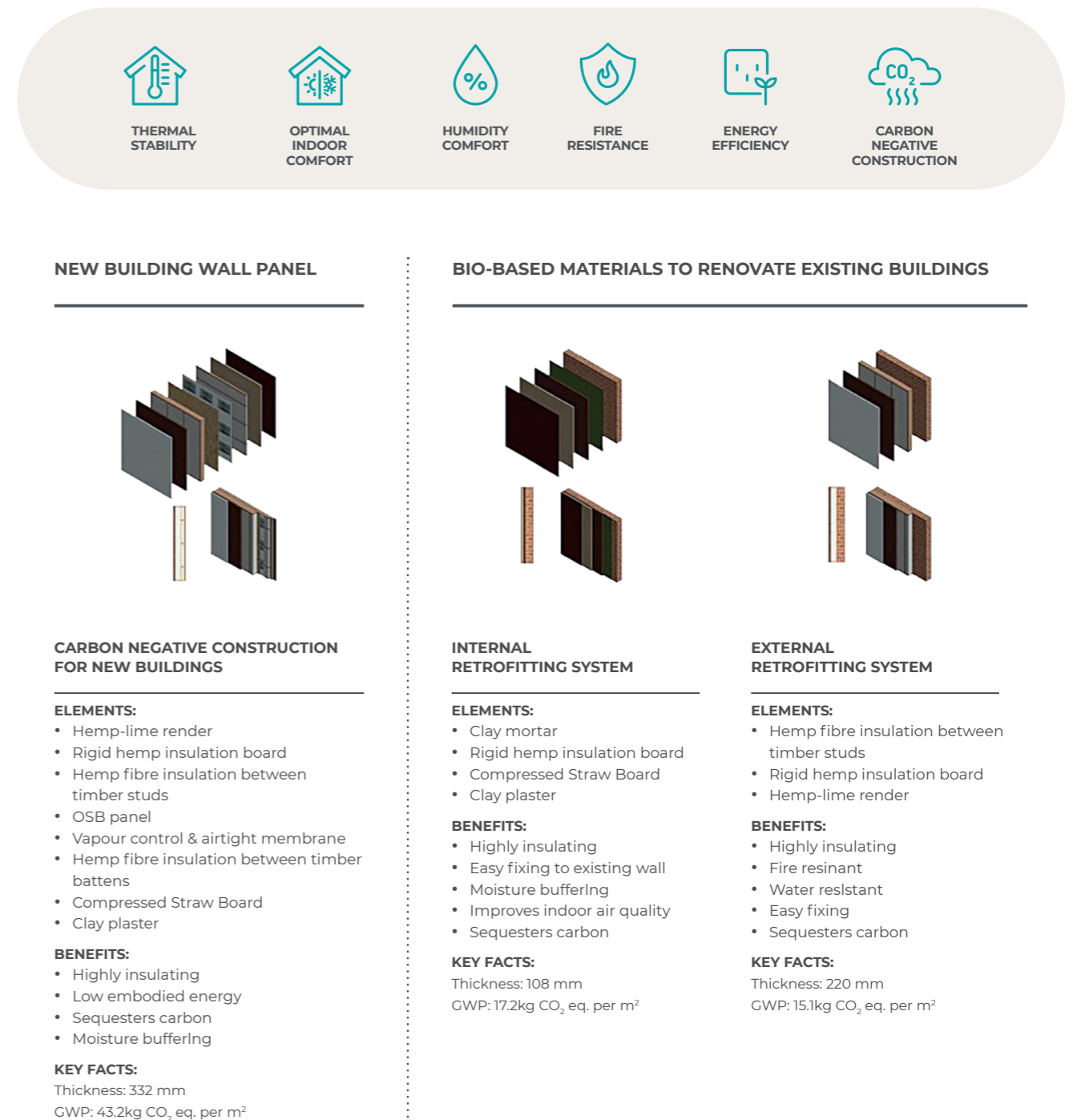
PROTOTYPE: DEVELOPMENT OF INNOVATIVE PRODUCTS FOR CONSTRUCTION

Material investigations from the research phase were then used to develop different bio-based wall panel prototypes and insulation boards, as well as plasters and renders. A composite wall panel for new buildings and two composite panels for renovating existing buildings were developed that consist of a new building wall panel and a bio-based materials retrofitting system for both internal and external use in existing buildings, as illustrated in Figure 11. The new building composite wall panel consisted of the following layers: hemp-lime render, rigid hemp insulation board, hemp fibre insulation in between, timber studs, oriented strand board (OSB) panel, vapour control and airtight membrane, hemp fibre insulation between, timber battens, compressed straw board and clay plaster.

The key benefits claimed for such a panel include a highly insulated finish, a low embodied energy, the ability to sequester carbon and excellent hygric¹⁰ and moisture-buffering principles. During the prototyping stage, the panels and products were tested, and life-cycle assessments were performed to calculate the environmental impact of the products in terms of their global warming potential and stored sequestered atmospheric carbon capacity. Results from these analyses showed a positive environmental impact with more CO₂ equivalents being stored in the biogenic content of the panels than were emitted during the panels' production phase (Hill and Dibdiakova 2016; Tellnes *et al.* 2017; ISOBIO 2019).

FIG. 11

Composite wall panels developed during the prototyping phase to be then tested as a proof of concept in the demonstration phase



Source: ISOBIO 2019

3.2.5

DEMONSTRATE: CONCEPT AND INDUSTRIAL SCALABILITY

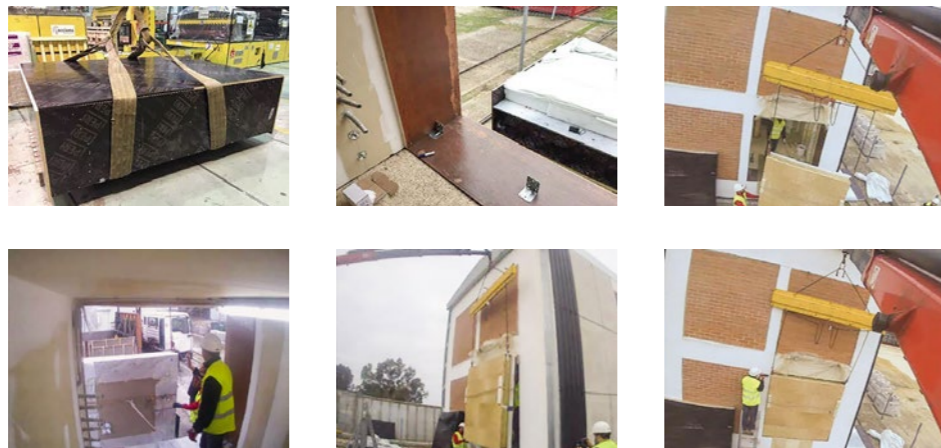
The demonstration phase of the ISOBIO project involved a series of prototype-level demonstrations of the new construction technology to highlight its social, environmental and financial benefits to the building sector. According to ISOBIO (2019), the goal of this phase was to demonstrate the potential of optimizing the construction process for energy-efficient buildings and to become a leader in "green" construction technologies in Europe's construction sector, thereby strengthening European competitiveness in this field.

The demonstration projects included incorporating ISOBIO products in several pilot building projects: the HIVE facility at the University of Bath in the United Kingdom and other associated infrastructure in Spain, as illustrated in Figure 12. This phase established a proof of concept to test

the scalability of the biomaterial products through demonstrations and field trials for evaluation. Figure 11 illustrates how laboratory-scale testing was complemented with the demonstration of a building-scale "real-world" scenario in Spain with Acconia construction company (Uranga 2019). The demonstration carried out at the UK's Hive testing facility compared a wall section of a conventional façade with that of the same size wall section of the ISOBIO façade (Ansell *et al.* 2020).

Research shows that demonstration projects help to provide a tangible reference to both scientific and local committees at large and to facilitate the transition from lab-scale prototype to marketplace scale-up (Broto and Bulkeley 2013; Zeng *et al.* 2014; Bossink 2017). These studies identify that the final stage in a demonstration project is typically a market study, carried out by private actors in order to prepare the technology for commercialization. The ISOBIO project followed this trend, as described in the next section.

FIG. 12
A demonstration phase involving the installation of both the new build and retrofitting ISOBIO systems in different demonstration buildings



Note: As outlined by Ansell *et al.* (2020) and Uranga (2019) of Acconia construction company, these demo buildings were throughout Europe including at the HIVE facility at the University of Bath and at the building shown in the image, located in Spain. This allowed for the prototypes to be tested in different climate types. The image illustrates the installation of an ISOBIO new-build façade panel. All panels were pre-manufactured off-site, allowing for a modular design and reducing installation time and costs on-site. During the demonstration phase, different sections of the building are installed with different ISOBIO systems and tested and compared to conventional insulated brick-block cavity wall sections.

Source: Uranga 2019

3.2.6

SCALE-UP: WIDE-SCALE MARKET UPTAKE

To achieve acceptance of ISOBIO's biomaterial products in the marketplace, this phase involved introducing experts from the private sector with knowledge of the construction and technology markets. These experts included Greenovate! Europe and the independent consultancy firm Van der Meer & Van Tilberg, which helped to develop an exploitation strategy. The firm specializes in new business development by integrating the domains of strategy, technology, marketing and organization. A key focus of the scale-up strategy was raising the profile of bio-based construction materials for commercialization through communication and dissemination activities, as illustrated in Figure 13.

The ISOBIO project targeted professionals, academic audiences and the broader public in disseminating the benefits of its materials and their environmental, social, economic and implementation viability. The aim was to create awareness of the potential to create "eco" homes. The target audience for project communications was all of Europe by means of a wide-scope media campaign using innovative media technologies. Although broad, such an approach was deemed relevant to enable the products to successfully enter the marketplace and be competitive with traditional construction materials. From a technical viewpoint, the ISOBIO team collaborated with Progetic, a Spanish sustainable engineering and consultancy firm, to produce a set of construction details to offer practical information to architects, contractors, developers and engineers seeking to use the ISOBIO system. Such details are standard in the building design process.

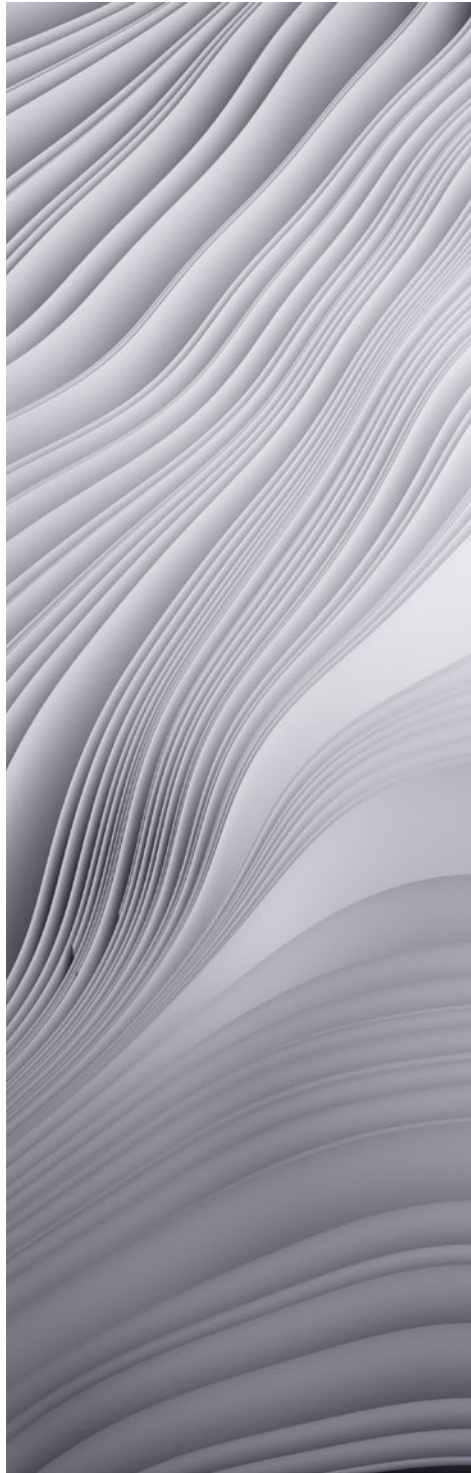
Source: ISOBIO 2019

FIG. 13

Examples of ISOBIO's commercialized products including hemp insulation board (left), hemp-lime plasters and renders (middle) and novel clay plasters (right)



CASE STUDY 3: SUPPORT FOR “GREEN” BUILDING MATERIALS VIA GUIDELINES AND THE ROLE OF HYBRID SOLUTIONS (BIOMATERIALS + MINERAL-BASED MATERIALS)



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This section looks at the developments by governments in South Africa, the Netherlands and the United Kingdom in developing catalogues, handbooks and guidelines for using “green” building materials and technologies.

The South African handbook (GreenCape 2014) is targeted at the construction sector and offers a practical and useful reference guide for specific green building materials, providing support and information to the building community in the Western Cape. It aims to give clear guidelines on the pros and cons of different materials in terms of performance, life-cycle impact, cost of material, fire-retardant factors and ease of installation.

The handbook of the Dutch government (van Dam and van den Oever 2019) is aimed at the entire built environment supply chain including architects, construction companies, contractors, developers and various clients from government to collective private clients. Commissioned by the Dutch Ministry of Economic Affairs and Climate, it aims to outline biomaterials that are commercially available. It also addresses research and innovation and products that are not yet market ready but that potentially will offer low-carbon alternatives in the near future. Therefore, from a practical viewpoint, the handbook discusses the need for hybrid, flexible solutions (i.e., biomaterials plus petrochemical or mineral-based materials) that will allow for the integration of new biomaterial innovations in buildings as they become available.

The UK government-funded website GreenSpec (GreenSpec 2020) offers a green building resource. It is edited by practicing architects and specifiers and is targeted at design professionals and the self-build audience. In addition to biomaterials, all guidelines address the use of low-carbon concrete. The website promotes the reduction of cement content in concrete, a material that is ubiquitous in global construction due to its low cost and use of local content. Although low-carbon concrete is not a biomaterial, the following section focuses on its role in the context of promoting green and hybrid solutions to construction materials.

3.3.1

THE ENVIRONMENTAL CHALLENGES ASSOCIATED WITH CONCRETE PRODUCTION

Cement, a key ingredient in concrete, is the second most consumed product in the world after potable water (Czigler *et al.* 2020). However, cement is also a major contributor to climate change. More than 4 billion tons of cement are produced each year (Lehne and Preston 2018), and concrete and cement production are responsible for 9 per cent of global greenhouse gas emissions (OECD 2019). In particular, the production of cement involves chemical and thermal combustion processes that are a key source of CO₂ emissions.

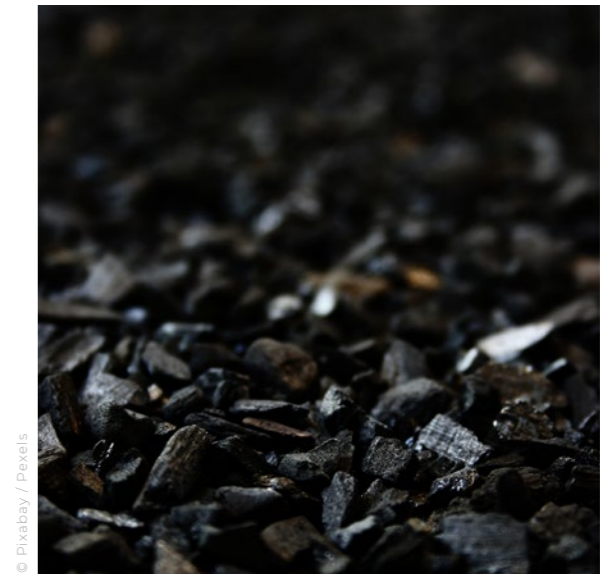
In an attempt to mitigate the carbon emissions associated with concrete production, a number of factors are being considered. These include:

- increasing the energy efficiency of cement plants,
- replacing fossil fuels with low-carbon alternatives, and
- capturing and storing the CO₂ emitted during cement production.



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3.3.2

POTENTIAL DECARBONIZATION LEVERS

As much as 50 per cent of the emissions related to cement production are inherently linked to a chemical reaction that occurs during the process of making cement clinker, one of the main ingredients in cement. Research into reducing emissions associated with this process has studied ways to lower or replace entirely the use of clinker in cement mixtures. Promising decarbonization levers being investigated include the potential to blend clinker with alternative materials such as clinker substitutions, novel cements and innovative technologies such as carbon capture and storage (CCS).

In a recent Chatham House report, Lehne and Preston (2018) estimated the theoretical decarbonization potential of different approaches, with:

- clinker substitutions representing a 70-90 per cent decrease in CO₂ emissions;
- CCS representing a 95-100 per cent decrease; and
- novel cements representing a 90-100 per cent decrease.

Some novel cements and CCS technologies aim to be carbon negative, meaning that they sequester carbon, thereby capturing more carbon than is emitted during the production process.

3.3.3

CLINKER SUBSTITUTES

Clinker substitutes are materials added to cement or concrete to lower the amount of clinker. Supplementary cementitious materials (SCMs) are one form of clinker substitutes. They include pulverized fuel ash (PFA), or “fly ash,” a by-product of coal-fired power plants; granulated blast furnace slag (GBFS) a by-product of iron and steel production; and silica fume, a by-product of silicon manufacturing. Another clinker substitute is limestone fines, which are less reactive with clinker.

Although these clinker substitutes have deep decarbonization potential, challenges still exist with this approach. These clinker alternatives are typically associated with by-products from industrial processes that in themselves pose risks to the environment and are often not sustainable solutions. For example, PFA relies on coal production, a process that multiple countries are gradually phasing out, eventually making PFA unavailable. The same is true for GBFS, where decarbonization progress in the iron and steel sectors will result in reduced availability of the by-products needed for clinker substitutes (Czigler *et al.* 2020). These clinker alternatives are outlined in detail on the UK website GreenSpec (GreenSpec 2020).



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3.3.4

NOVEL CEMENTS AND CARBON CAPTURE AND STORAGE (CCS)

Lehne and Preston (2018) note that challenges associated with CCS include the cost of the technology and scepticism regarding its potential for rapid scale-up. The deployment of novel cements also faces similar challenges in terms of scale-up and their ability to achieve commercial viability. More investment in research and large-scale demonstration projects is necessary in order to see the substantial growth needed if novel cements are to be competitive in meeting the market demand for concrete. According to Lehne and Preston (2018), although research among experts shows broad acceptance for clinker substitutes and novel cements as a vital step towards low-carbon concrete, they are failing to receive policy attention.

3.3.5

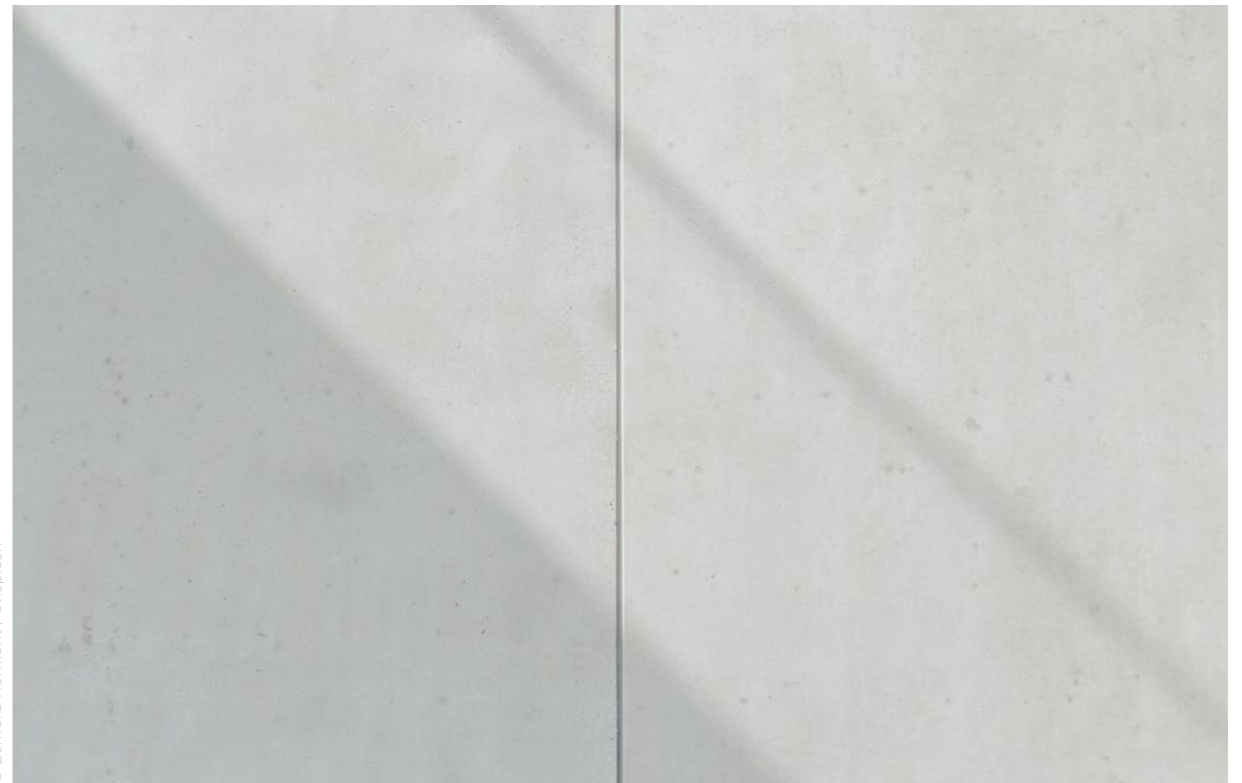
GOVERNMENT GREEN BUILDING MATERIALS CATALOGUES AND GUIDELINES

The South African catalogue of green building materials (GreenCape 2014) considers the use of concrete for modular technologies and for walling. It categorizes concrete according to various “resource efficiency indicators,” such as containing local content, being cost effective and providing a potentially lightweight option.

The Dutch government’s *Catalogue of Bio-based Building Materials: Green and Circular Building*, published in 2019, explores the potential of biomaterials as part of the country’s agenda to transition to a “Circular Netherlands in 2050” (van Dam and van den Oever 2019). This programme to incentivize the circular economy aims to create an overview of biomaterials that are currently commercially available. The catalogue outlines composite building materials such as fibre cement,

which is developed using wood fibres, or hemp wood pipe and mineral binders (lime, sand, cement), such as hempcrete. These products aim to reduce the amount of Portland cement used and hence are less carbon intensive.

Foam concrete, also known as lightweight cellular concrete or low-density cellular concrete, is also investigated. This can be used for new foundations as well as for the subfloors in renovations. It uses animal or vegetable proteins as the foaming agents in concrete production. This creates small enclosed air bubbles in the concrete, making it more lightweight. The Dutch catalogue also highlights the need to explore hybrid conditions where both biomaterials and petrochemical or mineral-based materials are used in conjunction in the design and renovation of buildings. This is needed because certain commercially available biomaterials do not yet comply with building regulations, and others are not purely made of bio-based materials, often being a composite.



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3.3.6

EXAMPLE: THE UK CONCRETE INDUSTRY'S ACTION PLAN TO ADVANCE TOWARDS A ZERO-CARBON CEMENT FUTURE

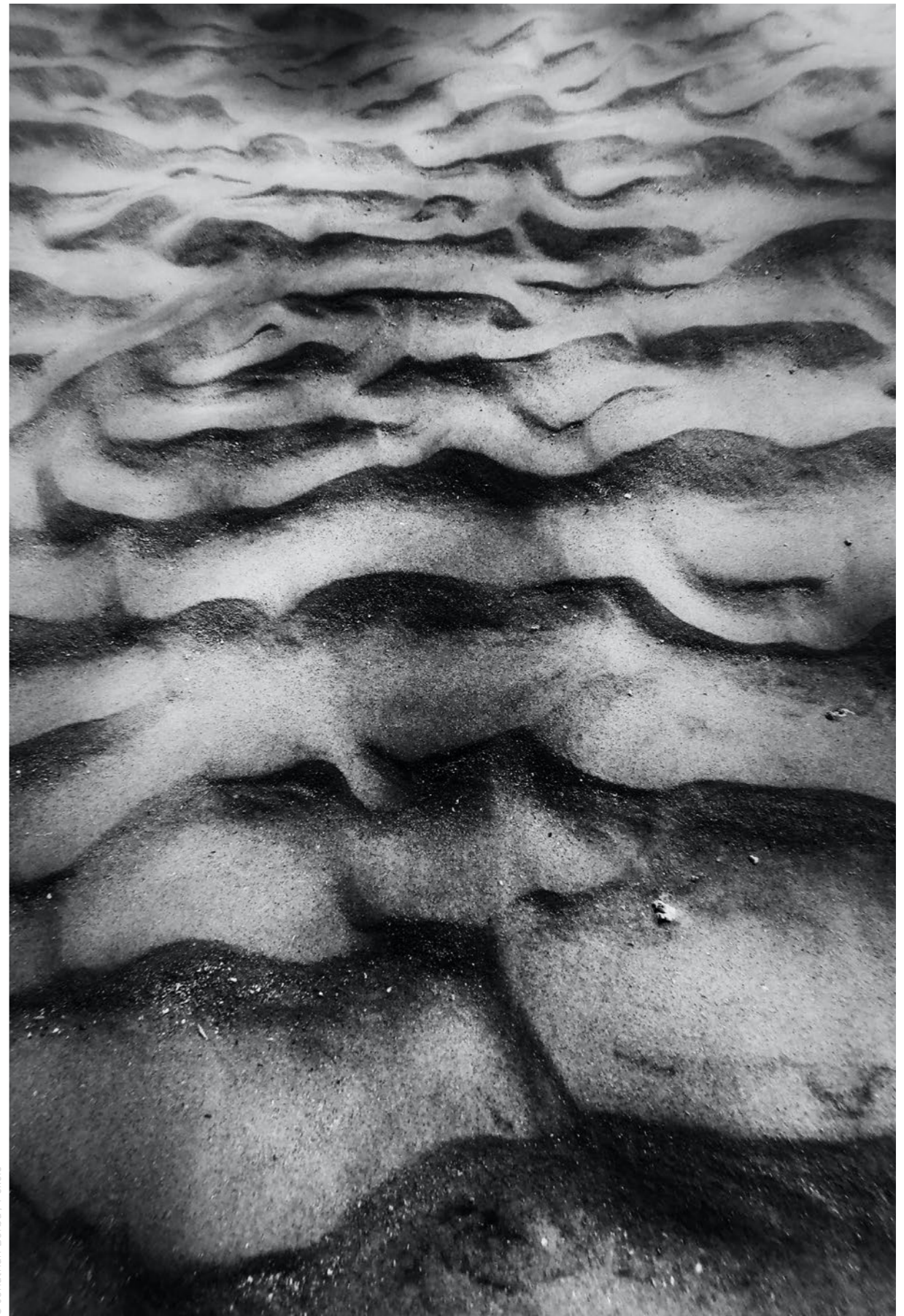
The GreenSpec (2020) resource outlines commitments made by the UK concrete industry to establish concrete as a contributor to a sustainable built environment. The industry has set milestones for 2020 and 2050 and laid out the following targets:

- 1. Contribute to the delivery of a zero-carbon built environment.** This involves publishing case studies of best practices, providing the relevant information needed for integration into Building Information Modelling (BIM) models and keeping up-to-date with sustainable metrics and frameworks as well as data requirements for low-carbon concrete monitoring.
- 2. Provide life-cycle assessment data that are compliant with codes and standards.** This involves the data provided on the embodied energy and carbon values of concrete production – in particular, making sure that the boundaries of analysis are established, allowing for data transparency and the production of reliable environmental product declarations (EPDs) as well as supporting life-cycle assessment data requirements.
- 3. Develop a Material and Resource Efficiency Programme to inform best practice across the life cycle of concrete in the built environment.** This includes identifying guidance on reducing waste in the process of producing concrete, as well as on practices of recycling and re-using concrete at the end-of-life and using recycled materials in concrete production.
- 4. Develop a Low Carbon Freight Initiative to support improvement in transport performance through the concrete supply chain to construction sites.** This includes promoting best practices to reduce carbon-related transport in concrete production activities.

- 5. Develop a Water Strategy to support the measurement and reporting of sustainability performance and target setting.** This involves promoting and developing targets on the efficient use of water in the concrete industry.
- 6. Target continuous improvement of sustainable production performance, and report performance annually.** This involves setting new targets for performance improvement, including developing performance indicators towards relevant reporting and data collection.

As is explained in GreenSpec (2020), the UK concrete industry has committed, in partnership with the Waste & Resources Action Programme (WRAP) (a not-for-profit, government funded company, recognized in the United Kingdom and internationally as experts in resource efficiency and product sustainability) to engage and carry out the commitments set out in Resource Efficiency Action Plans (GreenSpec 2020). Such partnerships and incentives are crucial to encourage concrete and cement organizations globally to rethink current production processes. Governments can play an important role in promoting and incentivizing potential decarbonization pathways.

As climate pressures increase, traditional concrete and cement production face many challenges, from CO₂ emissions to scarcity of resources such as sand. At the same time, faced with rapid urbanization, particularly in the Global South, the demand for concrete and cement will increase. The concrete industry will need to adopt a new process and a circular economy mindset to achieve zero-carbon cement. With the right approach, this process can reinforce innovation and decarbonization simultaneously towards a sustainable built future. The reliance on concrete and cement also highlights the need for diversity of construction materials. Alternatives, such as biomaterials, are of particular interest because by their very nature they have the potential to contribute to decarbonization and a greener path forward.



THE ROLE OF POLICY IN ENABLING BIOMATERIAL SUSTAINABLE DEVELOPMENT

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In order to achieve the UN Sustainable Development Goals and reach the Paris Agreement target of limiting global warming to well below 2 degrees Celsius, with respect to construction and the built environment policy makers are urgently seeking strategies to decarbonize construction, known as one of the most energy- and carbon-intensive industries. The UN Environment Programme's Global Alliance for Buildings and Construction (GlobalABC) has released a guide on how best to incorporate building actions in countries' Nationally Determined Contributions (NDCs) towards reducing greenhouse gas emissions under the Paris Agreement (UNEP 2018). The guide outlines how fundamental emission mitigation actions in the buildings sector can be included in NDCs. It concludes that exceeding the current level of ambition in NDCs is vital for effective decarbonization of the buildings sector towards achieving the Paris goals.

GlobalABC's *GlobalABC Roadmap for Buildings and Construction 2020-2050* (GlobalABC, International Energy Agency [IEA] and UNEP 2020) sets processes and develops a framework based on life-cycle thinking for resilient and efficient buildings towards decarbonization of the construction sector by 2050; it is complemented by regional roadmaps targeting Africa, Asia and Latin America. In addition, GlobalABC's 2019 *Global Status Report for Buildings and Construction: Towards a Zero-emission, Efficient and Resilient Buildings and Construction Sector* (GlobalABC, IEA and UNEP 2019) tracks progress and gaps towards meeting the Paris Agreement goals and highlights the question of materials. At the national and local levels in Europe and North America, a range of policy options are being implemented to help tackle the environmental impacts of the construction industry, including those associated with the production of construction materials.

In the United States, building rating and certification programmes, such as the US Green Building Council's (USGBC) Leadership in Energy and Environmental Design (LEED), encourages a shift towards the use of biomaterials. These rating systems are used as cross-cutting policy instruments to highlight the need for the use of low-carbon and non-toxic construction materials. Biomaterials fall into both of these categories and are addressed in more detail in the

most recent version of LEED (version 4.1). The USGBC has introduced a number of additional "Materials and Resources" prerequisites and credits (USGBC 2019a; USGBC 2019b; USGBC 2019c; USGBC 2019d; USGBC 2020a; USGBC 2020b) aimed at offering an expanded focus on materials to include not only the use of materials in buildings but also their impact on human health and the environment.

In Europe, France's E+C- (energy plus, carbon less) labelling scheme aims to encourage a life-cycle approach in achieving high-performing buildings with low embodied carbon (ADEME 2020). Also in France, the HQE (Haute Qualité Environnementale) label denotes the environmental quality of a product. Biomaterials fare well in these categories and thus are enabled by such environmental schemes. By setting carbon and energy targets for buildings and placing more focus on life-cycle thinking in regard to building design, built environment design teams are persuaded to give extra consideration to the embodied carbon and energy when selecting construction materials, and such targets in turn promote the use of bio



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KEY POLICY CONSIDERATIONS, POTENTIAL POLICY ENABLERS AND THEIR MAPPING TO THE UN SDGS







Table 3 offers suggestions of key policy considerations and potential enablers in the development of policy that can help in decarbonizing the built environment and construction process, while at the same time creating an environment that enables and supports the use of bio-based materials in addressing these concerns. Such policies are deemed necessary to encourage the effective widespread adoption and implementation of bio-based materials in the buildings sector in the Global South. Each key consideration and policy enabler is mapped to related UN Sustainable Development Goals as a means to characterize these policy considerations within a common and established framework. As illustrated in Figure 14 and itemized in Table 3, biomaterials used in the construction industry could directly contribute to 10 of the 17 SDGs.



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TABLE 3

Policy considerations and key enablers towards the production and widespread implementation of biomaterials in the construction industry of the Global South, mapped to related UN SDGs

POLICY CONSIDERATIONS	KEY ENABLERS	RELATED UN SDGS
INCENTIVES FOR THE IMPLEMENTATION OF BIO-BASED CONSTRUCTION MATERIALS		
Ensure the implementation of bio-based construction materials. Policies are needed to enable and incentivize bio-based products to be used by construction industries in the Global South.	Government incentives can encourage the adoption of bio-based materials in the buildings sector that meet set carbon and energy targets for buildings.	   
Policies are key to enable the producers of bio-based materials to establish material manufacturing industries that meet local building demand (does not need to serve a global industry).	Instruments that can help to establish local manufacturing industries include easily accessible streamlined communication that can advise and direct homeowners and building sector professionals of the best solutions and qualified workers.	   
Ensure sustainable land use in the sourcing of “raw biomaterials” for the production of bio-based construction materials. Prevent the exploitation of land for biomaterial resources and avoid generating competition for land that is marked for agricultural food production. Prevent deforestation, harmful land-use change and biodiversity loss.	The use of agricultural by-products and growing plants that help regenerate soils between cultures can encourage circular economy practices and sustainable sourcing of raw biomaterials. Where raw biomaterials are needed, incentivizing small- to medium-scale localized production of biomaterials can prevent land exploitation and competition while enabling sustainable land use. Ensure sustainable forestry practices and land-use patterns to prevent loss of biodiversity.	  
Ensure climate-responsive building design.	The use of building rating and certification systems as cross-cutting policy instruments can encourage climate-responsive building design. Examples include the adoption of EDGE (Excellence in Design for Greater Efficiencies) green building certification, which was developed by the International Finance Corporation and encourages sustainable building development, with an emphasis on emerging economies. A key focus is on resource-efficient buildings, making it an important instrument in facilitating the use of bio-based materials (EDGE 2020).	 

POLICY CONSIDERATIONS

KEY ENABLERS

RELATED UN SDGS

BUILDING REGULATIONS

Enact performance-based building standards and regulation reform.

Building codes in countries can be established or revised to allow for greater material choice towards low-embodied energy and low-embodied carbon in buildings. Such revisions would facilitate the use of biomaterials; for example, the International Code Council's (ICC) ad hoc committee on tall wooden buildings explored the building science of high-rise timber, resulting in a code change to allow for construction with mass timber of buildings up to 82.3 metres tall, to take effect with the 2021 version of the ICC building code (ICC 2018). Revisions that focus on performance rather than prescription-based standards enable the use of alternative materials (IRP 2020).



Ensure the use of construction materials that do not negatively impact human and environmental health.

Guidance in building codes, building certification systems and material passports can act as incentive mechanisms to prevent and reduce the use of toxic construction materials and those that alter the indoor air chemistry. These incentives can encourage the use of non-toxic materials (e.g., bio-resins and bio-gluing agents) that protect the health and well-being of building contractors and building occupants.



POLICY CONSIDERATIONS

KEY ENABLERS

RELATED UN SDGS

ECONOMIC INCENTIVES

Ensure that economic and market settings make it possible for new and innovative bio-based material companies to expand and support local economies.

Government funding and economic incentives to produce and use bio-based construction materials, such as tax incentives, grants and green loans by banks, can support the creation of jobs in local communities and the enhancement of local economies.



Promote sustainable public procurement.

Government incentives, such as tax incentives and promoting green public procurement, can encourage stakeholders to adjust their current choices, practices and activities towards a more circular built environment and life-cycling thinking in building design.



Ensure that funding mechanisms are in place to advance research and development of bio-based materials.

Incentives can be offered at the country level to encourage public-private partnerships towards financing innovation and applied research. This may involve research institutes working with the private sector to blend public and private finance.



POLICY CONSIDERATIONS

KEY ENABLERS

RELATED UN SDGS

TRAINING, EDUCATION AND RESEARCH

Ensure technical training, education and knowledge exchange on the construction practices and skills needed to use bio-based materials.

Key measures include relying on architects for all projects, even small scale, and ensuring that the profession is well aware of the benefits of biomaterials. This can lead to behavioural change at all stages of the building life cycle towards encouraging sustainable practices.



Ensure the continued research and development of innovation in sustainable bio-based construction materials and technologies, and promote a circular economy.

Forging partnerships and collaboration between public and private sectors is key in supporting the continued research and development of innovation in sustainable bio-based construction materials and technologies that promote a circular economy. Collaborations between industry and universities can be enabled through centres of excellence, doctoral programmes, grants and scholarships.



POLICY CONSIDERATIONS

KEY ENABLERS

RELATED UN SDGS

COMMUNICATION AND SOCIO-CULTURAL FACTORS

Address socio-cultural perceptions that often associate local biomaterials and vernacular design with undesirable or "old-fashioned" aesthetics, rather than modern or contemporary lifestyles that are often linked to concrete, steel and glass.

Steps include promoting awareness campaigns (competitions, awards, etc.) to make bio-based materials desirable and mainstream, to lift remaining doubts about their properties, resistance, lifespans and health benefits. Case studies and precedents can be used to showcase a new and modern form of "neo-vernacular" design that uses bio-based materials in climate-responsive architecture.



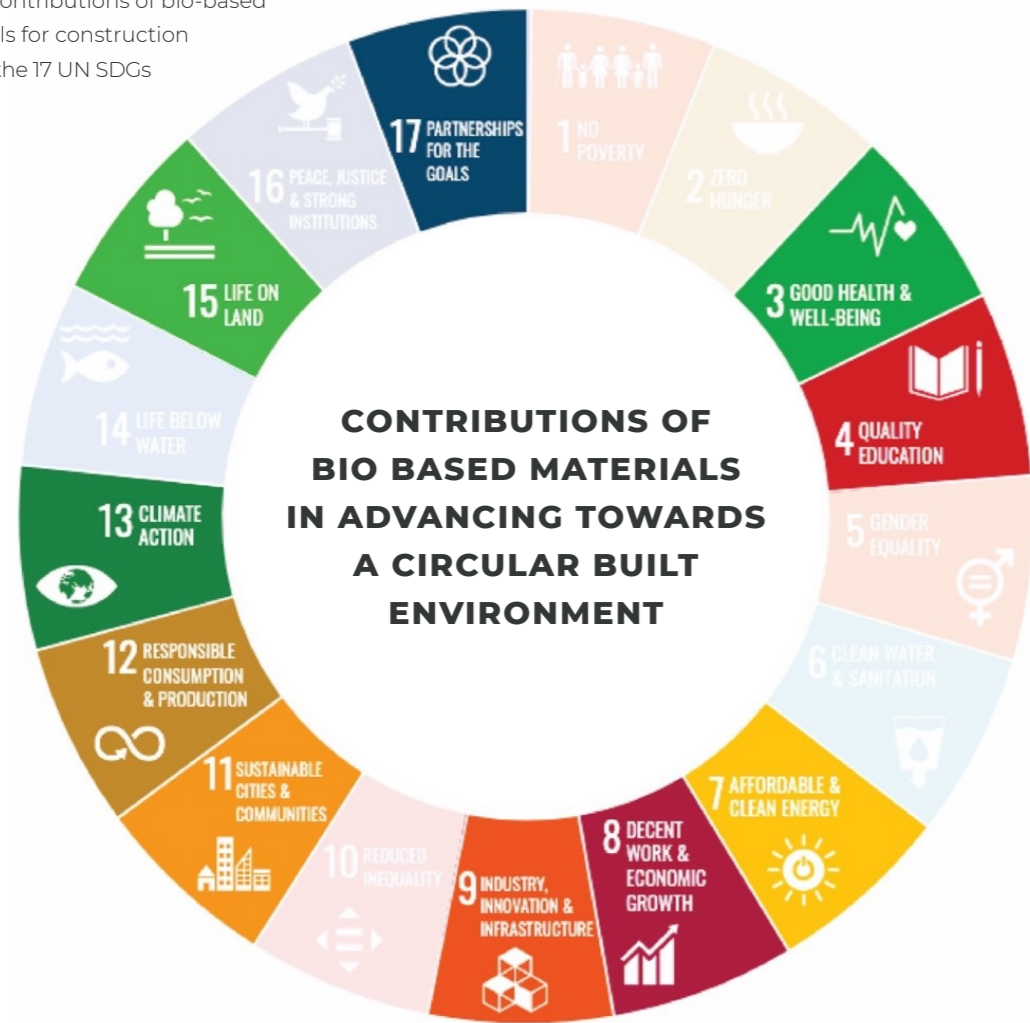
Enhance the socio-cultural perceptions of bio-based materials.

This includes promoting solutions adapted to refurbishment and also to heritage buildings, which, as visible and visited buildings, can be great examples of the use of biomaterials and vernacular design.



FIG. 14

Direct contributions of bio-based materials for construction to 10 of the 17 UN SDGs



As outlined in this study, many challenges and barriers exist towards bringing bio-based products to market. To successfully integrate biomaterials into the construction materials marketplace as a viable and widely available option, partnerships must be forged across multiple stakeholder groups, as is highlighted in Table 3 in relation to SDG 17. Key stakeholders in the process include academic and research institutions, agricultural material suppliers, producers and manufacturers, government bodies, local small and medium-size businesses, architects

and engineers, construction sector and training representatives, as well as local communities. Each of these stakeholders, from both the public and private sectors, plays a key role in facilitating the successful adoption of biomaterials in the construction sector.

The following recommendations are structured along the design, development and deployment life cycle. They focus on the potential roles of the public and private sectors at each step.

4.2

DESIGN, TESTING, PROTOTYPING AND DEMONSTRATION PHASES

These early phases typically occur within research environments. Although this research phase is generally within academia in laboratory environments, it can also take place in the research laboratories of private companies. For funding this research phase, governments can play a pivotal role in supporting applied research at the national level towards innovation in biomaterial design. Such support could be provided through grants, financing centres of excellence or other research funding.

Particularly at the prototyping and demonstration phases, public and private sector engagement is

crucial. The role of the private sector is fundamental in helping to test new products in buildings and to demonstrate “real-world” conditions, as highlighted in the first two case studies of section 3. Funding for such private sector and research institute partnerships may take the form of blended financing between the public and private sectors. As is highlighted in section 3.2.1, the demonstration phase may also involve the research entity collaborating with industrial partners and a national or regional funding organization. Following this, a market demonstration project with private sector experts is often carried out to initiate the commercialization process.

4.3

COMMERCIALIZATION, PRODUCT DEPLOYMENT IN THE MARKETPLACE AND WIDE-SCALE MARKET UPTAKE

The commercialization phase involves private sector stakeholders, ranging from material suppliers (often in the agricultural sector) to private manufacturers and small and medium-size companies that will sell the product. Private and public partnerships can also be valuable at this stage to ensure successful knowledge transfer of how the new products function and to assure proper implementation. In addition, market demonstration projects can help with knowledge transfer and encourage social engagement, awareness and ultimately adoption of biomaterials.

As seen with the ISOBIO case study in section 3.2, developing technical documentation for architectural and engineering design teams is an important step towards mainstream application of these alternative construction materials. Technical documentation

and data are also important in providing industry standards for these materials such as life-cycle assessment, embodied energy and carbon values as well as heat transfer values (e.g., U and R values). Other health-related documentation, such as material safety data sheets and material declaration forms, should be produced.

Again, this phase may involve collaboration between research institutes and the private sector. At the national level, regulatory approval of bio-based products by any federal or local regulatory agency will act as a milestone towards uptake of the manufacture, use and sale of the products. In addition, such approval would help in building trust within the industry on the use of bio-based products towards wide-scale market adoption.



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Bio-based products that promote innovative sustainable research and circular economy methodologies can help in setting standards. These standards can be used to convince policymakers. Policies can also help guide the commercialization process, especially by allowing experiments before the actual regulations are in place; otherwise, the innovation is too risky for major projects as they may not obtain insurance, and, consequently, uptake is more difficult. At the policy level, incentives for using biomaterials and low-carbon products will help these options successfully enter the construction marketplace and be competitive with traditional construction materials.

Governments at the national and local levels can use fiscal and structural incentives to promote sustainable public procurement. For example, governments may offer subsidies for the procurement of low-carbon and non-toxic construction materials for government and city-level buildings. Leading by example, these buildings can promote the use of bio-based materials. By providing stringent environmental and health criteria for material selection, governments can shift the built environment supply chain, create new opportunities for material suppliers and enable a competitive bidding process. In addition, government regulations and procurement policies can encourage circular innovation by requiring the use of low-embodied-carbon materials and zero waste in government projects. This can benefit bio-based material suppliers while setting new standards in government procurement.



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Within the construction sector, training on the successful implementation of bio-based products is critical during the commercialization and deployment phase. This training phase, supported by government or local incentives, could also be conducted by the academic research institutions or centre of excellence teams that have developed the initial prototypes and demonstrations. This will play a part in encouraging knowledge transfer.

Private sector marketing and advertising can help promote awareness of these new low-carbon materials. Creating visibility and instilling confidence in the use of such products is key to their adoption. Visibility can also be achieved through the use of biomaterials in helping to achieve numerous building ratings and certification programmes. These programmes encourage a shift towards the use of materials that benefit the environment and the health of occupants. Hence, the rating systems can also act as cross-cutting policy instruments to motivate the use of low-carbon and non-toxic construction materials. With growing demand for sustainable and healthy built environments, achieving sustainability certification or green rating for a building can be attractive and lucrative to private sector developers. This in turn can benefit biomaterials suppliers.

TABLE 4

Recommendations structured along the design, development and deployment life cycle of a bio-product

PHASE	DESCRIPTION	CHALLENGES	SOLUTIONS / ENABLERS
I DESIGN + TESTING	This research phase is typically within academia in laboratory environments; however, it can also take place within the research laboratories of private companies.	<ul style="list-style-type: none"> Funding and economic support for initial research and development, especially in local areas. Ensuring research and development in this area. 	<ul style="list-style-type: none"> Government-supported applied research. Promoting research via national government grants, the financing of centres of excellence and other research funding mechanisms.
II PROTOTYPING + DEMONSTRATION	<p>Prototyping involves developing a prototype of the material product for testing, typically in an academic laboratory (although private sector partnerships may also occur).</p> <p>The demonstration phase involves showcasing the product in a building and collecting test data. Here, public and private sector engagement is crucial.</p>	<ul style="list-style-type: none"> The need to deploy and test "real-world" scenarios. Funding for this demonstration phase. 	<ul style="list-style-type: none"> Public-private engagement towards testing new products in buildings and demonstrating "real-world" conditions. Funding for public-private partnerships, e.g., blended financing between the public and private sectors or the research entity collaborating with industrial partners and a national or regional funding organization.
III COMMERCIALIZATION	The commercialization phase involves private sector stakeholders, ranging from material suppliers (often in the agricultural sector) to private manufacturers and small and medium-size companies that will sell the product.	<ul style="list-style-type: none"> Proper implementation of new products and materials so they function as intended. Adoption of bio-based products by the building industry. 	<ul style="list-style-type: none"> Knowledge transfer between the research entity and the private sector. Documentation and industry standards, which are essential for industry adoption. Regulatory approval. Using policy-level incentives, public procurement and building rating systems to help promote the use of non-toxic and sustainable materials. Including financial mechanisms such as tax incentives to encourage the use of bio-based materials by developers and to support the early upfront cost.
IV PRODUCT DEPLOYMENT AND WIDE-SCALE MARKET UPTAKE		<ul style="list-style-type: none"> Creating awareness of bio-based construction products. Changing public perception of these materials and associating them with a contemporary sustainable lifestyle that is desirable and progressive. 	<ul style="list-style-type: none"> Using bio-based products in public buildings to help promote awareness of these materials among a wider audience, thus helping to change public perceptions and encourage broader adoption. Advertising campaigns, relying largely on private sector marketing. Incorporating these materials into government and industry catalogues and platforms on green building materials, to help create awareness of the materials.

DISCUSSION AND CONCLUSION

With many cities still yet to be built, countries in the Global South are faced with a huge opportunity to shape a sustainable future. This report explored the environmental, economic and social challenges facing current energy-intensive, mineral-based construction materials of petrochemical origin. It laid out the multi-faceted promising opportunities of biomaterials for the building sector. In addition, it highlighted the importance of taking a local and climate-responsive approach in material selection and bioclimatic design. At the same time, the report outlined the barriers and challenges that biomaterials face in entering the construction marketplace. Both the challenges and opportunities of biomaterials were investigated from multiple standpoints.

Through a series of case studies, the report explored the potential of low-carbon biomaterials as well as promising pathways for their mainstream adoption. It also outlined the need for robust sustainability criteria to ensure sustainable land-use patterns in the sourcing of “raw biomaterials” for the production of bio-based construction materials. The report warned against the potential negative impacts of scaling up biomaterials production if such sustainability criteria are not clearly adhered to. In the transition to a bio-based economy, it is vital that unsustainable practices are avoided, such as the potential exploitation of land for biomaterial resources, the generation of competition for land marked for agricultural food production, irresponsible forestry practices and deforestation, and environmentally harmful land-use change.

In the Global South, many bio-based materials are still being used, originating from vernacular architecture solutions (adobe, tach, attap, bamboo, wood, earthen bricks, etc.). However, they are losing traction and are not seen in a desirable light, despite various efforts to continue promoting them due to their many benefits. More design and innovation are necessary to support these initiatives (as illustrated by Strawtec and Willow Technologies as well as Typha, ISOBIO, Ecovative, etc.; see Annex Table 5) and to encourage more widespread understanding and adoption of these materials.

Supporting innovation and start-ups can spur new materials and designs inspired by vernacular architecture that address local cultural identity – thereby promoting bio-based materials and making them more desirable. The manufacturing of bio-based materials relies on the use of local raw materials, leading to new economic and job opportunities that are highly beneficial to supporting the UN SDGs and Covid-19 recovery plans.

Future cities of the Global South have the opportunity to become leaders in the design of circular built environments. They can set the stage for sustainable development in cities worldwide through the use of low-carbon, bio-based materials. Although material selection is just one aspect of the entire built environment process towards the advancement of sustainable cities and communities, a transition to a bio-based material economy yields contributions to 10 of the 17 SDGs and can pave the way for a greener and more sustainable future.



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ANNEX

TABLE 5

Material types, embodied carbon and carbon storage values, costs of bio-based materials compared to traditional construction materials, additional notes, and globally current companies and government research institutes in the area of bio-based materials for construction

MATERIALS	CARBON METRICS		COST / UNIT	NOTES	COMPANIES / RESEARCH INSTITUTIONS (REFERENCES)
	EMBODIED CARBON (KGCO ₂ E/KG)	CARBON STORAGE (KGCO ₂ /UNIT)			
EXTRACTIVE FOSSIL-BASED MATERIALS					
ALUMINIUM ¹	13.1	-	\$1 794 / metric ton	-	(World Bank 2020)
BRICKS ²	0.45	-	\$0.25-3.75 / unit	-	-
CEMENT (PORTLAND CEMENT) ³	0.912	-	\$123.5 / metric ton See cement ³	-	(USGS 2020)
CONCRETE ³	0.103	-	See cement ³	-	-
GLASS ⁴	1.44	-	\$6.8 / square foot	-	(National Glass Association 2010)
PLASTER BOARD ⁵	0.39	-	\$8 / metric ton	-	(USGS 2020)
POLYURETHANE FOAM ⁶	3.48	-	\$ 0.44-2.50 / board foot	-	-
STEEL (section: I-beams, H-beams, etc.) ⁷	1.55	-	\$870 / US short ton	-	(Credit Suisse 2018)
STEEL (rebar), recycled content ⁷	0.73	-	\$710 / US short ton	-	(Credit Suisse 2018)

MATERIALS	CARBON METRICS		COST / UNIT	NOTES	COMPANIES / RESEARCH INSTITUTIONS (REFERENCES)
	EMBODIED CARBON (KGCO ₂ E/KG)	CARBON STORAGE (KGCO ₂ /UNIT)			
BIO-BASED MATERIALS					
BAMBOO	0.13	-	-	Structural, interior paneling, flooring	Africa: (Muthike and Githiomi 2017; Kenya Forestry Research Institute [KEFRI] 2019; Wekesa <i>et al.</i> 2019)
LAMINATED BAMBOO BOARDS (range of MOSO products from flattened bamboo 3-ply (lowest) to veneer panel (highest) (excludes carbon storage) ⁸	1.38 to 0.62	-	-	Typically more expensive than plywood due primarily to transport costs – when used in locations where bamboo is locally found, it is more affordable.	Europe: (van der Lugt and Vogtländer 2014); MOSO ⁸ (Netherlands) (MOSO 2020)
LAMINATED BAMBOO BOARDS (range of MOSO products from flattened bamboo 3-ply (lowest) to veneer panel (highest) (includes carbon storage) ⁸	0.62 to -0.017	-0.62 to -0.63	-	-	-
BIO-MATERIAL COMPOSITE WALL PANELS (ISOBIO) ⁹			New Building Wall Panel (structural): 43.2 kg CO ₂ e/m ² Internal Retrofit System: 17.2 kg CO ₂ e/m ² External Retrofit System: 15.1 kg CO ₂ e/m ²	New Building Wall Panel (structural): €67.48/m ² (excluding VAT) Internal Retrofit System: €32.46/m ² (excluding VAT) External Retrofit System: €36.18/m ² (excluding VAT)	See section 3.2 Europe: ISOBIO ⁹ (ISOBIO 2019)
BIO-BASED RESINS (e.g., natural fibres, mycellium) ¹⁰		1.49 (POND)	-	€0.13-0.54 (POND) \$0.25-0.66 / board foot (Ecovative) Ecovative insulation comparable to structural insulated panels (SIPs)	Europe: POND ¹⁰ (Denmark) (Solar Impulse 2020a); Biohm (UK) (Card 2020) North America: Ecovative Design (Ecovative 2018); (Ellen MacArthur Foundation 2017)

MATERIALS	CARBON METRICS		COST / UNIT	NOTES	COMPANIES / RESEARCH INSTITUTIONS (REFERENCES)
	EMBODIED CARBON (KGCO ₂ E/KG)	CARBON STORAGE (KGCO ₂ /UNIT)			
BIO-BASED MATERIALS					
COCONUT	-	-	-	See section 3.1.3.4	Africa: Willow Technologies (Ghana) (Lokko 2016)
CROSS-LAMINATED TIMBER (CLT) (excludes carbon storage) ¹¹	0.44	-	-	Europe ¹¹ : CLT construction comparable to concrete and steel in Europe	Many companies in Europe and North America, as listed below (for a full list see the notes ¹¹) Europe ¹¹ : Some of the largest companies are Binderholz (Austria, Germany, Sweden), Stora Enso (Austria) and KLH Massivholz (Austria), and others such as Arvet (Sweden) that relate their CLT work to the UN SDGs. North America ¹¹ : First CLT plant is under construction.
CROSS-LAMINATED TIMBER (CLT) (includes carbon storage) ¹¹	-1.2	1.64	-	North America ¹¹ : Cost of CLT construction comparable to concrete in United States, and in some studies CLT was 0.6-1.4% cheaper.	
GRASS INSULATION MATERIAL ¹²	-	1.5	-	Lower total cost of ownership than for glass wool insulation due to a 50-year lifespan	Europe: Gramitherm ¹² (Switzerland) (Solar Impulse 2020b)
FIBREBOARD (excludes carbon storage)	0.72	-	-	-	-
FIBREBOARD (includes carbon storage)	-0.86	1.58	-	-	-
CAST HEMP-LIME (excludes carbon storage)	0.468	-	-	-	-
CAST HEMP-LIME (includes carbon storage)	-0.414	0.882	-	-	-

MATERIALS	CARBON METRICS		COST / UNIT	NOTES	COMPANIES / RESEARCH INSTITUTIONS (REFERENCES)
	EMBODIED CARBON (KGCO ₂ E/KG)	CARBON STORAGE (KGCO ₂ /UNIT)			
BIO-BASED MATERIALS					
MINERAL WOOL	1.2	-	-	Insulation material	-
STRAW / AGRICULTURAL WASTE BOARDS (includes carbon storage – data from Eco-board) ¹³	- 0.985	1.781	-	Strawtec affordable home prototypes cost \$250/m ²	Africa: Strawtec (Rwanda) (Strawtec 2019) Europe: (Kallakas et al. 2018); ECOBOARD (Netherlands) (ECOBOARD 2020) North America: Enviro Board (USA)
TYPHA	-	-	-	Earth-typha building materials, vegetable concretes, rigid panels, insulation boards and bulk, thatch	Africa: Typha Fuel Construction West Africa (TyCCAO) (Senegal and Mauritania) (Dione and Sabathié-Akonor 2019); Vegetal(e), 2019
WOOD (excludes carbon storage)	0.493	-	-	-	-
WOOD (includes carbon storage)	-1.03	1.52	-	-	-
WOODWOOL INSULATION	0.98	-	-	-	-
AUGMENTED WOOD (molecularly enhanced wood materials) ¹⁴	400 kg of CO ₂ emitted per m ³ during manufacturing and 700 kg of CO ₂ stored in the material ⁸	50% less energy needed than concrete, 1700% less than glass (Woodoo) ⁸	-	Applies nanotechnology to enhance wood at the molecular scale – removes lignin from the material's cellular scaffold and replaces it with a bio-based polymer. Translucent, weatherproof, fire-resistant, high-resistance ⁸	Europe: Woodoo ⁸ (Paris) (Solar Impulse 2020c)

ABBREVIATIONS:

\$ = US dollar

€ = euro

m² = square metre

kg = kilogram

kgCO₂e/kg = kilogram of carbon dioxide equivalent per kilogram of material

kgCO₂/unit = kilogram of carbon dioxide storage per unit of material

(-) = N/A or data not available

NOTES:

Unless otherwise indicated, all embodied carbon and carbon storage data are sourced from the Inventory of Carbon and Energy (ICE) databases (Hammond and Jones 2008; Hammond and Jones 2011; Hammond and Jones 2019) and from literature sources (Lawrence 2015; Yu, Tan and Ruan 2011). Note that these data are on a per unit weight basis; therefore, the embodied carbon and carbon storage values will vary substantially based on the amount of material used. For further explanation, see Figure 1 in section 1.3. | ¹ Cost data for aluminium reflect 2019 data, with data sourced from World Bank Commodities Price Data (World Bank 2020). | ² Based on the US market, bricks are sold in bulk with the prices for 1,000 pieces being \$250 (low), \$550 (average) and \$3,730 (high) (local US construction sector information). | ³ Cement cost data from the US Geological Survey (USGS 2020, p. 42). | ⁴ Glass costs reflect 2019 projected data in the United States for safety glass, with data from the National Glass Association (2010). | ⁵ Plasterboard or "gypsum" cost data are for 2019 and are from USGS (2020, p. 74). | ⁶ Polyurethane foam prices in the US market range from \$0.44 to \$1.50 per board square foot for spray insulation costs. Expanded foam insulation costs range from \$0.50 to \$2.50 per square foot (local US construction sector information). | ⁷ Steel costs reflect 2018 data from Credit Suisse (2018, p. 4). | ⁸ Embodied carbon and carbon storage values show the min and max of MOSO bamboo boards for multiple applications including panels and beams, flooring, outdoor decking and cladding (MOSO 2020). A full list of values can be found in van der Lugt and Vogtländer (2014, pp. 31-33). | ⁹ These ISOBIO embodied carbon numbers do not include stored carbon – studies show that with all panels, more CO₂ equivalents are stored in the biogenic content of the panels than is emitted during the panels' entire production phase (Sid 2018; Hill, Dibdiakova and Zukowska 2019). | ¹⁰ POND's Bio resin system produces 1.49 kgCO₂e/kg compared to 2 kgCO₂e/kg for polypropylene and 2.71 kgCO₂e/kg for polyethylene terephthalate (PET). Limited details of embodied carbon data and cost data are available (POND 2020). | ¹¹ CLT has many companies in Europe and North America; for a full list see UNECE 2018, p. 107 and Beck Group 2018, p. 13. UNECE 2018 also highlights a growing CLT industry in the Russian Federation. | ¹² All data describing Gramitherm come from the company website (Gramitherm 2020) and from a life-cycle assessment report (Franchi, Brouwer and Compeer 2020). | ¹³ ECOBOARD (2020) indicates life-cycle assessment values for total net balance global warming potential including the carbon storage of the straw, stating that 0.797 kgCO₂e/kg is the total embodied carbon for methylene diphenyl diisocyanate (MDI) resin, production, and packaging processes, and that the carbon storage of straw is -1.781. | ¹⁴ Woodoo data from the Solar Impulse website state 90% made from renewable resources and formaldehyde-free material; limited details of embodied carbon data and cost data are available (Solar Impulse 2020c).



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