Building for the Future

1

A Knowledge Product Collection
by Bauhaus Earth

Series 2 — Regenerative Buildings

Building with Bio-Based Materials

BAUHAUS EARTH

Supported by:

TONI PIËCH FOUNDATION

BAUHAUS EARTH

What to Expect:

As the climate crisis deepens and mineral-based materials become scarce, it is crucial to reconsider the materials with which we build and maintain our cities. This first Knowledge Product of Series 2 “Regenerative Buildings” highlights the necessity of transitioning to renewable, bio-based materials in construction.

Discover the advantages of plant-based materials, including their global availability and potential to turn buildings into carbon sinks. Learn about the barriers to their widespread adoption and explore innovative and scalable solutions to overcome them.

Rethinking Construction: The (Re)turn to Bio-Based Materials

After centuries of building with predominantly carbon-intensive, mineral-based materials such as concrete, steel, and brick, the climate crisis and the sheer finite nature of these materials are forcing us to rethink how we choose and use building materials. The (re)turn to renewable, bio-based options seems inevitable. In the past, building with bio-based materials such as wood, bamboo, or straw was common practice because these materials could be sourced locally and without much machinery. This resulted in architecture that responded to the local environment, the local climate, and local culture.

Currently, the use of bio-based materials in the construction industry is limited. In Europe, they account for only 3 per cent of the total mass of construction material[1]. However, bio-based materials have significant advantages compared to conventional materials given their carbon sequestration, substitution, and storage potential (see Knowledge Product 2 of Series 1) as well as their renewability. By promoting the knowledge of bio-based building practices, we have the opportunity to move towards a regenerative built environment. However, to mainstream these materials, we need to further explore their potential and prove their applicability in research and demonstration projects around the world.

BAUHAUS EARTH

Bio-based materials are derived from living organisms and are therefore renewable. While the term can also refer to animal biomass, it is mainly plant-based materials that are relevant in the construction sector. Bio-based materials are not necessarily biodegradable. This depends on the material's chemical structure rather than its raw material. For instance, bio-based plastics emit less CO_2 compared to conventional plastics because they are not based on fossil fuels. However, they are often not biodegradable and pose a threat to the environment. Therefore, only bio-based materials that are biodegradable after processing are presented here.

Bio-Based Building in a Nutshell

"If bio-based materials are used in buildings for longer than the amount of time that it takes for an equivalent amount of biomass to regrow, then the buildings are effectively transformed from a carbon source into a carbon sink"

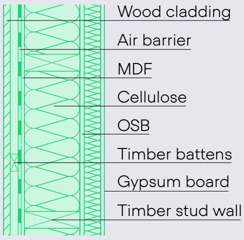
Transitioning to a variety of bio-based building materials is critical to future-proofing the built environment. Plant-based materials have a significant advantage over conventional materials. They naturally sequester carbon as they grow and store it in their biomass. In addition, their processing is generally less carbon intensive than conventional materials because no or little heat is required. As a result, bio-based materials tend to have a very low or even negative carbon footprint (see also Fig. 1: Emissions in kg CO_2 eqv. of construction materials). If bio-based materials are used in buildings for longer than the amount of time that it takes for an equivalent amount of biomass to regrow, then the buildings are effectively transformed from a carbon source into a carbon sink[2] and have a climate positive impact. Recent research shows that if 90 per cent of the world's new buildings were constructed using timber, more than 100 Gt of CO_2 could be saved by 2100[3], which is currently more than a third of our remaining carbon budget if we are to stay below the critical 1.5°C threshold[4]. This does not even take into account the substitution effect, which refers to the emissions avoided by using bio-based materials compared to conventional building materials.

Next page
Figure 1: Emissions in kg CO_2 eqv. of construction materials. Graphic based on The Construction Material Pyramid[5]

Carbon Footprint of Construction Materials

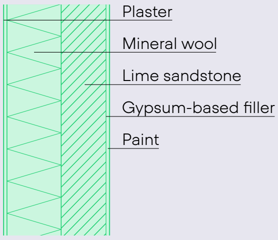
The graph illustrates material emissions per m³ during production and shows that bio-based materials tend to outperform conventional materials. However, it is important to note that materials have different properties that affect the volume and mass required to fulfil a particular purpose. When used for roofing, 1m³ of aluminium sheet can cover an area of 300m², whereas 1m³ of straw can cover only 2.5m². Although the use of aluminium in this example would still result in significantly higher emissions, it illustrates the need for careful consideration in the choice of materials. In addition, materials are rarely used in isolation: Comparing the production emissions of 1m² of wooden stud wall with cellulose insulation, a wall structure made largely from bio-based materials, with a conventional exterior wall, such as lime sandstone and stone wool, clearly shows the high emission reduction potential of bio-based construction.

Wooden stud wall and cellulose insulation

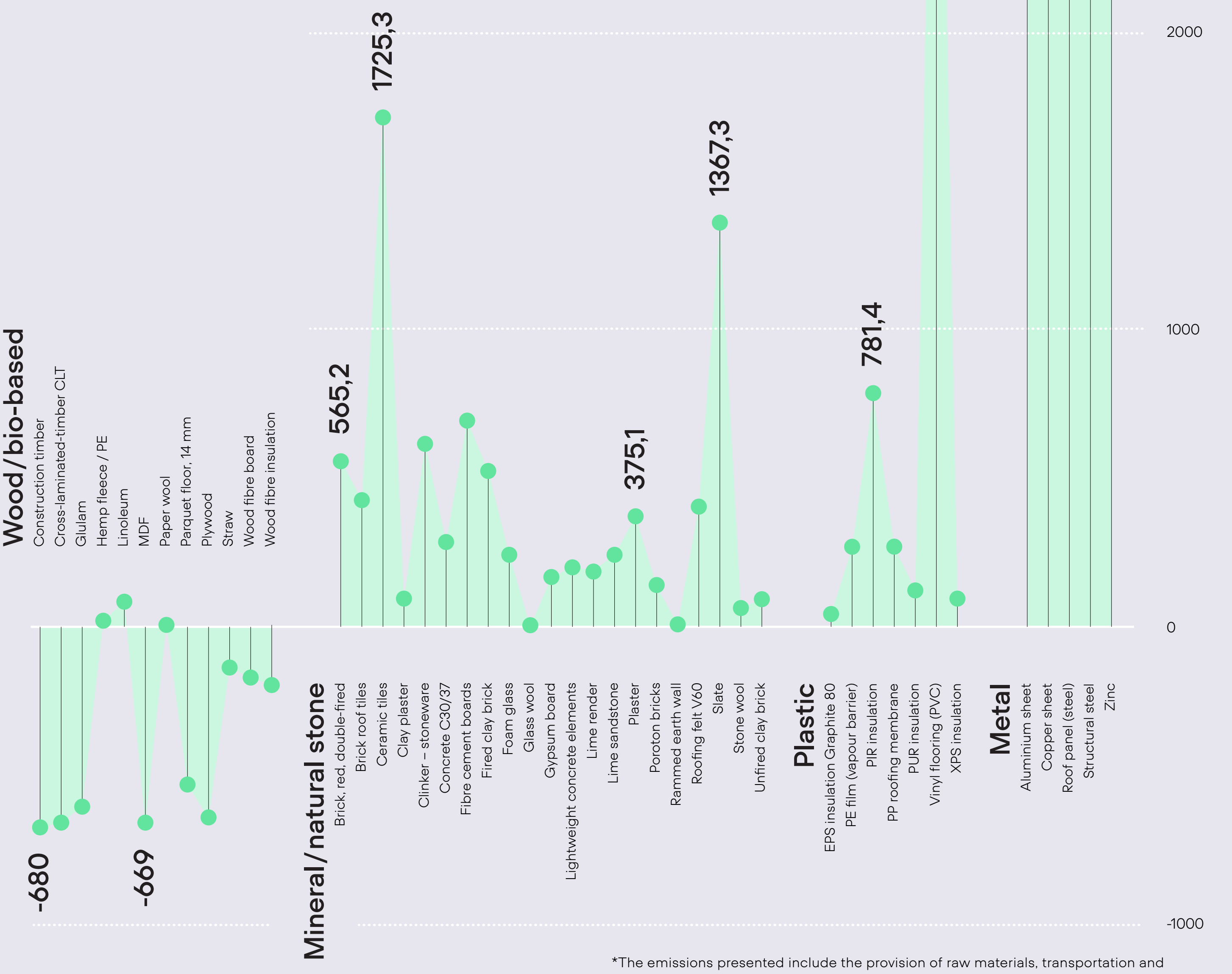


-116 kg CO_2 eqv. / m²*

Lime sandstone and stone wool



89 kg CO_2 eqv. / m²*



*The emissions presented include the provision of raw materials, transportation and manufacturing as summarised in module A1 - A3 according to the German ÖKOBAUDAT.

BAUHAUS EARTH

> “To successfully shift from concrete and steel to bio-based materials, it is important to consider a broader mix of these resources, as well as incorporate strategies for reuse and recycling.”

Beyond carbon savings, bio-based materials provide numerous advantages. They offer a wide array of benefits for human health and well-being, including the regulation of indoor humidity and stress reduction. Moreover, these materials often require less processing and less skilled labour, making them a potential source of new employment opportunities along their value chain, particularly in countries of the ‘Global South’[6].

With a vast variety available globally, this Knowledge Product highlights five key bio-based materials based on their global availability, advanced applicability, and carbon sequestration potential: wood, bamboo, Typha (which is also known as bulrush or cattail), straw, and hemp. However, this list is by no means exhaustive. Other promising materials include cork, flax, linoleum, fungi (mycelium) and many others. Clay is also frequently mentioned alongside bio-based materials. Although it is a mineral-based material, its low energy requirements, wide availability, and high recyclability are very promising for use in the construction sector.

The availability of bio-based materials will differ across regions (see fig. 2: Global availability of selected bio-based materials), so material choice should be based on factors such as local availability, specific building requirements, material properties, and land use requirements. However, to successfully shift from concrete and steel to bio-based materials, it is important to consider a broader mix of these resources[7], as well as incorporate strategies for reuse and recycling (see Knowledge Product 2 of Series 2).

Next page
Fig 2: Global availability of selected bio-based materials. Graphic based on Huang et al. (2017)[8], Langmaack et al. (2021)[6], UNEP (2022)[9] and Schumacher et al. (2020)[10]

Global availability of selected bio-based materials

Bamboo

Though technically a grass, bamboo's weight-to-strength ratio is significantly higher than that of concrete. Bamboo grows rapidly – up to 50 cm per day – and can be harvested every 3–5 years. Because of its rapid growth, bamboo can produce building materials up to 12 times faster than wood.[11] Bamboo grows mainly in tropical, subtropical and temperate climates[8].

a b c d e

Wood

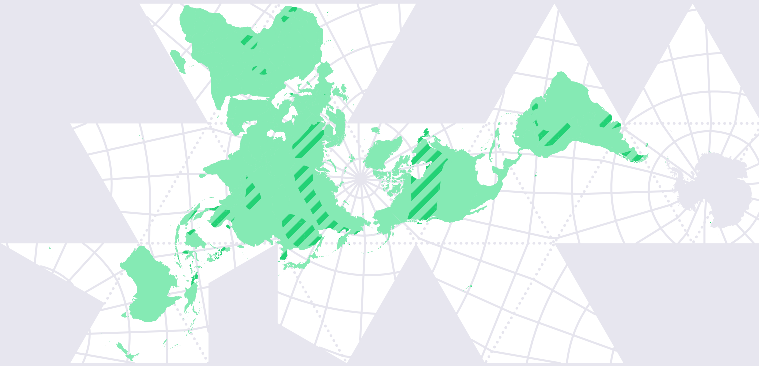
Forests grow naturally on every continent and cover about one third of the world's land area[12]. Countries with the greatest forested areas include Russia, Canada, Brazil, China, and the United States[6]. While many forests are rightly protected and should not be touched, managed forests provide building materials for a variety of uses - from load-bearing timber structures to wood fibre insulation and cladding. Compared to other bio-based materials, the growth and harvesting cycles are relatively long. Pine, for instance, has a harvest cycle of 25–30 years[13] and is still considered a fast-growing species that is commonly used in construction.

a b c d e

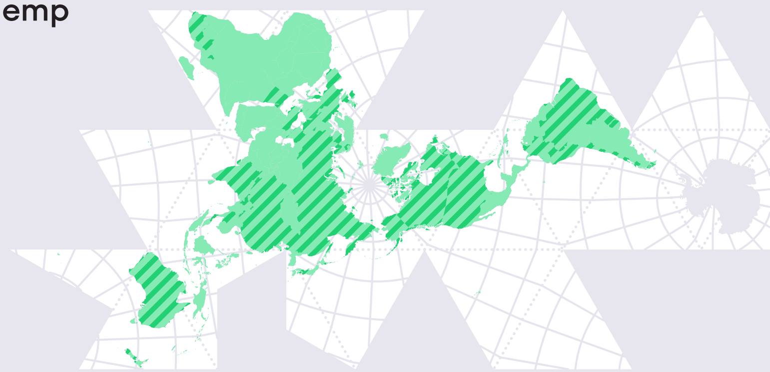
Typha

Typha, also known as bulrush or cattail, grows in peatlands in subarctic to tropical regions, the largest of which are in the northern regions of Asia, Europe and the Americas. Peatlands store twice as much carbon as the biomass of all forests combined, despite covering only 3 per cent of the world's land area.[9] The cultivation of plants from peatlands, known as paludiculture, and the added value of their use as a building material provide an incentive to maintain and expand peatlands. Typha plants can be harvested annually and produce up to 20 tonnes of dry matter per hectare per year[14].

d e



Hemp



Hemp is a versatile crop, grown for use in textiles, food, and medicine. It has recently been reintroduced as a building material with excellent insulation properties. The plant grows about 50 times faster than wood and in just 5 months, a hectare of hemp will produce enough biomass to build a small family home[15]. Although hemp would grow naturally in many parts of the world, only some countries have passed legislation to allow its cultivation, as shown on the map[10].

b c d

- a load-bearing walls
- b non-load-bearing walls
- c insulation
- d cladding
- e interior

Straw

Straw is essentially the leftover biomass from harvesting grains such as rice, wheat, and barley. While straw is therefore available wherever grains are cultivated, China, India and the USA are currently the largest producers[6]. In Germany alone, there is a surplus of approximately 20 per cent of straw produced by agriculture each year – enough to insulate up to 350,000 single-family homes[16].

a b c d

Cross-Laminated Timber (CLT) is a wood panel product made by gluing together layers of solid sawn timber at right angles to each other, creating panels that can vary in size and thickness. As a result of this manufacturing process, CLT achieves higher levels of structural rigidity and reduced shrinkage, as well as other important benefits not normally associated with wood. The strength of CLT is similar to that of reinforced concrete[19].

Glue-Laminated Timber (GLT/glulam) is a structural engineered wood product consisting of layers of timber bonded together by adhesives running in one direction. Due of the unidirectional bonding, glulam can reach enormous lengths and is often used in long span structures[20].

Tradition meets Innovation: Bio-Based Building Materials in Practice

Building with bio-based materials is nothing new, but today's processing and manufacturing techniques are opening up entirely new applications - even in high-density urban contexts. Projects around the world demonstrate the seemingly endless possibilities - from 85-metre-high mass timber buildings to 12-storey hempcrete structures. However, the use of bio-based materials is not limited to new construction; they are increasingly being used to retrofit and renovate buildings.

Timber

Wood is the most common bio-based building material and has been used in construction for more than 10,000 years[17]. In Europe north of the Alps, half-timbered buildings were the most common form of construction for a long time, while in East Asia traditional wooden skeleton buildings, characterised by a highly detailed roof construction, were widespread[18]. Much of our current knowledge of woodworking comes from this period. But these techniques were limited to building low-rise structures. However, new manufacturing techniques have resulted in new engineered wood products. Cross Laminated Timber (CLT) and Glue-Laminated Timber (GLT/glulam) have made it possible to achieve larger spans and higher load-bearing capacity, allowing timber to be used as a

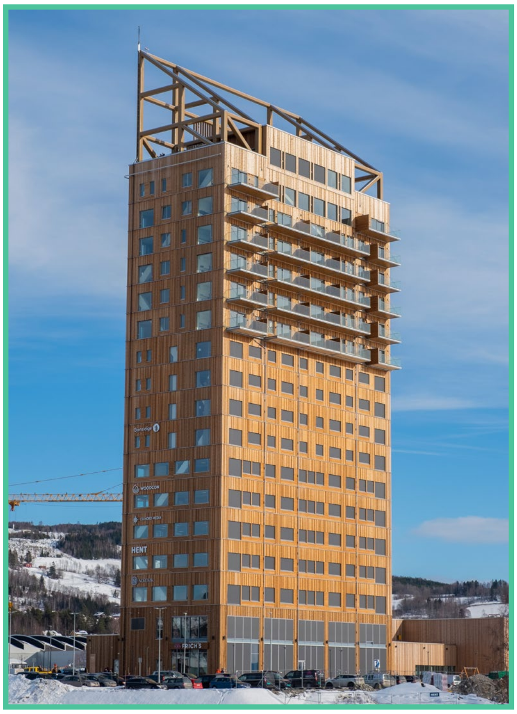


Fig. 3: Mjøstårnet

— Architects: Voll Arkitekter;
— Local Supplier: Moelven
— Completion: 2019
— Location: Brumunddal, Norway

load-bearing structure in high-rise buildings. A good example of this is the Mjøstårnet project in Norway. In addition, even untreated solid wood such as CLT or GLT has a high fire resistance because when the outer layer chars in a fire, it creates a natural protection and protects the inner layers from fire damage.

At 85,4 metres, Mjøstårnet is the highest timber building in the world. With 18 floors and a total floor area of 1050 square metres, the building houses a hotel, apartments, offices, a restaurant, and common areas. The building was constructed using sustainably sourced timber and glulam from a local supplier. The main load-bearing structure consists of external glulam trusses and internal columns and beams, giving the building the necessary rigidity. CLT walls provide secondary support for three lifts and two staircases. To speed up the construction process, certain building components, such as the timber cladding elements that make up the building envelope, were prefabricated.

Bamboo

In regions where bamboo naturally thrives, it has been a traditional practice to use the material for constructing scaffolding and rural homes. In urban settings, the use of bamboo for multi-storey construction is still rare. However, with recent advancements in technology and manufacturing techniques, this may soon change. Like wood, bamboo can now be processed and transformed into glue-laminated bamboo (also known as laminated bamboo lumber), similar to glulam. Thus, this new form of bamboo has properties that make it a potential substitute for wood in structural applications, with the added advantage of bamboo's rapid growth rate.[21] Pilot projects, such as the Arc at the Green School in Indonesia, demonstrate the great potential of bamboo in creating organic structures that respond to and embrace the local context.

Anticlastic gridshells are architectural structures with a grid-like frame and a surface that curves in two directions. This unique design ensures both strength and even distribution of forces throughout the structure.

Fig. 4: The Arc

— Architects: IBUKU
— Concept: Jörg Stamm
— Completion: 2021
— Location: Sibang, Indonesia

The Arc is the gymnasium of the Green School Indonesia and was built in just 8 months. Prior to construction, extensive research and development were conducted to create the supporting structure. Bamboo was used in such a way that allowed the material's natural strengths to shape the structure of the building. The Arc consists of a series of intersecting bamboo arches that span over 18 metres. These arches are connected by anticlastic gridshells, which derive their strength from curving in two opposite directions. This ground-breaking and novel use of bamboo resulted in an innovative spatial quality and showcased the material's versatility.

Typha

The use of Typha in construction is still niche, but nevertheless promising and slowly gaining traction. In Germany, 95 per cent of the peatlands have been drained for peat extraction and the development of agricultural land - despite their incredibly high carbon storage potential. The cultivation of Typha could help to regenerate and stabilise them. Within just two years, a Typha stock can be established on drained peatlands. When used as boards, Typha exhibits properties similar to wood fibre insulation, but with the added benefit of being significantly less energy-intensive due to its ability to dry in the air.[22]

Fig. 5: Typha boards

Fig. 6: Japanese bath in the Bora Hot Spa Resort

— Architects: studiobrunofranchi
— Completion: 2018
— Location: Radolfzell, Germany

The Japanese bath in the Bora Hot Spa Resort in Radolfzell, Germany, was developed as a wooden skeleton structure. The walls and the roof are infilled with Typha boards. They provide both the insulation and the horizontal stiffening of the walls and fulfil the necessary requirements for sound insulation and fire protection. The Typha walls are finished with lime plaster on the outside and clay plaster on the inside.

Straw

As with other bio-based building materials, the use of straw in construction is not new. Its high thermal insulation properties have made straw a popular material choice for centuries, particularly in combination with clay in half-timbered houses. With the rise of industrialised farming practices and the advent of straw bales, straw bale houses emerged - starting in Nebraska in the late 19th century[23]. With this construction method, the straw bales not only form the walls but also carry the load of the roof structure. Despite its niche existence in the past, straw has recently made a comeback due to its global availability and high carbon uptake potential[7], both in new construction with straw bales, such as single-family homes, and in retrofitting project.

In fact, there is more than enough straw to achieve the 3 per cent retrofit rate required to attain carbon neutrality in the 'Global North'[7]. While individual projects such as the Alte Brauerei in Schwerin, Germany, have successfully showcased this approach, the necessary supply chains needed for main-stream adoption are not yet in place.

Fig. 7: Straw insulation

Fig. 8: Alte Brauerei

— Architects: Schelfbauhütte
— Completion: Under Construction
— Location: Schwerin, Germany

With 22 buildings – some traditional brick houses, others concrete buildings from the German Democratic Republic (GDR) era – the Alte Brauerei, an old brewery in Schwerin, Germany, is the largest project in Europe using straw for thermal retrofitting. The straw was sourced locally and used in bales as external insulation. The bales were 36 cm thick, which was sufficient to achieve passive house standards. The bales were mounted with holders from recycled plastic designed and manufactured specifically for this project. The previously vacant site is now home to around 200 residential and commercial units, including doctors' offices and assisted living.

Hemp

Although hemp is best known for its use in rope and textiles, it has also been utilized in construction for over 1,500 years. Researchers have found hemp fibres in a bridge from this period[4]. Today, despite its long history and versatile applications, hemp faces many prejudices. In many parts of the world, its cultivation is still illegal due to its close association with marijuana.

However, there are two varieties of the plant Cannabis sativa. Compared to marijuana, hemp has much lower levels of THC (tetrahydrocannabinol), which causes psychoactive effects[25]. Nevertheless, the benefits of hemp as a crop and building material are gaining recognition. Hemp building products include hemp fibre insulation and hempcrete, a mixture of hemp shives, the by-products of fibre production, and lime. Hempcrete comes in a variety of forms, from plaster to blocks, as demonstrated in the 84 Harrington Street project.

Fig. 9: Hempcrete blocks

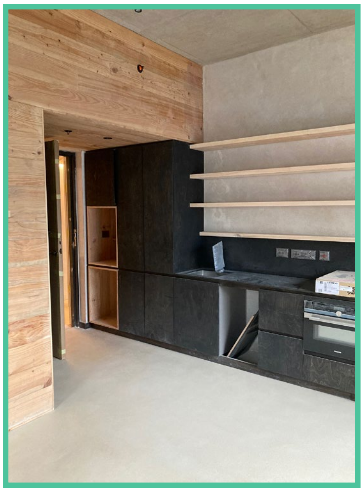


Fig. 10: 84 Harrington Street

— Architects: Wolf & Wolf Architects
— Location: Cape Town, South Africa
— Completion: Under construction

The 12-storey building at 84 Harrington Street in Cape Town is the tallest building in the world to be constructed using hempcrete blocks and other hemp materials. The building will house a flagship store showcasing the versatility of hemp, a restaurant, and a hotel where visitors can experience hempcrete first hand. Although the use of hempcrete is not entirely new in the South African context, a building of this scale required the use of hempcrete blocks as infill, demonstrating the applicability of hempcrete in buildings of this scale. Due to the load bearing limitations of the hempcrete blocks, the building has a conventional structural frame.

Overcoming Challenges in Building with Bio-Based Materials

Bio-based building materials have numerous advantages, and their wide applicability is being successfully demonstrated in projects worldwide. However, the industry is still relatively new and faces many barriers that limit the widespread adoption of bio-based building materials. These challenges include the issue of higher costs, incomplete supply chains, restrictive regulations, misconceptions and concerns about safety and durability, and a lack of technical expertise among many architects and professionals. Nevertheless, there are several innovative approaches and initiatives aimed at overcoming these challenges and promoting the use of bio-based materials in the construction sector. The table below highlights some of the key challenges and promising ways forward.

TYPE OF CHALLENGE	DESCRIPTION OF CHALLENGE	INNOVATIVE APPROACHES AND INITIATIVES
FINANCING	Currently, many bio-based building materials are more expensive than conventional materials due to the lack of established markets and supply chains. The up-scaling of production is hampered by, for example, high up-front costs associated with developing new standards and obtaining certification.	In Europe, the Triodos Bank offers a 'bio-based mortgage' that aims to increase demand and make bio-based materials more competitive by offering lower interest rates for bio-based buildings. Based on the Dutch 'Environmental Performance of Buildings', the bank assesses the environmental impact of the materials used in buildings and calculates the interest rate of a mortgage based on this assessment[26]. Carbon trading schemes could be another way of offsetting the cost of bio-based materials. Companies such as Credible Carbon sell carbon credits from smaller projects that measurably reduce carbon emissions, allowing them to balance any additional costs[27].
POLICY AND REGULATORY ENVIRONMENT	Many bio-based materials currently have no or incomplete standards and codes for their use in construction[7], which can take several years to develop[28]. In Germany, for example, fire regulations hinder the wider use of bio-based materials, making it complicated to use them for insulation in buildings higher than three storeys.	In France, from 2022, all new public buildings must be built with at least 50 per cent bio-based materials[29], while Finland is aiming for a 45 per cent share in public construction by 2025[30]. Such policies will boost the portfolio of bio-based buildings, encourage investment in the industry, and ultimately make it more affordable to build with bio-based materials. For bamboo, the International Organization for Standardization has recently developed a standard for the design of load-bearing structures using round bamboo[31]. Countries with local bamboo resources, such as China, Colombia, Ecuador, India, and Peru, have taken the lead in developing building codes and standards, providing a valuable resource for adoption elsewhere[32].
AVAILABILITY OF BIO-BASED MATERIALS	The transition from conventional to bio-based building materials requires a solid knowledge base on the extent to which future urban construction and retrofitting demands can be met by sustainably managed and ideally regionally available bio-based materials, while considering conflicting interests and competing sectors. However, information on the extent to which supply and demand can be matched at a global level is scarce and sometimes contradicting[2,33]. At the regional level, there is often a lack of knowledge about the potential availability of different types of bio-based materials, and thus a lack of evidence-based transition scenarios.	The Climate Smart Forest Economy Programme has developed a methodology to assess the supply and demand of bio-based materials within a given region[34]. Bauhaus Earth will further develop and refine this methodology, taking into account a range of regionally available bio-based materials as well as competing land claims and urbanisation dynamics.
PERCEPTION AND CULTURAL ACCEPTANCE	There is a perception problem with bio-based building materials. In many countries around the world, people often associate locally available bio-based building materials such as bamboo, wood or straw with primitiveness and poverty, or have misconceptions about safety - especially fire safety. In addition, industry professionals often believe that bio-based construction is inevitably the more expensive option, which limits their confidence in using such materials[35].	The Timber Perception Lab seeks to understand and actively address the perceptual and cultural barriers to the uptake of mass timber in the construction industry through demonstration projects, collective learning, and a strategic communications strategy involving stakeholders along the timber value chain including developers, investors, cities, designers, insurers, and asset owners[36].
KNOWLEDGE AND SKILLS	The uptake of bio-based materials is often hampered by a lack of technical skills and knowledge among architects, building professionals, and contractors. There is a great deal of uncertainty about, for instance, thermal performance, potential durability issues, or susceptibility to insect infestation, which often leads to decisions to continue using the perceived 'safer' conventional material[37].	The German Informationsdienst Holz provides an overview of timber construction projects and publications and offers free assistance in planning and building with wood – from design questions to the detailing of individual elements[38]. In Indonesia, the education company Bamboo U offers online courses on bamboo design and sustainable architecture to enhance knowledge and skills in building bamboo structures[39]. While these are important sources of information, they are often scattered and difficult to find. A global knowledge centre or one-stop-shop that brings together such information and provides support and assistance would be a useful way forward.

Embracing a Bio-Based Future

As we set out to transform the construction industry, bio-based materials are an essential component of a regenerative built environment and key to solving the climate crisis. Despite obstacles such as finance and regulations, ground-breaking solutions are emerging. By harnessing the benefits of bio-based materials and gaining a deeper understanding, we can unleash their complete potential and construct a more regenerative future.

However, building with bio-based materials is not enough. To fully harness their ability to mitigate climate change, we must improve the use and maintenance of the existing building stock and implement strategies for reuse and recycling to prolong the life cycle of building materials. The upcoming Knowledge Product 2 of Series 2 "Regenerative Buildings" emphasizes the importance of circular practices within the building industry.

KEY TAKEAWAYS

→ Bio-based building materials can sequester, substitute, and store carbon, making them a powerful lever for climate change mitigation.

→ To ensure that the harvesting of bio-based materials does not exceed their regenerative capacity, the transition must be based on a variety of sustainably sourced bio-based materials.

→ Using bio-based materials alone is not enough. It's important to also prioritize the optimal use and maintenance of existing buildings and implement strategies for reusing and recycling materials to extend their lifespan.

→ Wood, bamboo, Typha, straw, hemp, and other bio-based materials all have unique properties and can be used in construction in different ways. Careful consideration should be given to regional availability and technical requirements.

→ While building with bio-based materials is not new, it is crucial to update traditional techniques and develop new ones to meet current needs. Valuable insights can be gained from existing projects.

BAUHAUS EARTH

References

1 Cardellini, G., and J. Mijnendonckx. "Synergies, Energy Efficiency and Circularity in the Renovation Wave - Bio-Based Products for the Renovation Wave." *European Organization for Nuclear Research*, June 17, 2022. doi: 10.5281/zenodo.6530825.

2 Churkina, G., A. Organschi, C. P. O. Reyer, A. Ruff, K. Vinke, Z. Liu, B. K. Reck, T. E. Graedel, and H. J. Schellnhuber. "Buildings as a Global Carbon Sink." *Nature Sustainability* 3, no. 4 (January 27, 2020): 269–76. doi: 10.1038/s41893- 019-0462-4.

3 Mishra, A., F. Humpen.der, G. Churkina, C. P. O. Reyer, F. Beier, B. L. Bodirsky, H. J. Schellnhuber, H. Lotze-Campen, and A. Popp. "Land Use Change and Carbon Emissions of a Transformation to Timber Cities." *Nature Communications* 13, no. 1 (August 30, 2022). doi: 10.1038/s41467-022-32244-w.

4 Mercator Research Institute on Global Commons and Climate Change (MCC). "Remaining Carbon Budget." Accessed April 20, 2023. https://www.mccberlin.net/en/research/co2-budget.html.

5 The Construction Material Pyramid. "Byggeriets Materialepyramide." Accessed April 03, 2023. https://www.materialepyramiden.dk/.

6 Langmaack H., P. Scheibstock, S. Schmuck, and T. Kraubitz. *Climate and Employment Impacts of Sustainable Building Materials in the Context of Development Cooperation.* Bonn: Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH, 2021.

7 Göswein, V., J. H. Arehart, C. Phan-Huy, F. Pomponi, and G. Habert. "Barriers and Opportunities of Fast-Growing Biobased Material Use in Buildings." *Buildings & Cities* 3, no. 1 (January 1, 2022): 745–55. doi: 10.5334/bc.254.

8 Huang, Z., Y. Sun, and F. Musso. "Assessment on Bamboo Scrimber as a Substitute for Timber in Building Envelope in Tropical and Humid Subtropical Climate Zones - Part 2 Performance in Building Envelope." *IOP Conference Series: Materials Science and Engineering* 264 (November 1, 2017): 012007. doi: 10.1088/1757-899x/264/1/012007.

9 UNEP. *Global Peatlands Assessment – The State of the World's Peatlands: Evidence for action toward the conservation, restoration, and sustainable management of peatlands. Summary for Policy Makers.* Nairobi: Global Peatlands Initiative, United Nations Environment Programme, 2022.

10 Schumacher, A. G. D., S. Pequito, and J. A. Pazour. "Industrial Hemp Fiber: A Sustainable and Economical Alternative to Cotton." *Journal of Cleaner Production* 268 (September 1, 2020): 122180. doi: 10.1016/j.jclepro.2020.122180.

11 Yadav, M., A. Jain and P. Mathur. "Bamboo as a Sustainable Material in the Construction Industry: An Overview." *Materials Today: Proceedings* 43 (January 1, 2021): 2872–76. doi: 10.1016/j.matpr.2021.01.125.

12 Sobek, W. *Non Nobis – Über das Bauen in der Zukunft: Ausgehen von dem was man hat*. Stuttgart: AVEdition, 2022.

13 Forests NSW. "The Pine Plantation Rotation." Accessed April 03, 2023. https://www.forestrycorporation.com.au/.

14 Fraunhofer Institute For Building Physics IBP. *Innovative Construction with Cattail as Raw Material.* Valley: 2023.

15 Hanfsteine - Hanfputze - Hanfmörtel. "Bauen mit Hanf!" Accessed April 03, 2023. https://www.hanfstein.eu/

16 Fachagentur Nachwachsende Rohstoffe. *Strohgedämmte Gebäude*. 2nd ed., 2017.

17 International Timber. "Timber: The Past, Present and Future." September 21, 2020. Accessed April 03, 2023. https://internationaltimber.com/resources/timber-the-past-present-and-future/.

18 BauNetz. "Geschichte des Holzbaus." Accessed April 03, 2023. https://www.baunetzwissen.de/holz/fachwissen/einfuehrung/geschichte-des-holzbaus-6640622.

19 naturally:wood. "What Is Cross-Laminated Timber (CLT)?" March 16, 2022. Accessed April 03, 2023. https://www.naturallywood.com/products/cross-laminated-timber.

20 naturally:wood. "What Is Glue-Laminated Timber (Glulam)?" September 3, 2021. Accessed April 03, 2023. https://www.naturallywood.com/products/glulam/.

21 Xiao, Y. J., R. Yang, and B. Shan. "Production, Environmental Impact and Mechanical Properties of Glubam." *Construction and Building Materials* 44 (July 1, 2013): 765–73. doi: 10.1016/j.conbuildmat.2013.03.087.

22 Gebäudeforum. "Rohrkolben (Typha)." Accessed May 5, 2023. https://www.gebaeudeforum.de/realisieren/baustoffe/nachwachsende-rohstoffe/rohrkolben-typha/.

23 Mutani, G., C. Azzolino, M. Macri, and S.Mancuso. "Straw Buildings: A Good Compromise between Environmental Sustainability and Energy-Economic Savings." *Applied Sciences* 10, no. 8 (April 20, 2020): 2858. doi: 10.3390/app10082858.

24 Bedlivá, H. and N. Isaacs. "Hempcrete – An Environmentally Friendly Material?" *Advanced Materials Research* 1041 (October 1, 2014): 83–86. doi: 10.4028/www.scientific.net/amr.1041.83.

25 Visković, J., V.D. Zheljazkov, V. Sikora, Jay S. Noller, D. Latković, C. Ocamb, and A. Koren. "Industrial Hemp (Cannabis Sativa L.) Agronomy and Utilization: A Review." *Agronomy* 13, no. 3 (March 21, 2023): 931. doi: org/10.3390/agronomy13030931.

26 Triodos Bank. "Triodos Bank has First Bio-Based Mortgage." June 8, 2022. Accessed June 21, 2023. https://www.triodos.com/en/articles/2022/triodos-bank-netherlands-has-first-bio-based-mortgage.

27 Credible Carbon. "The Carbon Offsetting Process | How Does It Work? | Credible Carbon," August 29, 2023. Accessed May 23, 2023 https://www.crediblecarbon.com/the-process/.

28 Vrins, M. "Standards and Regulations for the Bio-Based Industry: Report on Implementation for Creation of New or Revised Standards." *STAR4BBI*, 2018. https://wpn.acceptatie.nen.nl/app/uploads/sites/11/2019/05/STAR4BBI_WP4_D4.3_Final-Report.pdf.

29 Fabris, P. "France to Mandate All New Public Buildings be 50% Timber or Other Natural Materials." *Building Design + Construction,* March 5, 2020. Accessed April 03, 2023. https://www.bdcnetwork.com/france-mandate-all-new-public-buildings-be-50-timber-or-other-natural-materials.

30 Ministry of the Environment. "Wood in Public Construction." Accessed April 03, 2023. https://ym.fi/en/wood-in-public-construction.

31 International Organization for Standardization "ISO 22156:2021(en): Bamboo structures – Bamboo culms – Structural design" June, 2021. Accessed June 21, 2023. https://www.iso.org/obp/ui/#iso:std:73831:en.

32 Gatóo, A., B. Sharma, M. Bock, H. Mulligan, and M. H. Ramage. "Sustainable Structures: Bamboo Standards and Building Codes." *Proceedings of the Institution of Civil Engineers* 167, no. 5 (October 1, 2014): 189–96. doi: 10.1680/ensu.14.00009.

33 Pomponi, F., J. Hart, J. H. Arehart, and B. D'Amico. "Buildings as a Global Carbon Sink? A Reality Check on Feasibility Limits." *One Earth* 3, no. 2 (August 21, 2020): 157–61. doi: 10.1016/j.oneear.2020.07.018.

34 CSFEP. "CASSA." Accessed April 03, 2023. https://www.csfep.org/our-work-cassa.

35 Markström, E., A. Bystedt, M. Fredriksson, and D. Sandberg. "Perceptions of Swedish Architects and Contractors for the Use of Bio-Based Building Materials." *New Horizons for the Forest Products Industry. 70th Forest Products Society International Convention,* Madison: Forest Products Society, 2016. http://ltu.diva-portal.org/smash/record.jsf?pid=diva2:1045840.

36 Timber Perception Lab. "About." Accessed April 03, 2023. https://timberperceptionlab.org/en/.

37 Dams, B., D. Maskell, A. Shea, S. Allen, V. Cascione, and P. Walker. "Upscaling Bio-Based Construction: Challenges and Opportunities." *Building Research and Information*, April 30, 2023, 1–19. doi: 10.1080/09613218.2023.2204414.

38 Informationsdienst Holz. "Willkommen beim Informationsdienst Holz." Accessed April 03, 2023. https://informationsdienst-holz.de/.

39 BambooU. "Bamboo U." Accessed June 15, 2023. https://bamboou.com/.

BAUHAUS EARTH

About Bauhaus Earth

We envision a future where buildings, cities, and landscapes proactively contribute to climate restoration and have a positive impact on the planet and its inhabitants. Our mission is to transform building and human settlements from a driver of climate and societal crises into creative forces for systemic regeneration.

Only a complete systemic overhaul of our built environment will prevent a global climate catastrophe.

The Knowledge Product Collection “Building for the Future” is an ongoing project. The present publication is part of Series 2: “Regenerative Buildings.”

Impressum

Supported By:

TONI PIËCH FOUNDATION

Published by:
Bauhaus der Erde gGmbH

Peschkestr. 13 – 12161 Berlin
Amtsgericht Charlottenburg HRB 224356B

Prof. Dr. mult. Hans Joachim Schellnhuber
Prof. Dr. Philipp Misselwitz

www.bauhauserde.org
contact@bauhauserde.org

Authors:
Johanna Westermann, Franziska Schreiber, Eva-Maria Friedel, Christian Gäth (Bauhaus Erde)

Review:
Jonas Hiller (Toni Piëch Foundation)

Editing:
Aseman Golshan Bahadori (Bauhaus Erde)

Design & Layout:
www.sans-serif.de

Graphics:
All graphics by © Mule Studio

Images:
Fig. 3: © Moelven, Fig. 4: © Tommaso Riva, Fig. 5: © kuhnle + knödler fotodesign, Fig. 6: © Bruno Franchi, Fig. 7+8: © Schelfbauhütte, Fig. 9+10: © Bauhaus Erde

Berlin, 2023

Building for the Future
ISSN 2941-7171