BuildingGreen

SPOTLIGHT REPORT

The Promise of Biobased Materials—And How to Use Them Now

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About BuildingGreen

BuildingGreen is an independent consulting and publishing company committed to providing accurate and timely information to help building industry professionals and policymakers improve the environmental performance and reduce the adverse impacts of buildings. Our purpose is to foster a thriving and equitable world through a regenerative and resilient built environment. To this end, BuildingGreen facilitates collaboration, learning, and trust to accelerate the transformation of the building industry into a force for positive change.

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The Promise of Biobased Materials—and How to Use Them Now

There is a lot of hype over carbon storage and other benefits of natural materials, but their potential is real. Here are some that are ready for prime time—and the ones we hope will take off next.

by Brent Ehrlich

Before petrochemicals, our buildings were made primarily from local, natural materials, making the most of the resources at hand. We had a circular economy—using and reusing high-value goods until they fell apart completely and became valuable fertilizer for future high-value goods—by necessity. The embodied carbon of these natural materials was minimal. Their production and use supported entire communities. And the buildings made from them reflected the natural surroundings and connected people to the land.

The steel, concrete, plastic, and other synthetic products that replaced these natural mainstays came to symbolize progress. And they did usher in our modern era of cheap, durable, and sometimes beautiful buildings. But this progress has come at significant carbon, environmental, social, and health costs. These high-embodied carbon synthetic materials are some of the biggest carbon emitters. Now, faced with the impacts of pollution and climate change, our love affair with them seems to be waning, and there is a renewed interest in natural, low-carbon, biobased alternatives that are not just "carbon neutral" but can actually store carbon.

Where does the hype meet reality?

In this report, we look at which natural alternatives can truly fight climate change, focusing on their benefits, limitations, and future possibilities.

Photo: MASS and Iwan Baan

MASS Design Group uses local natural and biobased materials throughout its buildings, supporting local communities and merging contemporary and traditional building practices.

Biobased: Animal, Vegetable, or Mineral?

Many of our building products are made from abundant natural materials. Some are plant based, while others are mineral. A scant few are of animal (or even fungal) origin.

Portland cement comes from limestone. Brick from clay and minerals. And steel from iron ore. These geological raw materials are usually manufactured with fossil fuels, creating products with high *embodied carbon* (the greenhouse gas emissions associated with products, materials, and construction). Though natural, they are not low carbon.

They are also not biobased—which is also true of minimally processed, non-

renewable materials like natural stone. The ability to re-grow something is at the heart of the definition of "biobased," according to the U.S. Department of Agriculture (USDA), which states that biobased components are "derived from raw materials such as plants and other renewable agricultural, marine, and forestry materials."

Biobased is a broad definition, however, which can refer to highly processed compounds used as substitutes for similar synthetic compounds. Examples include plant-derived chemicals used in plastics or lubricants, enzymes used as chemical catalysts, and more.

Some biobased materials have the potential to significantly reduce the embodied carbon of our buildings by replacing those conventionally made from fossil fuels, reducing the other environmental, socioeconomic, and health impacts of petrochemical production. But these materials are not always perfect either. Some biobased materials come from agricultural or forestry practices that are harmful to people and the environment (such as deforestation or using genetically modified crops) and have nothing to do with reducing carbon.

And the biobased compounds found in some plastics, such as spray polyurethane foam (SPF), often make up a small percentage of the overall material. In SPF, the biobased portion is added to only one of the products two components—the polyol—that react with the isocyanate to create the SPF. That means the final "biobased" product is still a plastic foam with the same manufacturing and onsite health risks from the *isocyanate*, which is known to cause or exacerbate asthma and chemical sensitivities in some people who are exposed.

In theory, biobased materials are less toxic during use, and they decompose at the end of their lifespan. But most biobased plastics are not biodegradable. Those plant-based materials that are biodegradable need to be protected from decomposition by chemicals that manage moisture intrusion, prevent UV damage, kill pests and organisms of decay, and suppress fire.

Such chemicals include biocides such as boric acid. Borates are natural compounds and are used to protect cellulose and many other biobased products from fire and pests, but they are also potential endocrine disruptors and reproductive toxicants when workers and others are chronically exposed at high doses. There is no free lunch for some product categories, so design teams may have to choose a product with a higher global warming potential (GWP), such as mineral wool, if they want to avoid flame and pest retardants altogether.

Other biobased products also come with health and environmental risks. For example, to protect wood cladding from moisture and light, acrylic latex coatings are applied and reapplied over decades of use. Low-VOC paint may seem benign nowadays in comparison with the lead-based coatings of the past, but acrylic latex is contributing to microplastic pollution while also complicating our ability to reuse or recycle the "natural" cladding it protects.

Biobased Equals Low Carbon, Right?

We've used wood building materials for years. They're biobased, so they store carbon, making those products carbon neutral or even carbon negative—especially when compared with concrete and steel. Right?

The reality is more complicated, as BuildingGreen's two-part series on the climate impact of wood products explains in depth. The issues surrounding wood and other biobased materials are complex. Wood's embodied carbon depends on many factors, including (but certainly not limited to):

USDA BioPreferred: Biobased Content, Not Sustainability

The U.S. Department of Agriculture certifies products, including building products, as biobased through its USDA BioPreferred program.

Listed products have to contain a certain percentage of biobased content, which is calculated using the ratio of biobased carbon to total carbon (biobased + fossil carbon). ASTM D6866 is the test method used to calculate this ratio. Water, non-carbon elements like nitrogen and silicon, and *inorganic carbon*—which is found in limestone, iron ore, and other carbonates—are excluded from the calculation. There are no substantive sustainability criteria beyond biobased content.

To be considered USDA BioPreferred, products need to hit a certain threshold of biobased content, a threshold that varies depending on the product type. A BioPreferred foam insulation or carpet, for instance, only needs to have 7% biobased content, while a countertop has to have 89%.

Those products that undergo third-party testing can be labeled *USDA Certified Biobased*. There are currently 139 BioPreferred product categories.

The USDA instituted the BioPreferred program to promote agricultural products, including soy and corn, and the chemicals made from them. Though the program has the potential to encourage the development of innovative binders and other materials, using it to assess building products should be done with a very large grain of salt. For example, the BioPreferred program does not include inorganic glass in its calculations, only the resin, so a fiberglass insulation that uses a biobased resin might

continued

- Forest type and tree species
- How and where the trees have grown
- Amount of time between harvest cycles
- Harvesting practices (e.g., clearcutting, soil disturbance)
- Durability and longevity of all the products made from the wood

Even with robust industry backing, international standards, and an increasing number of life-cycle assessments (LCAs) and environmental product declarations (EPDs) available for scrutiny, the carbon data associated with wood products are still rife with uncertainty.

Hemp, straw, bamboo, and other biobased materials—as well as the products made from them—have similar challenges, but have the advantage of being rapidly renewable, somewhat simplifying the long-term carbon accounting associated with forestry practices.

"Biobased shouldn't be used synonymously with low carbon," according to Lindsay Baker, CEO of the International Living Future Institute (ILFI), developer of the Living Building Challenge, the Zero Carbon certification, and other programs.

That's because, in many cases, we just don't know a material's carbon footprint. Currently we look to EPDs for that carbon data, but only a handful of biobased products have them. The reasons for that vary, but some of these products are made by small companies that cannot afford to commission third-party life-cycle assessments. Many have not scaled production to meet mass demand. Some materials, such as straw bales, might not even be marketable products. Without

advertise 98% biobased content, when that clearly isn't the case for the product as a whole. But products meeting the program's requirements are eligible for the U.S. government's Mandatory Federal Purchasing Initiative, making the label useful for manufacturers using biobased materials trying to reach a larger market.

Photo: Arkin Tilt Architects

Straw can create carbon-storing, but thicker, wall systems with excellent thermal performance and fire resistance, without the use of fire retardants.

carbon and performance metrics, many of our most viable biobased materials are eschewed for commercial use.

EPDs for biobased products: two paths to "carbon neutral"

As with wood products, getting accurate carbon data for materials like straw and bamboo is challenging. It doesn't help that there are two different ways of expressing how carbon gets sequestered in plants, stored in products, and eventually released back into the atmosphere. These two approaches are known in shorthand as *–1/+1 and 0/0.*

The "0/0" methodology assumes that, as long as a plant or other living thing is replaced (for example, a cornfield is harvested annually and replaced with new corn), any biogenic carbon sequestered and stored is eventually released, making the material carbon neutral—with no atmospheric impact. "The 0/0 method is not generally considered a standard practice because that can become a little deceptive," said Amlan Mukherjee, sustainability director at WAP Sustainability who chaired the American Center for Life Cycle Assessment (ACLCA) subcommittee on biogenic carbon from 2022 to 2023. That's largely because 0/0 cannot capture the important nuances of a product's carbon impacts.

"Minus-one/plus-one is the important one because that's what ISO 21930 requires," according to Mukherjee. That standard governs how manufacturers report the impacts of their products on an EPD.

The ACLCA explains the +1/–1 approach in its guidance on applying ISO 21930. Reporting on CO_2 storage is based on rapidly renewable biobased materials and is "calculated based on the biogenic carbon content of the raw materials used to manufacture the product." ISO 21930 assumes CO_2 has been removed from the atmosphere through the natural process known as *sequestration* and is now stored in the biomass as biogenic carbon.

Because of this removal of carbon, products at the beginning of their life cycles—from the "cradle" of growth and harvesting to the "gate" of the factory—are assigned a value of –1 kg CO_2e/kg CO_2. In other words, a negative number gives the product credit for sequestering carbon. But the biogenic carbon in

Glossary

Biomass: organic material derived from living things.

Biobased: derived from biomass.

Biogenic carbon: carbon produced by living plants and other organisms.

Environmental product declaration (EPD): a summary of a product LCA that can be either industry specific (for an entire product category) or product specific (for a specific brand). A Type III EPD follows ISO protocols and is third-party verified. An EPD typically provides data on ozone depletion, global warming potential, acidification, eutrophication, ground-level ozone (smog), and fossil fuel depletion.

Fossil carbon: ancient biogenic carbon that's been transformed by geological processes over hundreds of millions of years.

Life-cycle assessment (LCA): a third-party-verified process that quantifies the environmental impacts of a product from raw material extraction through manufacture ("cradle to gate") or disposal ("cradle to grave"). The results of the LCA include impact assessments across a set of environmental impact categories, including embodied carbon. An LCA is the basis for a product's environmental product declaration.

Product category rules (PCRs): the guidelines that each LCA follows, helping to ensure consistent data across each product category. PCRs are developed through stakeholder engagement, and in the U.S. they follow ISO 14025 when used for EPDs.

Rapidly renewable: able to regenerate in ten years or less.

Time value of carbon: the relative importance of near-term greenhouse gas emissions, based on the recognition that only rapid decarbonization of the global economy can prevent irreversible climate feedback loops.

the product doesn't remain in its "carbon-negative" state forever. Instead, at the end of the product's life cycle, the same biogenic carbon will inevitably return to the atmosphere. That's characterized as a +1 kg CO_2 e/kg CO_2—showing that the biogenic carbon is re-emitted as the product decays or is burned.

On the surface, these seem similar, but the –1/+1 approach allows for more granularity in reporting because it can include the length of the life cycle and the rapidity of re-emission (remember the time-value of carbon?) based on what happens at the end of the life cycle—such as burning, decay in a landfill, lower-emission composting, recycling, or reuse.

Neither method is perfect. For example, look at a product made from a tree that takes 60 years to grow. "If you just multiply it by –1, that's an overly optimistic assumption because if you just cut down the tree and you just put it into that building, you didn't just magically suck all that carbon out of the atmosphere that year," said Anthony Pak, principal at Priopta, experts on whole-building LCA. Does it take you 60 years or 100 years to re-sequester that same amount of carbon? How much time is accounted for in the use phase? How is the material treated at the end of its life?

With a rapidly renewable crop, though, the biomass is often grown annually, sequestering carbon quickly in the short term and then storing it over a much longer period of time. This simplifies the carbon accounting compared to that of forestry products.

Importantly, regardless of which approach the LCA uses, it is only the *biogenic carbon* that is treated this way. Emissions of fossil carbon and other greenhouse gases are not included in biogenic carbon reporting.

"I think some of the science needs revisiting," said Mukherjee, because we don't look at what agriculture does to the land, the amount of nitrogen oxides that go back into the atmosphere, and more. "We're only looking at carbon dioxide." And more fundamentally, the same formula is used for all biomass—and not all biomass is sequestering the same way (rate, amount, etc.), he said.

Complicating our understanding of –1/+1 further is how the data are then reported on an EPD. The assumptions for a cradle-to-grave LCA might include a specific end-of-life scenario that may or may not be followed. Unpacking the carbon data in LCAs is difficult. Is it a cradle-to-gate or cradle-to-grave LCA? Does the biogenic material come from an annual plant like straw, a perennial like bamboo, or a plant with a longer growth cycle, like cork? Is the material a byproduct of agriculture or grown as a raw material? Is the product slated to last 35 years? 15? Afterwards, will it be placed in a landfill? Recycled? Used as fuel? All of these assumptions influence the embodied carbon data on EPDs, and since different product categories use different product category rules (PCRs) to conduct their LCAs, we can't compare carbon data between them.

So with all these unknowns, how can we compare the most basic materials, let alone try to assess the climate impact of a blended, biobased plastic additive with unknown provenance that makes up a fraction of a product?

A first step to addressing these challenges could be creating specialized product category rules (PCRs) for biobased material LCAs that would better define the parameters used for carbon reporting. Katie Poss, director of global policy and procurement at Building Transparency and board member of the California Straw Bale Building Association, is part of a group sponsoring the development of a PCR for these materials. "We are still early on [in] deciding what is in scope and out of scope," she said, and they are

looking at whether separate PCRs are needed. "As we dive deeper into planting, harvesting, and manufacturing, they all look different per plant type." The complexity of the PCR(s) is challenging, she said, so they will not be ready for some time. It will be years before we see an LCA or EPD that uses them.

What if you don't have an EPD?

There are plenty of LCA tools available for standard commercial building materials. The Embodied Carbon in Construction Calculator (EC3) run by Building Transparency offers category-by-category comparisons of product EPDs and more, and acknowledges in the database where product PCRs do not align. But how do you account for the complexities of biobased products where the data are less standardized?

Builders for Climate Action has developed the BEAM v1.1 estimator tool, which is essentially a spreadsheet of specific product carbon data that includes standard greenhouse gas data from EPDs but also has data on the biogenic carbon in products such as straw panels and hempcrete. The data can then be used to estimate the embodied carbon of low- and mid-rise residential buildings.

According to the organization, BEAM uses a "cradle-to-gate" approach, meaning it covers raw material extraction, transportation, and manufacturing, but not transportation from the factory, use and maintenance of the product, or the product's fate at the end of its life. Products that contain biobased material often use a cradle-to-grave methodology because it better captures their carbon-storage stories. But BEAM chose the former because, as its website states, "This is where the vast majority of life-cycle emissions occur for building products, and they have an immediate impact on our climate."

According to Chris Magwood, a manager with RMI's Carbon-Free Buildings Program, BEAM started as an in-house tool and uses EPDs as the primary source of its carbon data. But, he noted, "BEAM will call [it] out if a product has a different PCR." For instance, a foamboard insulation has a different PCR than wood board insulation. "In cases with no EPD, we use peer-reviewed data," Magwood continued. "We try to be transparent around what is comparable or not."

BEAM

PROJECT NAME: Wall Assembly Comparison
SCENARIO: Scenario 6
BEAM VERSION: V1.1

SECTION	CATEGORY	MATERIAL	NET EMISSIONS kg CO_2e	GROSS EMISSIONS kg CO_2e	STORAGE Short Cycle kg CO_2	STORAGE Long Cycle kg CO_2	QTY
		SELECTED PROJECT MATERIALS REVIEW	-2,305	8,356	10,660	0	
Exterior Walls	CAVITY INSULATION	Spray polyurethane foam - Closed Cell (HFO gas) / R 6.6-inch / SPFA [Industry Avg | US & CA]	1,136	1,136	0	0	1000.0 ft²
Exterior Walls	CAVITY INSULATION	Mineral wool batt / [BEAM Avg]	504	504	0	0	1000.0 ft²
Exterior Walls	CAVITY INSULATION	Fiberglass batt / NAIMA / R 4.4-inch [Industry Avg | N.America]	331	331	0	0	1000.0 ft²
Exterior Walls	CAVITY INSULATION	Hemp Fiber Batt / R 3.6-inch [BEAM Avg]	-152	380	532	0	1000.0 ft²
Exterior Walls	CAVITY INSULATION	Cellulose / dense pack / CIMA / R 3.7-inch / [Industry Avg | US & CA]	-648	366	1,014	0	1000.0 ft²
Exterior Walls	CAVITY INSULATION	Wood fiber batt / [BEAM Avg | EU]	-527	388	915	0	1000.0 ft²
Exterior Walls	CAVITY INSULATION	Hempcrete / R 2.4-inch [BEAM Avg]	-1,346	2,160	3,506	0	1000.0 ft²
Exterior Walls	CAVITY INSULATION	Straw Bale / Wheat & barley straw / SNaB (UK) / R 2.8/inch [Industry Avg | EU]	-1,975	220	2,195	0	1000.0 ft²
Exterior Walls	CONTINUOUS INSULATION	XPS foam board / R 5.0/inch [BEAM Avg | US & CA]	1,787	1,787	0	0	1000.0 ft²
Exterior Walls	CONTINUOUS INSULATION	Cork board insulation / Amorim / Expanded Insulation Corkboard (ICB) / R3.6-inch, 115 kg/m3 [EU]	-1,414	1,084	2,497	0	1000.0 ft²

Image: Jacob Racusin, New Frameworks

BEAM v1.1 tool showing embodied carbon estimates of different insulation materials, including potential carbon storage.

To account for carbon storage, BEAM uses the chemical composition of the material, as reported in the E.U.-funded Phyllis database, with a "10% reduction applied to provide a conservative value in line with other carbon-storing methodologies," according to the user guide. This can lead to negative emissions—in other words, net *storage* of carbon—for some products. Magwood understands the data are not perfect, which is why the tool is called an "estimator," but he claimed it provides the best information that's currently available for assessing the upfront embodied carbon of biobased products.

Builders for Climate Action is putting BEAM through the ANSI consensus process to establish the methodology as a standard for assessing and reporting on the climate footprint of products containing biogenic carbon. Magwood claims the tool helps ensure apples-to-apples comparison of multiple products' biomass.

BEAM was designed to be easy to use and does not require LCA knowledge. It currently has data for structural materials as well as for those used in foundations, walls, floors, roofs, cladding, and windows. "You put in the dimensions of the building from the energy model," Magwood elaborated. "So if you want to compare insulation, all the embodied carbon numbers are there." This allows project teams to select materials and get immediate feedback, he said, including whole-life performance data—meaning you can optimize for embodied carbon of the insulation based on how effectively the insulation reduces operational carbon emissions. That data can then be

Photo: Edward Caldwell Photography

This 2015 Sonoma, California, made with straw bale walls, survived through one of the state's significant wildfires.

shared (though it is not compatible with other software at this point).

Circularity, carbon, health: can we have all three?

Biobased materials often do not contain the potentially hazardous compounds found in standard petrochemical-based products, but that does not mean they are all inherently safe and free of all hazards.

Formaldehyde occurs naturally in wood. Dust from rice husks can pose silicosis risks. And without protection, many biobased materials naturally decompose over time, becoming food sources for mold and pests that can cause health issues due to poor indoor air quality.

Improving the longevity and performance of biobased materials often requires adding potentially hazardous, petroleum-derived ingredients. Biobased countertops, for example, are often topped with epoxy or other hazardous coatings to protect them from moisture and abuse. Biobased insulation materials almost always contain a biocide to protect them from decay, mildew, and pests. As mentioned above, cellulose insulation typically uses boric acid (it can also contain inks and other unknown hazards from its recycled content).

All that can put design teams in the uncomfortable position of choosing between multiple imperfect products, most of which have tradeoffs that include:

- Upfront embodied carbon
- Potential chemical hazards up and down the value chain
- Functional performance
- Durability and resilience

And that's all on top of the biggest driver: first cost.

The Informed tool, developed by Habitable (formerly the Healthy Building Network), offers a general rating system for several product categories that can aid product selection based on health. But there are other sustainability metrics at play. The tool, for instance, rates dense-pack cellulose as worse than unfaced fiberglass based exclusively on health metrics. But dense-pack has much lower embodied carbon and generally performs better.

In terms of carbon, using the BEAM tool and looking at cavity insulation that provides R-20 (187.8 m^2 for the wall-assembly example), the best unfaced fiberglass has an embodied carbon of 436 kg CO_2e/m^2, whereas the industry-average dense-pack cellulose is –1310 kg CO_2e/m^2, meaning it is storing carbon. And dense-pack provides better sealing, easier installation, and better overall performance.

But sometimes health and carbon do go hand in hand. For example, wood batts, which score well in Informed, have an impressive industry average embodied carbon of –1066 kg CO_2e/m^2.

Using certifications to weigh climate and material health

Carbon is not part of transparency labels that focus exclusively on material health, such as Declare and health product declarations (HPDs). But two holistic product certifications incorporate climate impacts along with more direct health considerations: the Living Product Challenge (LPC) and Cradle to Cradle (C2C). The LEED building rating systems also offer pathways to evaluating product sustainability in multiple categories.

As these programs evolve, they appear to be moving away from any prior assumption that biobased content is inherently climate friendly or otherwise sustainable, instead requiring metrics to assess all materials in more nuanced and sophisticated ways.

Living Product Challenge 2.0

LPC, from the International Living Future Institute (ILFI), has categories, called petals, each of which has one or more category-specific requirements, called imperatives. All imperatives must be met for full LPC certification. The program also permits partial achievement through what is called petal certification.

The LPC Materials Petal states that "Living Products should be intentionally made of materials that foster positive impacts throughout the product's life cycle by reducing the unnecessary extraction of virgin materials, sequestering carbon, utilizing regenerative materials, decreasing existing waste, and avoiding the creation of new waste at the end of the product's life."

Within that petal, the Regenerative Materials Imperative calls for product manufacturers to maximize the use of natural, biobased, and carbon-sequestering materials and to take their full material life cycles into account.

According to ILFI, products have to meet one of the following criteria: be part of a viable manufacturer take-back program, be 100% recyclable, and they must also be compostable and able to break down within five years.

Cradle to Cradle 3.1 and 4.1

C2C certification, from the Cradle to Cradle Products Innovation Institute (C2CPII), looks at five sustainability categories, and it demands not only adherence to its requirements but also evidence of continuous product improvement over time.

To that end, the program has tiered levels of certification—Bronze, Silver, Gold, and Platinum—and the sustainability category with the lowest achievement level determines the overall certification level of the product. C2CPII also has a separate program called the Material Health Certificate, which only looks at health impacts.

In a past version (the one achieved by most currently certified products), C2C Product Standard v3.1, the intent of the Material Reutilization category was "to increase the material utilization potential" of products; a Material Reutilization score was calculated based on the origin of the product contents (recycled or rapidly renewable) as well as the contents' ability to be cycled back into the system (recyclable or biodegradable/compostable).

In the most recent update, C2C Product Standard v4.1, the Material Reutilization category has been renamed Product Circularity, and it uses more nuanced metrics to rank products. In v4.1, "products are intentionally designed for their next use and are actively cycled in their intended cycling pathway(s)." The criteria differ depending on the level of certification, but for C2C Gold they include high compatibility "with the intended cycling pathway(s)," whether that be recycling or composting, and manufacturer programs that "support high-value cycling," according to C2CPII.

LEED 4.1 MRc3: Sourcing of raw materials

The LEED rating systems for whole buildings have encouraged use of biobased materials in many different ways over time, originally by incentivizing the use of any rapidly renewable material—meaning one with a harvest cycle shorter than ten years.

The most recent version of the building and interior construction standards, v4.1, makes a significant departure from prior versions by combining multiple product attributes into one Sourcing of Raw Materials credit, and by aligning the pathway for non-wood biobased materials with the USDA BioPreferred program. Products and materials can be

certified USDA BioPreferred or merely tested using ASTM Test Method D6866. (LEED v4 required Sustainable Agriculture Network certification for biobased materials, but v4.1 moved away from this because building materials are not certified under that program.)

If the original purpose of incentivizing rapidly renewable materials in LEED was to take advantage of their reduced climate impacts, the stated credit intent has never reflected that, and both v4 and v4.1 address embodied carbon in separate credits relating to life-cycle assessment and environmental product declarations.

The first public-comment draft of LEED v5 integrates five product attributes, including ecosystem and climate health, into an elaborate scoring system that's based on the categories of the AIA Materials Pledge and the related Common Materials Framework.

Social equity

Beyond the climate issues, the other environmental and social-equity impacts of synthetic materials are significant. Products containing polyvinyl chloride (PVC), for instance, are used throughout our buildings, but they have significant life-cycle problems, including pollution from the raw materials, transport, manufacturing, and end-of-life disposal. Other synthetic materials can pose similar problems—so much so that the world is now awash in per- and polyfluoroalkyl substances (PFAS), microplastics, and other potentially harmful chemicals.

The impacts of our dependence on synthetic materials are most acutely felt by the disadvantaged communities sited near manufacturing facilities, but we all (along with other species) suffer from their impacts. And we rarely know where the materials in our products even come from, complicating our ability to select more natural, sustainable options.

On the flip side, using biobased materials can often mean buying those that are harvested locally, connecting our buildings to the people who make the products.

Selecting Biobased Natural Materials

There are a lot of low-carbon building products and systems made from wood, bamboo, cork, linoleum, straw, and other natural materials. Each has a unique sustainability story, performance quirks, and market scalability. Whether design teams can use them on their next job often depends on a company's intended market. A biobased insulation company, for instance, might focus on residential applications, where the product can meet thermal performance requirements. But the company might not have the necessary testing for fire or acoustics required for commercial applications. Below, we've assessed many of these materials, some of which could find their way into your next project.

Note that this list does not include natural materials from geologic sources (such as natural stone and rammed earth).

Wood: more complex than crops

Wood products have arguably had the most buzz of all biobased products, largely because of a surge of interest in mass timber—an engineered structural material that can replace high-embodied-carbon concrete and steel structural components.

However, wood's climate and environmental stories are intertwined and complicated, as laid out in BuildingGreen's two-part series titled "Wood: Is It Still Good?" As critical as it is to select low-carbon materials, maintaining sustainable forests and the ecosystems they support is also vital: among other things, they are currently buffering

humanity from the worst impacts of climate change.

Carbon neutral? Not inherently

Tracking wood's embodied carbon is not easy due to all the variabilities in forestry practices, regional forest types and ages, tree species, and more. And many EPDs for wood products are based on an assumption of "carbon neutrality" (the –1/+1/ method discussed above) that misinterprets Intergovernmental Panel on Climate Change (IPCC) guidance from 1996. But not even wood products taken from Forest Stewardship Council-certified forests—the standard long used to verify wood's sustainability—can be considered inherently carbon neutral, though FSC certification can provide other potential ecosystem and community benefits. New methodologies are emerging, though, that may someday help us more accurately understand the climate impacts of different forestry practices.

There are some wood sources that could claim lower embodied carbon, though—namely:

- Reclaimed wood
- Wood from sustainably managed local forests
- Certain byproducts of logging and milling
- Wood from forests killed by pests

Documenting these benefits in the form of embodied carbon data is not straightforward, but the principles are sound. Using reclaimed wood from trees that were felled and processed years ago means there is minimal recent release of carbon into the atmosphere. When we reuse it, that carbon continues to be stored, avoiding the release of carbon through decomposition or burning.

Wood byproducts, such as those left by lumber production, can have some similar benefits, in that they are often burned, either for fuel at the lumber facilities or when sold for use as pellets. By using these byproducts as building materials, such as insulation, we can store their biogenic carbon in the building instead of immediately releasing it. The same goes for using "beetle-kill" wood from the western U.S. and Canada that would otherwise decay in the forest and release methane, a powerful greenhouse gas.

The BEAM tool takes this into account for non-virgin wood products when making its carbon calculations. EPD embodied carbon data are not automatically included for virgin wood products, not even those used in plywood, oriented strand board (OSB), or other engineered wood. But end users can turn on a feature that then includes stored carbon data.

Wood's benefits

- **Socioeconomic regeneration**—When sourced locally and responsibly, wood products can support local jobs and the community.
- **Forest regeneration and resilience**—These activities can also be part of natural forest regeneration—storing more carbon and promoting long-term climate resilience (see "Wood: Is It Still Good? Moving from Carbon to Climate").
- **Connectedness**—Locally sourced wood products can also provide a connection to place, especially when the wood is exposed to view. The biophilic aesthetics of wood can also promote a sense of meaning and calm, helping improve our health and well-being.

Wood's limitations

- **Climate questions**—For architectural products, finding accurate carbon data is very difficult.

- **Petrochemical preservatives**—Wood products need to be protected, often by potentially hazardous topcoats and biocides, to improve their durability.

Bamboo: rapid growth, some durable products

Bamboo has been used as a building material since antiquity. With a unique combination of tensile strength and hardness, bamboo is a versatile material typically used for flooring—and increasingly for structural panels and even rainscreens.

Moso bamboo can grow more than 60 feet in two months under the right growing conditions and does so in dense forests, but it can take three to five years for bamboo to develop its strength. After harvest, the bamboo is cut into strips, dried, and combined with resin to form flooring or panels.

Bamboo flooring is manufactured as:

- Horizontal, where strips of bamboo are layered on top of each other
- Vertical, where the strips are side-by-side
- Strand, where the bamboo is shredded and pressed together with resin

Horizontal bamboo is slightly softer than hard maple, while strand bamboo is one of the hardest floorings available.

But strand bamboo also contains more resin, typically a low-emitting, formaldehyde-based resin similar to that in composite wood. The resulting floors usually meet CDPH Standard Method emissions testing as well as the CARB ULEF standards used for composite wood products. But those looking for formaldehyde-free products may need to look elsewhere.

As with wood, determining the amount of carbon sequestered in a bamboo forest is difficult and often exaggerated. As such, estimates vary widely and can use different methodologies to draw conclusions.

- A 2024 literature review referenced two studies from China that estimated Moso bamboo forests sequester between 6.0 and and 8.1 tons of carbon per hectare.
- Project Drawdown estimates that bamboo sequesters 0.9 tons of carbon per acre per year.
- Still other sources claim that hundreds of tons of carbon are sequestered per acre.

Bamboo's benefits

- **Renewability plus durabilit**y—Bamboo's great asset is its rapid growth, and in the right application, it can be made into strong, durable, scalable, and affordable products.
- **Low carbon**—Bamboo flooring and plywood have the lowest embodied carbon of the materials in their product categories, according to the BEAM tool.

Bamboo's limitations

- **Sourcing**—Most bamboo is imported to the U.S. from China, so it requires transportation energy and does not provide a connection to the community or local natural resources. Bamboo cannot be grown in the U.S., however, since it is considered an invasive plant.
- **Durability**—Bamboo products can be susceptible to moisture, so bamboo flooring can fail if it isn't manufactured using effective quality control measures or stored or installed properly.
- **Material health**—Bamboo products often use formaldehyde resins.

Cork: a versatile material with built-in sustainability features

Cork has been used in various products for thousands of years. It comes from the outer bark of the cork oak and is stripped from the trees approximately every nine years. The cork then grows back, making it rapidly renewable.

Cork forests are carefully managed, and many are FSC certified.

Most cork is used to make stoppers for wine bottles, but cork left over from production can be turned into "expanded" cork. In this process, the cork granules are steamed under pressure, where they expand and release the naturally occurring biopolymer suberin, which acts as a natural binder. Expanded-cork blocks can be used to make insulation, flooring, and other products.

Cork's benefits

- **Forestry practices**—Cork is rapidly renewable and comes from responsibly managed forests.
- **Low toxicity**—Because cork is inherently moisture resistant and flame resistant, products made from it don't require many of the chemical additives needed to protect other biobased materials.
- **Acoustical properties**—Cork provides good sound dampening.
- **Versatility**—It can be used in buildings as flooring and underlayment, wall covering, tackboards, insulation, and more.
- **Low carbon**—Cork flooring and insulation products have low (and possibly even negative) embodied carbon, depending on the product and its use.

Cork's limitations

- **Sourcing**—Cork is imported from the Western Mediterranean region, and there is limited supply for scaling building products.
- **Cost**—It can be expensive, depending on the product category.
- **Petrochemical protection**—As a flooring, it is not robust enough for high-traffic areas, but it can be a good option for lower-traffic areas as long as it is protected. However, this often means applying a second layer of polyurethane after the flooring is installed.
- **Pest management**—For insulation, cork is not a good food source for termites but, as with foam boards, carpenter ants can still tunnel through.

Hemp: promising (again) but not scalable yet

Hemp was once the U.S.'s most valuable crop. It can mature in three to four months with little water and no fertilizer. It can regenerate poor topsoil by fixing nitrogen collected from deeper layers, be grown on small plots, and replace synthetic materials or those with larger carbon footprints.

In the past, hemp was grown primarily for its fibers, but increasing plastic production supplanted the need for hemp fibers, and a wave of "reefer madness" (though industrial hemp is not psychoactive) essentially killed hemp production in the U.S. Now, however, industrial hemp can be grown legally again and is making a comeback as a building material.

Hemp products are made primarily from two different parts of the plants' stems: the fiber, which is used in textiles, flooring, and insulation; and the "hurd," the interior core of the plant, currently used primarily for bricks, and a product called hempcrete. Hempcrete combines hemp hurd with a lime-cement binder and gets formed into wall assemblies.

Hemp's benefits

- **Versatility**—Hemp has the potential

to replace a number of synthetic materials.

- **Low carbon**—Hempcrete, a non-structural material that fills wall cavities and provides insulation and thermal mass, has the potential to significantly lower our buildings' embodied carbon. The best available data suggest that batt insulation made from hemp is carbon negative and provides an R-value of about 3.6.
- **Resource efficiency**—Hemp is a hearty plant that is relatively inexpensive to grow. Plants grown for their fiber can also supply hurd as a byproduct for other materials.
- **Sourcing**—Products made from hemp today often use fiber that was harvested and processed locally.

Hemp's limitations

- **Manufacturing barriers**—The fibers that provide hemp's strength also make it difficult to process. As with other agricultural fibers, there are few processing facilities, so hemp plants usually need to be shipped to be processed, making it difficult to scale production.
- **Profitability**—Industrial hemp used for building products is a victim of hemp's newfound popularity for medicinal and recreational uses. Industrial hemp does not contain any psychoactive properties and does not yield the cannabidiol (CBD, used as an herbal remedy) or tetrahydrocannabinol (THC, the psychoactive chemical in marijuana). There is more profit in those products.
- **Constructability**—Hempcrete is also most typically installed manually, with workers mixing hurd and binder, lifting the mix into forms along the wall. When a small section is done, the forms are moved up and the process repeated. It is a labor-intensive process that requires several people and a lot of time. And the product

Photo: Luke Awtry Photography

Pre-fabricated panels simplify, standardize, and speed up installation of straw construction.

then has to spend weeks drying, and the manual mixing process can create an inconsistent product. Spray-applied hempcrete is now available that solves most of these problems and could bring hempcrete into the mainstream.

Straw: repurposing our leftovers

Straw is a byproduct of grain production that is typically burned or left to rot after cultivation, releasing its carbon into the atmosphere. Using it as a building material can instead store that carbon, a prospect that offers unique, scalable opportunities that can be leveraged anywhere in the world where grain is grown. Wheat is the most common source of straw, but barley, rice, and others can also work.

Straw bale, in combination with wood framing, can be used to construct the walls of buildings, taking advantage of local "waste" materials to provide a thick layer of insulation and thermal mass. But straw can also be used in prefab panels, a popular building method in Europe that is even used in larger commercial buildings and is gaining traction in the U.S.

Composite boards for interior applications can also be made from straw. CalPlant, for instance, was slated to make boards from rice straw before a series of unfortunate events (including the COVID-19 pandemic) forced it into bankruptcy. But there is talk of trying to resurrect the product.

Straw's benefits

- **Sourcing**—Straw is inexpensive, readily available, scalable, and rapidly renewable. Building with straw bales means connecting with local farmers.
- **Low carbon**—It has one of the best carbon-storing potentials of any building material.
- **Unique set of properties**—Straw also has good thermal and acoustic properties, and it is fire resistant, charring much like mass timber, according to David Arkin, AIA, (former director of the California Straw Building Association).
- **Material health**—Straw assemblies are also usually coated with natural clays or lime plasters, creating a wall assembly with minimal material health concerns.

Straw's limitations

- **Constructability**—Strawbale buildings are not off-the-shelf items. With walls that are typically more than 18" thick, they are not built the same way as standard wood-framed buildings, so building a strawbale structure usually requires learning new skills.
- **Availability for commercial use**—Although straw bales are readily available, prefab strawbale walls are specialty systems found in only a few places in the U.S.
- **Vulnerability**—Moisture and pests could also be potential problems if the products are not properly stored, installed, or maintained.

Promising but not available yet

Other biobased materials with possible futures include those made from grasses, mycelia (the "root" systems of fungi), and seaweed.

Biobased Materials in Practice

So which biobased material has practitioners most excited? For David J. Lewis, principal at LTL Architects, dean and professor at Parsons School of Design, and co-author of Manual of Biogenic House Sections, "We've been focusing a lot on straw because it is a waste product and is available on a massive scale."

Biobased Building Materials: Guidance for Sourcing

Material	Best sourcing options	Product examples	Benefits	Limitations
Wood	Reclaimed wood Beetle-kill wood Residual materials from FSC-certified lumber production Post-consumer recycled content	Wood-fiber insulation Sheathing Soundproofing Cellulose insulation	Readily available Long use history Potential for low embodied carbon	Products need to be protected, often by potentially hazardous topcoats and biocides
Bamboo	FSC-certified Moso bamboo	Flooring Wall panels Structural products	Grows to maturity in three to five years Carbon storage Can be used structurally	Imported Potential quality issues that impact durability, performance, and total embodied carbon Formaldehyde-based resins
Cork	FSC-certified material	Flooring Wallcovering Insulation Tackboards	Renewable bark from responsibly managed cork forests Comfortable flooring Good sound attenuation	Imported For flooring: topcoats required; only useable in low-traffic areas Limited availability
Hemp	Locally grown hemp Imported materials with a proven track record of quality control	Insulation Hempcrete Flooring Textiles	Hardy, soil-regenerating, and drought-resistant annual crop requiring no fertilizers or pesticides Resource efficiency (both fibers and hurd are used) Strong fibers Can replace synthetic materials	Limited availability in the U.S.
Straw	Locally grown straw	Straw bales Panelized wall assemblies Agfiber panels	Widely available, locally grown material Annual byproduct of grain production, so use does not take up farmland Stores carbon Keeps the straw from decomposing or being burned Scalable anywhere in the world where grain is grown	Hard to specify Few manufacturers of panelized wall assemblies used for large commercial projects
Other biobased materials: mycelium, seaweed, switchgrass, sorghum, and other agricultural byproducts	Locally abundant materials Materials requiring minimal processing and no petrochemical treatments	Acoustical insulation made from eelgrass Sorghum and grass agfiber panels	Could be a great use of unique, plentiful biobased material	Niche products with limited availability

Of all the biobased materials, he says, straw is the one that is not displacing food crops or expanding agriculture.

Renewed interest in natural, biobased materials is demonstrated by an Architectural League of New York panel discussion series called "From Field to Form," one of which covered straw and included Lewis as a panelist. Bringing agriculture and architecture together, he sees straw as moving beyond the humble design assumptions associated with strawbale construction. He says there are huge opportunities for combining contemporary technology with traditional forms of knowledge—not seeing them as antithetical but rather hybridizing. In the panel discussion, he said, a "straw bale is not the end; it's the beginning of the process … and an opportunity for different models altogether."

ILFI's Lindsay Baker agrees, stating, "I think it is important for us to celebrate and highlight buildings that visually show natural materials as part of the architecture."

Europe is further along with its adoption of natural materials and with melding ancient and modern technologies. An example of this is the seven-story Passive House-certified housing complex in St. Die des Vosges. Constructed in 2013, it combines mass timber and straw bales.

U.S. Straw Bale

Although Europe is further along, several firms in the U.S. are also building with biobased natural materials. Arkin's firm has designed a number of strawbale homes and small commercial buildings over the years, including a home in Santa Cruz, California, that garnered several design awards. With low embodied carbon and excellent thermal performance (about R-30 for a standard wall, but values differ depending on type of straw and other factors), straw bales seem like a no-brainer. Building codes are not even as much of a challenge as they once were. In 2015, a strawbale construction appendix was added to the International Code Council's residential code. As such, "Code officials have allowed us to look at that for guidance," Arkin said.

"I've been scratching my head for 20 years asking, why has this not taken off," Arkin told BuildingGreen. But he also recognizes some of the current challenges to wider adoption, including one of the main ones: since straw bales are not a manufactured product, per se, "You can't specify strawbale construction" in construction documents.

To manage procuring and installing the bales, his firm puts in allowances to cover the extra work. Panelized straw-panel buildings should make this process easier and are now available from New Frameworks, Croft, and Ecococon, but there are other hybrid methods as well. One of the systems Arkin's firm used in

Photo: Daniel J. Cardon, Photographer

New Frameworks uses local straw to manufacture its wall panels.

a residence in Crested Butte, Colorado, used straw cells. They built a 2”x4”-and-plywood assembly that was insulated with cellulose and also fit straw bales vertically on the interior between the studs. The bales were mechanically fastened and finished with clay plaster. This system allows the use of any cladding, he said.

Jacob Racusin stopped building single-family homes five years ago and pivoted toward using straw to make small prefabricated homes and panelized systems his company calls Straw Structural Insulated Panel (S-SIP). Racusin is director of building science and sustainability at New Frameworks, a 23-person worker-owned co-op architectural studio in Essex Junction, Vermont. “Straw is still the most effective method of storing carbon per mass,” he argues, adding that these systems have “reduced a lot of friction for adoption.” Making the panels in controlled environments improves quality control and reduces the amount of specialized onsite labor and supply-chain challenges of straw bales. Racusin stated, “We’re able to make more of a product than a service out of this material.”

New Frameworks is sourcing its straw locally from a nearby Vermont farm, investing in the local community, and helping to preserve farmland under threat from potential development. Along with custom panels, it is offering fully built, all-electric tiny homes ranging from 300 to 1,200 square feet. Full carbon data is available for each via the BEAM tool, which Racusin helped develop. The final 14”-thick wall assemblies are approximately R-35.

In terms of healthy materials, “We don’t have any binders or chemicals of concern,” Racusin said. The interior finish goes over the top of a mix of clay, lime, sand, and chopped straw. The surface is repairable, and “on the interior, we do push for plaster” rather than drywall, he added. “We can more or less meet cost parity with drywall, primer, and paint,” he said, while also noting that the final coat is up to the owner.

Using local materials

According to James Kitchin, director of performance and provenance at the nonprofit firm MASS Design Group, “Not all biobased materials are good. They are context- and location-specific.” Kitchin uses the example of soy and palm oil that have led to rainforest deforestation in Brazil, Indonesia, and Malaysia, pointing out that these oils end up in biobased products. MASS (short for Model of Architecture Serving Society) was the winner of The American Institute of Architects’ (AIA) 2022 Architecture Firm Award for Architecture, in part because of its commitment to “ensuring its architecture addresses the world’s most pressing social issues,” according to AIA. In keeping with that mission, “we want to be using materials that are bio-specific and support local communities,” Kitchin explained.

Based in Boston and in Kigali, Rwanda, MASS has done a lot of design work in nations throughout the African continent. The firm strives to use primarily local materials. For example, while working on the Ilima Primary School in the jungles of the Democratic Republic of the Congo, the team discovered that “it took two months to get anything transported there,” said Kitchin, so all of the materials were local for practical reasons. The project employed 120 people from the local community, 20% of whom were women, and used a mix of Indigenous knowledge and scientific rigor, Kitchin added, noting the termite mound they used as a source of clay for the walls was tested and found to be the “best soil we could pick,” according to the firm.

The school was built in 2015, and “that was the first time we looked at embod-

Photo: MASS Design Group and Iwan Baan

The dining center at Rwanda Institute for Conservation Agriculture (RICA) was built by MASS Design Group out of natural, local, and biobased materials.

ied carbon," noted Kitchin, who added, "There is a very strong correlation between using local materials and low embodied carbon." MASS has also built universities, hospitals, and other larger commercial buildings in Rwanda and has employed a similar philosophy of working with locals, supporting local businesses, and helping build town pride that endured after the projects were completed.

"I came from working in Rwanda and central Africa and wanted to bring those lessons learned to the U.S.," Kitchin said. (MASS also formed the Northeast Bio-based Materials Collective to engage those interested in the topic.) "You know it's technically possible, but then you come across the challenges." Among these, he cited supply chains, codes, and budgetary pressures. "We are always getting pushbacks from contractors for cost. It is very difficult." But he says they now have their first strawbale building project, which is located on the Hopi Reservation in Arizona, where they can be more flexible with design because the region is under Tribal governance. "So we are able to push the limits more outside the IBC," that is, International Building Code, he said.

Promising innovations in hempcrete installation

Hempcrete is drawing more attention these days as well.

"Standard installation of hempcrete is incredibly labor intensive," said Cameron McIntosh, owner of Americhanvre, which uses a spray-applied technology called Ereasy to install a form of hempcrete. The company's Ereasy system "is more similar to a gunite or a shotcrete

machine," he said, referring to the trade terminology for concrete that's sprayed rather than poured.

With this system, a four-person team spraying 12"-thick material can complete a house in seven days. And the material comes premixed, so every batch has the exact same *mix ratio*—the balance of water, fines, aggregate, and binder in the concrete—and performance (permeability and other factors could be inconsistent with hand-mixed hempcrete). Hempcrete is now permitted in the IBC, and Ereasy just received a one-hour fire rating, so "we can now be specified as a one-hour rated assembly, which is important for multifamily and commercial construction," McIntosh told BuildingGreen.

McIntosh added that there are ten owner–operators of this equipment in the U.S.—most notably, in his opinion, the Lower Sioux Indian Community in Morton, Minnesota. "They've done two houses so far specifically with our spray system on their reservation," McIntosh related. He also described a 12-unit apartment complex in Newburyport, Massachusetts, which was built with full-section tilt-up wall panels.

McIntosh claims it is the first commercial structure of its kind built with this material.

So, Is the Hype about Biobased Materials Justified?

Using more natural, locally grown materials can have profound benefits for our climate, environment, communities, and health. Even if our carbon accounting for biobased materials is not perfect (most carbon accounting isn't), it is getting better and more consistent. There are more and more biobased products that can be specified, more buildings being made with these materials, and more code acceptance.

There is more work to be done, though. "We need better policies to encourage a truly low-carbon built environment and not just lower-carbon *products* that we need to buy," Baker said.

That will require a deeper commitment to circularity—starting with strong embrace of reusing buildings and materials and designing new projects for later adaptability and reuse.

Along with that, Baker foresees a need to address the provenance of products and materials and reduce the complexity of ingredients and supply chains. In a globalized economy, it has become increasingly difficult to know where materials come from, she claims, and she doubts we will be able to transform the building industry within our current system of elaborate supply chains.

That said, "the system is not what we are trying to save," Baker stated. "It's the planet." And to that end, using biobased materials "opens [y]our eyes to products in your community and ecosystem."