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A Life-Cycle Approach to Investigate the Potential of Novel Biobased Construction Materials toward a Circular Built Environment

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Abstract: Conventional construction materials which rely on a fossil-based, nonrenewable extractive economy are typically associated with an entrenched linear economic approach to production. Current research indicates the clear interrelationships between the production and use of construction materials and anthropogenic climate change. This paper investigates the potential for emerging high-performance biobased construction materials, produced sustainably and/or using waste byproducts, to enable a more environmentally sustainable approach to the built environment. Life-cycle assessment (LCA) is employed to compare three wall assemblies using local biobased materials in Montreal (Canada), Nairobi (Kenya), and Accra (Ghana) vs. a traditional construction using gypsum boards and rockwool insulation. Global warming potential, nonrenewable cumulative energy demand, acidification potential, eutrophication potential, and freshwater consumption (FWC) are considered. Scenarios include options for design for disassembly (DfD), as well as potential future alternatives for electricity supply in Kenya and Ghana. Results indicate that all biobased alternatives have lower (often significantly so) life-cycle impacts per functional unit, compared to the traditional construction. DfD strategies are also shown to result in −10% to −50% impact reductions. The results for both African countries exhibit a large dependence on the electricity source used for manufacturing, with significant potential for future decarbonization, but also some associated tradeoffs in terms of acidification and eutrophication.

Keywords: sustainable construction; biobased materials; coconut; bamboo; life-cycle assessment

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1. Introduction

The growing density of urban environments across the globe has consequences for the materials used by the building sector; while smaller buildings were historically made using local biobased materials, they have been increasingly replaced by larger, carbon-intensive concrete and steel structures (Figure 1). This shift helps explain why the share of global greenhouse gas (GHG) emissions from material production increased from 15% in 1995 to 23% in 2015 [1,2]. With cement and steel as the most widely used materials overall [3], the construction sector is responsible for 94% of global cement and 23% of global iron and steel GHG emissions [2]. In addition to contributing to climate change, the production of many conventional building materials (e.g., concrete, steel, aluminum, and glass) relies on the use of nonrenewable resources [4] such as minerals, sand, gravel, crushed stone, and lime. These resources are typically mined or quarried and rely on long-term geological processes, such as natural sedimentary cycles, for their formation. Since the source of these materials is not infinite, the rate of consumption of such minerals is not sustainable.

Figure 1. Context of global urban development and densification. From left to right: informal, semiformal, and formal construction typologies.

In the US alone, according to the US Geological Survey (USGS) Mineral Commodity Summaries [5], crushed stone, used in construction aggregates, was the leading nonfuel mineral commodity in the country in 2021. On the global scale, the World Bank estimates that 300 million additional houses will need to be constructed by 2030, primarily in emerging economies, to meet the rapid increase in urban population growth [6]. Hence, the demand for construction materials will continue to grow in order to meet such housing needs. This increase in material production and the associated fabrication and/or construction processes could greatly exacerbate environmental impacts, particularly if proposed "sustainable circularity scenarios" (a combination of dematerialization and increased recycling) are not being implemented [7] and the current linear model of material production continues [8,9].

However, alternative source materials for building that are biobased are increasingly being considered [10], which may help alleviate the stress on the biosphere due to raw mineral-based material depletion. The recent advent of such biobased material systems presents novel emerging opportunities for adaptable, biobased systems to transition from smaller to larger, multistory construction.

Thus far, emerging biobased replacements for concrete structures such as cross-laminated timber (CLT) have been considered as a relatively environmentally friendly solution [11] over a building's life cycle [12,13]. Mass timber buildings have demonstrated over 30% lower operational energy demands compared to similar concrete buildings [14], and 40% savings in GHG when accounting for 55% recycling and 45% energy recovery rates for end-of-life CLT, while also comparing favorably in terms of ozone depletion, global warming, and eutrophication when compared with concrete buildings [13].

However, while biomaterials may offer a renewable alternative, they have their own associated risks [15], including a potentially negative change in land-use patterns that either leads to increased deforestation and/or the loss of regional biodiversity [16]. Furthermore, although biobased materials do sequester carbon during their growth and use phases [12–14], at the end of a building's life, once the building is deconstructed, the carbon stored in the biomaterial will be released back into the atmosphere, as the biomaterials decompose and degrade (depending on the specific waste management strategy being applied, which may include incineration, biodegradation, etc.).

Even if the biobased materials are recovered and repurposed for a second use via design-for-disassembly (DfD) strategies [17], or converted to biochar to minimize future carbon emissions [18,19], this only amounts to an extension of such temporary carbon storage, not a permanent removal. Thus, even in the most optimistic case, when extending the assessment over the full life cycle of the systems comprising such biomaterials (as applies to the four wall assemblies presented here), the result would be a net-zero biogenic carbon balance. Admittedly, this "steady-state" carbon accounting approach does not address the effects on climate of the different temporal rates at which carbon is removed and emitted by different processes, nor the net effect of the time lags between the initial sequestration and subsequent release of biogenic carbon (i.e., it lacks the "accounting for time" advocated, for instance, by Fearnside et al. [20]). However, conventional life-cycle assessment (LCA) is by its very nature an integrative method that characteristically looks at the whole life cycle as a "black box", and it is ill-equipped to accurately account for such dynamic effects within the timescale of the life cycle of the system being analyzed (e.g., the use of "C discount rates" proposed by Fearnside et al. is conceptually interesting, but still far from being adopted as standard practice in LCA). Moreover, in reality, the situation is further complicated by the fact that, depending on the nature of the final disposal (e.g., landfilling vs. incineration), part of the carbon originally removed from the atmosphere during biomass growth may even end up being anaerobically degraded and released as methane, instead of CO_2, in which case the overall net result over the full life cycle would be a positive (i.e., non-zero) contribution to global warming (since each mole of biogenic methane emitted at EoL has many times the global warming potential of one mole of CO_2 originally sequestered during the biomass growth phase).

In terms of urban development patterns, as global cities increase in density, engineered biomaterials such as CLT offer the potential to replace the concrete and steel components for new construction, as well as for retrofit construction, particularly for the widespread repurposing of older commercial buildings with the addition of new floors to supplement housing units across urban districts [21,22]. Because softwoods typically used in modern multistory timber construction have significantly lower density vs. concrete, used structurally, timber's light weight allows for significantly more extra stories to be added to existing structures, thereby offering a potential avenue to address global urban housing shortages with existing building stock. With comparable wall and floor panel thicknesses, the total building structural weight of timber-based systems such as CLT is around 20% that of the concrete [22], representing a very significant advantage to adapt and retrofit existing urban structures with biomaterial structures.

The market for biobased materials is expected to greatly expand across sectors; however, despite the potential of biomaterials as alternatives to carbon-intensive nonrenewable construction materials, they still face numerous impediments in various building construction applications, and their global production is still limited to a modest percentage of overall material deployment. As engineered products, they are restricted by building and fire codes, such as the International Building Code (IBC), which limits the height and square footage of buildings in which they can be used. In order to change the building codes, engineered biomaterials have to pass safety tests, such as those involving fire resistance and seismic performance, but early-adopting municipalities in North America and Europe are demonstrating built projects with the methods and potential to scale up to mid-sized buildings and infrastructure [23].

Overall, the carbon life cycle of biomaterials can be quite complex, often making it difficult to accurately quantify their whole life-cycle emissions. However, major recent innovations in the development and deployment of biomaterials toward larger-scale, adaptable structures that could support circular approaches that are designed for disassembly (DfD) and reuse are opening up new frontiers to consider, as they may offer the potential to sequester carbon and lower greenhouse gas emissions during material production, construction, and use phases [11–14]. Despite the prior studies mentioned here, many new and emerging biomaterials, including those that use agricultural byproducts as a raw material for their production, have not yet been studied in terms of their life cycle to understand their environmental impacts. There is a gap in the literature in terms of comparing multiple formats of biobased materials (both those manufactured from virgin materials and those manufactured from agricultural byproducts) that are local and climate-specific. In particular, scant literature exists that compares these ranges of biomaterials in terms of their manufacturing and their end-of-use potential.

Mindful of all these aspects, this paper aims to fill some of the existing research gaps, by performing a cradle-to-grave life-cycle assessment (LCA) to quantify and compare the associated potential environmental impacts across a set of three case study biomaterials with existing or projected potential for scale-up in the building sector, in different climate types globally. While timber-based materials have been promoted as a key biobased solution for replacing nonrenewable structural materials, faster-growing (<2 years) and more widely available bamboo resources are also considered here in comparison. Additionally, as a case study in building materials made from growing markets in post-agricultural waste streams, lignin-rich coconut husk derived building materials are chosen on the basis of their capacity to meet or exceed the mechanical performance and durability of timber-based panels [24,25]. While out of the scope of this paper, coconut fiberboards also demonstrate advantageous hygrothermal performance across a range of hot, humid climate types [26–28].

2. Materials and Methods

2.1. Alternative Products under Study

This paper examines the use of local or "climate-specific" biobased materials in wall construction assemblies. For each climate type, a wall construction assembly is proposed that relies primarily on biobased materials that are local to that climate type. Three distinct climate types with the following Koppen–Geiger climate classifications [29] are studied, namely: (a) warm and temperate climate, Koppen Cfb (Nairobi); (b) warm summer continental climate, Koppen Dfb (Montreal); (c) tropical savanna climate, Koppen Aw (Accra). A traditional engineered wood and plasterboard construction is also included in the analysis as a benchmark.

The four wall construction assemblies are illustrated in Figure 2 and briefly described below.

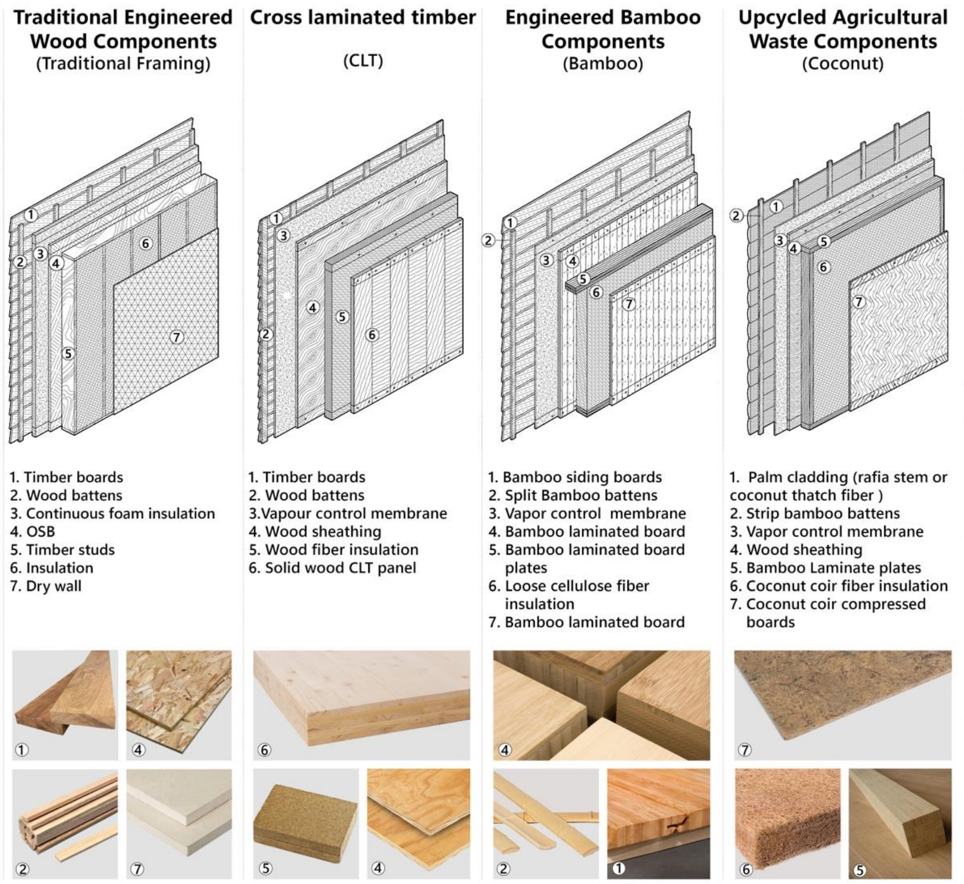

Figure 2. Wall assembly types for traditional framing, CLT, bamboo, and coconut, showing the construction assemblies designed to respond to the local climatic conditions in which they are found.

(a) Traditional wall assembly

The traditional wall section is composed of timber studs framing, drywall, 2″ insulation, oriented strand wooden board (OSB), an additional layer of continuous foam insulation, wood battens, and timber siding boards

(b) CLT wall assembly

The CLT wall section is composed of a 7″ CLT panel, 2″ wood fiber insulation, 1″ wood sheathing, vapor control and airtight membrane, and horizontal weatherboarding fixed to battens.

(c) Bamboo wall assembly

The bamboo wall section is composed of ¾″ compressed split bamboo boards, 4″ loose cellulose fiber insulation between 2″ × 4″ bamboo laminated plates, vapor control and airtight membrane, split bamboo battens, and bamboo siding boards.

(d) Coconut wall assembly

The coconut wall section is composed of ¾″ coconut coir compressed boards, 4″ coconut coir fiber insulation between bamboo laminated plates, ¾″ plywood sheathing, vapor control and airtight membrane, split bamboo battens, and non-processed palm (raffia stems or coconut fiber thatch).

Bills of materials for the four wall assemblies are reported in Tables 1–4, with indication of those materials which may be reused at end of life. More detailed and complete bills of materials is provided in the Supplementary Materials.

Table 1. Bill of materials for one functional unit (FU = 1 m^2) of traditional timber framing wall assembly. Reference flow = amount of material required per FU.

Material	Reference Flow	Units	Potential for Reuse at EoL
Gypsum board	7.8	kg	No
Rockwool panels (HD)	16	kg	Yes
OSB engineered wood panel	0.019	m^3	Yes
Sawn softwood, dried (u = 20%)	0.0020	m^3	Yes
Red cedarwood	0.020	m^3	No

Table 2. Bill of materials for one functional unit (FU = 1 m^2) of CLT-based wall assembly. Reference flow = amount of material required per FU.

Material	Reference Flow	Units	Potential for Reuse at EoL
CLT board	0.055	m^3	Yes
Polyethylene, high-density	0.46	kg	No
Plywood, for outdoor use	0.010	m^3	Yes
Sawn softwood, dried	0.021	m^3	Yes
Red cedarwood	0.020	m^3	No
Wood fiber insulation	16	kg	Yes

Table 3. Bill of materials for one functional unit (FU = 1 m^2) of bamboo-based wall assembly. Reference flow = amount of material required per FU.

Material	Reference Flow	Units	Potential for Reuse at EoL
Bamboo boards	0.018	m^3	No
Polyethylene, high-density	0.50	kg	No
Bamboo panel	0.040	m^3	Yes
Compressed bamboo beam and batten (HD)	0.0080	m^3	Yes
Cellulose fiber insulation	8.0	kg	Yes

Table 4. Bill of materials for 1 Functional Unit (FU = 1 m^2) of coconut-based wall assembly. Reference flow = amount of material required per FU.

Material	Reference Flow	Units	Potential for Reuse at EoL
Coconut coir boards, high-density	0.0050	m^3	Yes
Polyethylene, high-density	0.50	kg	No
Plywood, for outdoor use	0.010	m^3	Yes
Compressed bamboo beam and batten (HD)	0.0080	m^3	Yes
Coconut fiber insulation	45	kg	No

Three of the biobased materials are from virgin wood, i.e., the traditional wall assembly and the CLT in the Montreal wall study, and the bamboo in the Nairobi wall study, while the fourth is from post-agricultural waste, i.e., coconut husk in the Accra wall study.

More specifically, CLT is well established as a construction material in Europe and is increasingly gaining market adoption in North America [30–32]. Due to its many advantages, such as its comparatively high strength-to-mass ratio, CLT can be used as the primary structural material for mid- to high-rise buildings, which makes it a suitable alternative to replace concrete and steel in many construction projects [33]. CLT is a timber-based building system whereby a high level of control in the prefabrication and simplicity of handling reduces the overall construction duration [34], making this building system efficient, despite its comparatively higher initial material cost, with respect to traditional assembly types, including both concrete and traditional timber framing [35–37]. In terms of supporting circular construction, CLT allows the specification of reversible connections that can allow for the conversion of assemblies and subassemblies into basic materials; this can be a very significant contribution to transitioning traditional timber systems toward DfD, which is one of the fundamental tenants of designing for a future "circular" material economy in which the component parts of one type of construction can be renovated for adaptation and/or recuperation and reintegration into a different construction assembly [38]. In the context of emerging economies in the Global South, in which the projected consumption of nonrenewable, carbon-intensive construction materials such as concrete and steel is projected to accelerate with progressive densification of cities and infrastructure, the ability to reintegrate components and materials is significant. The prefabricated nature of CLT reduces the on-site complexities and provides a much leaner construction work sequence. However, as a potential drawback, this in turn may limit its use in informal contexts if smaller component sizes and weights are not developed for that market. Conversely, for larger commercial buildings, the potential for a relatively small workforce and on-site area yields a safer and cleaner production of building construction [39].

One aspect that is left out of this study is that for larger assemblies, CLT building systems are predominantly assembled with mechanical fasteners. While this construction method aligns perfectly with a DfD methodology, as the high-value metallic elements can be harvested from the structure and reused so that the material can return to the industry for the next use as part of the circular economy [21], the potential for larger metal components to stabilize walls and roofs would add significantly to an overall life-cycle assessment.

Bamboo is a fast-growing renewable material comparable in strength to other commonly used construction materials [40]. It can be used for many construction applications such as structural walls, non-load-bearing walls, roofing, interior panels, and flooring [41,42], and it can replace up to 70% of steel applications at less than 60% of the cost [41,43–47]. Bamboo has additional structural benefits and is often used in seismic zones due to its excellent flexibility and resilience [48]. During growth, bamboo absorbs carbon dioxide and releases 35% more oxygen into the atmosphere than other hardwood trees [41,49]. The high productivity rate and the short cycle of harvest enable bamboo to be an outstandingly flexible material compared to other naturally growing virgin resources [50,51].

Engineered bamboo has proven to be a highly versatile sector, with potential to replace many incumbent cladding and structural materials, although initial cost varies greatly across regions [51]; currently, bamboo is still largely imported into East Africa from China, but there are goals and initiatives to increase growing and processing in the African continent [52]. A very substantial comparative advantage of bamboo as a source material is that it has the potential for a wide range of structural characteristics and performance with potentially minimal processing, although it also lends itself to a wide variety of processed products [53,54]. A disadvantage in comparison to other engineered wood products is its vulnerability to rapid weathering in humid climates unless substantial postprocessing and maintenance cycles involving hydrophobic coatings that typically off-gas volatile organic compounds (VOCs).

Coconut is a renewable resource grown primarily for a global food and cosmetic industry, and the natural fiber and pith extracted from the husk of coconuts is increasingly attracting attention for its potential as a high-strength construction material, due to its hard, tough, and stiff natural fibers with high lignin content. Composite agrowaste-based coconut fiberboard panel systems, similar to other natural plant-based aggregates and bio-composite panels, have demonstrated excellent hygric and thermal performance in buildings by supporting hygric buffering and intrinsic evaporative cooling particularly in hot, humid environments [55,56]. Coconut fiberboard panels comprise coconut fibers and soy protein or pith bio-binders. Fiber-to-bio-binder ratios ranging from 50:50 to 60:40 have been shown to offer a low-carbon alternative to nonrenewable mineral-based building materials such as fiberboard materials in drywall partitioning, which relies on gypsum [26–28].

In addition to being designed to reflect the use of local biomaterials, each construction wall type is also assumed to be built to achieve the R-value recommended for that location. The R-value (or thermal resistance) in buildings and construction is a measure of the ability of the exterior wall assembly to resist the conductive flow of heat from across the building envelope. Table 5 shows the three locations identified and the respective recommended R-values for walls, the Koppen–Geiger climate classification for each location, and the actual R-value achieved by each wall assembly. The actual R-value of each wall (R_{tot}) was calculated using Equation (1) for calculating unidirectional total thermal resistance.

$$R_{tot} = R_{si} + \sum_{j=1}^{n} \frac{d_j}{\lambda_j} + R_{se}, \quad (1)$$

where R_{si} and R_{se} are the interior and exterior surface resistances ($(m^2 \cdot K)/W$), d_j is the thickness of homogenous material layer j (m), and λ_j is the thermal conductivity of material j ($W/(m \cdot K)$).

Table 5. Location, climate classification, and the associated recommended R-value for the wall construction in the three locations of study.

Location	Koppen–Geiger Climate Classification	Recommended R-Value for Wall	R-Value for Each Wall Type
Montreal	Dfb—warm summer, cold winter	23	23 (traditional timber frame and CLT)
Nairobi	Cfb—warm and temperate	13	14 (bamboo)
Accra	Aw—tropical savanna	13	15 (coconut)

The surface thermal resistances considered in calculations were R_{si} = 0.13 $(m^2 \cdot K)/W$ and R_{se} = 0.04 $(m^2 \cdot K)/W$. These R-value calculations for each wall type can be found in the Supplementary Materials.

2.2. Life-Cycle Assessment (LCA)

For each wall construction, an LCA was carried out from cradle to grave, i.e., including the following life-cycle stages: material sourcing and processing, wall assembly manufacturing, and end of life. Transportation of manufactured material to the construction site was not included. The use phase was also excluded, since all wall assemblies were designed to achieve the same appropriate R-value for the target climate zone; thus, the impacts associated to energy use during the use phase are equalized across similar applications. Comparing use-phase impacts across different climate zones falls outside of the intended scope of this paper.

In terms of modeling, the LCA was set up as an attributional analysis based on current practices and availability of resources. The specific implications of this approach are discussed in more detail in Section 4.

The manufacturing process for the CLT boards was not modeled directly; instead, a pre-existing environmental product declaration (EPD) was leveraged (cf. Section 2.2.1).

The manufacturing process for laminated bamboo boards (cf. Section 2.2.2) was modeled on the basis of foreground inventories reported in a previously published paper [57].

The manufacturing process for coconut coir boards was modeled in detail on the basis of the foreground inventory information available to the authors (cf. Section 2.2.3).

In all the case studies, both bioresource harvesting and biomaterial processing/manufacturing were assumed to be local to the three respective locations. avoiding the need for significant transportation between sourcing and manufacturing.

The four wall assemblies illustrated in Figure 2 are manually assembled; hence, any additional direct energy input to this manufacturing stage was assumed to be negligible.

The electricity supply scenarios considered were threefold for the African countries. Firstly, the current grid mix for all three locations was considered. Secondly, the future grid mix scenarios for both Kenya and Ghana were modeled referencing the IEA Africa Energy Outlook "Stated Policies" (STEPS) scenarios for the year 2040 [58]. These first two scenarios are illustrated in Figures 3 and 4, respectively, for Kenya and Ghana.

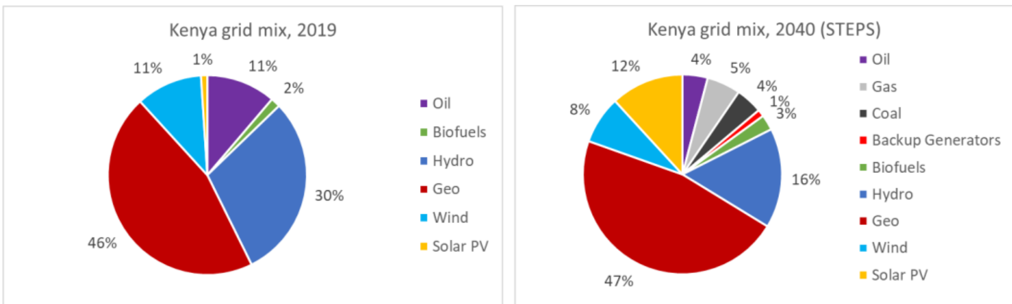

Figure 3. Current [58] and future electricity grid mix compositions for Kenya, with the latter based on IEA "STEPS" scenarios [58]. Note: Numbers may not add up to 100% due to rounding.

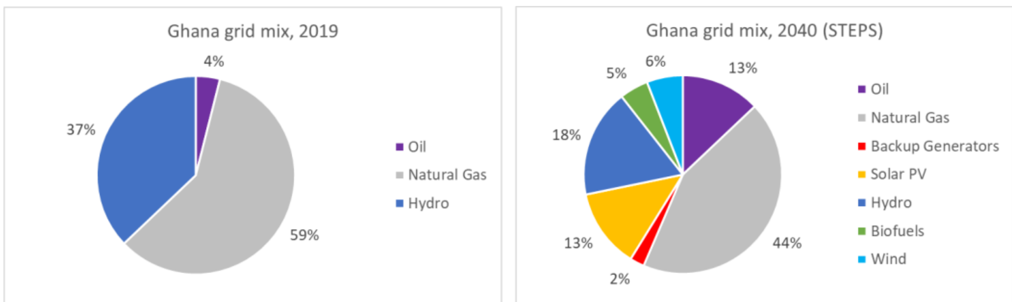

Figure 4. Current [58] and future electricity grid mix compositions for Ghana, with the latter based on IEA "STEPS" scenarios [58]. Note: Numbers may not add up to 100% due to rounding.

Thirdly, considering that the current Québec grid mix is already almost 100% renewable due to the use of hydropower, a third sensitivity analysis considered scenarios for Ghana and Kenya that would reflect a similar 100% renewable energy (RE) option. These latter scenarios highlight the possibility of using dedicated renewable energy either produced on site at the manufacturing plant or procured via power purchase agreements (PPAs). For these 100% RE scenarios in Ghana and Kenya, a mix of 50% onshore wind and 50% solar (mc-Si PV) was assumed, given that these two RE technologies are the least costly and, importantly, the most modular and easily scalable options available. In both cases, the Ecoinvent v3.6 process for PV electricity in the LCA model was updated to reflect the expected increase in efficiency, based on the latest Fraunhofer ISE report [59] and a recent IEA PVPS report on the future of PV [60].

All background processes were modeled using the Ecoinvent v3.6 life-cycle inventory (LCI) database [61]. End-of-life treatment for all biomaterials and plastics was assumed to be incineration, and the incinerator emissions and demand for energy per unit of waste treated were estimated on the basis of the Ecoinvent processes for "treatment of waste building wood, municipal incineration" and "treatment of waste polyethylene, municipal incineration". The gypsum boards and rockwool used in the traditional assembly were assumed to be landfilled, and the associated emissions were modeled using the Ecoinvent process for "municipal solid landfill operation". From a methodological perspective, the cutoff allocation principle was rigorously adopted, in compliance with CEN-EN 15978 (itself based on EN 15804), whereby producers of waste bear the burden of the waste treatment, based on the "polluter pays" principle, and all waste byproducts and recycled materials are assigned zero environmental burdens at their point of collection. Accordingly, no environmental credits were calculated for the energy recovered through incineration.

It is also noteworthy that manufactured products such as CLT and bamboo-based composites are increasingly being designed as modules for direct disassembly and reuse at end of life [38,62]. To partly take this into account, a further sensitivity analysis was performed, whereby those parts of the wall assemblies which could be reused in a similar application are labeled as such (see Tables 1–4), and their associated life-cycle impacts are discounted over two consecutive lifetimes.

Given that allocation has a large impact on LCA results, the allocation of coconut husk materials as a waste product with zero contribution to land use and inflows of coconut production in the base-case scenario was deemed important to discuss. It was decided to model the coconut husk resource as a zero-burden waste material because the annual production volume of coconuts in Ghana is extremely substantial, reaching over 412,000 tons in 2020 [63]. Unlike the coconut shell, which is deemed a byproduct because of its high calorific value, the husk is considered a waste product. The coconut agricultural crop residue in Ghana has a residue-to-product ratio (RPR) of 0.6 [64]. Such residue is typically that associated with agro-industrial byproducts produced after crop processing. Less typically, it can also include those materials left on the farms after harvesting the target crops or burnt on the farms. A study by Salzer et al. [65] showed that, even if an industrial-level scale-up occurred for coconut husk-based panel production, only close to 10% of available husks would be used. The same study also suggested that the eventuality of maximum availability of the resource being reached is currently far from being realistically achievable. Therefore, the designation as a pure waste product was considered appropriate.

Lastly, the choice of the life-cycle impact assessment (LCIA) method and categories to be used in the assessment was dictated by considerations of relevance, as well as by the need to ensure consistency with the pre-existing EPD for CLT boards. As a result, the TRACI 2.1 method was selected, and the following impact categories were assessed: global warming potential, excluding biogenic carbon (GWP, measured in kg of CO_2-eq), acidification potential (AP, measured in kg of SO_2-eq), and eutrophication potential (EP, measured in kg of N-eq). Additionally, the nonrenewable primary energy demand (nr-CED, measured in MJ of oil-eq) and total freshwater consumption (FWC, measured in kg) were assessed.

2.2.1. CLT Board Supply Chain

In Canada, there is ample availability of sustainably harvested spruce timber; therefore, it was assumed that the wood for the production of the CLT boards would be harvested from these forests, with no net associated land-use change. The LCIA impacts per unit of CLT board were obtained from a pre-existing EPD carried out for the "Nordic X-lam^{TM} CLT" manufactured by Nordic Structures in Québec [66].

2.2.2. Bamboo Board Supply Chain

The study of bamboo within the context of Nairobi, Kenya was deemed important given the government of Kenya's targets for future bamboo product development [67]. A recent 2021 INBAR report [52] outlined that the bamboo forest area in Kenya, across five regions, is over 1,300,000 m^2, which equates to more than 5 million tons of carbon (tC) being present in Kenya's bamboo forests. This highlights the potential for reductions in carbon emissions if forests are sustainably managed for durable product development, such as building materials. According to knowledge of bamboo processing in China, it is estimated that 40% of harvested bamboo biomass can sequester or store carbon in durable building material products. In such a scenario, over a period of 30 years, the INBAR study indicated that the carbon storage capacity in Kenyan bamboo products could be over 15 million tC (equivalent to over 56 million tCO_2). However, the report also stated that in Kenya bamboo forests are currently not managed, and they are consequently in very poor condition and contain a high proportion of dead and mature culms.

In addition, understanding land-use change associated with the scale-up of a new biomaterial for construction is critical. Most bamboo in Kenya is classified as "indigenous", but tobacco and eucalyptus farms are also being replaced with bamboo. The species vary depending on climate and soil conditions, but many are species from Asia that Kenya Forestry Research Institute (KEFRI) has tested and in some cases introduced [52]. However, for the purposes of this study, given the large availability of "natural" (non-managed) bamboo in public (i.e., "gazetted") forests in Kenya [52], it was assumed that the bamboo for biomaterial production would be harvested from these forests, with no net associated land use change, although there are potential risks to loss in regional biodiversity associated with the scale-up of these practices.

Processing of the harvested bamboo culm into laminated bamboo boards entails the following steps:

(i) Trimming of the culm using an electric saw;
(ii) Gluing with urea formaldehyde resin, and pressing;
(iii) Trimming of the boards using an electrical table saw.

It is worth noting that emerging research is exploring scenarios for reducing the environmental impacts in the production of laminated bamboo boards. Improvements include increasing the amount of formaldehyde-free resins used such as EPI (emulsion poly isocyanate). Although EPI is a better alternative to formaldehyde, it is still a synthetic resin. A key principle for circular economy material production involves preventing the mixing of technical and biological nutrients in the production of a product. Hence, switching to a fully biobased resin is a preferable scenario to promote a circular material economy and to facilitate end-of-life strategies such as biodegradation and/or bioenergy [68,69].

2.2.3. Coconut Board Supply Chain

As already mentioned, a large volume of coconut waste is currently available in Ghana [70]; as a result, all the collected husks were considered to be "zero burden" at point of collection. However, further specific modeling considerations were due for the two types of coconut husk waste available:

- Husks of mature coconuts, which are grown for coconut oil. Burning these relatively dry husks as waste directly on the farms results in their complete combustion to CO_2

and water vapor, with negligible local air pollution. While in Asia these mature husks are used as peat soil media, this practice is not widely established in Ghana.

- Husks of younger coconuts, which are grown for coconut water. These too are "burnt on the farms to facilitate the harvesting process" [64], but the burning of this higher-moisture-content waste results in "air pollution and blocked roadside drains that facilitate the breeding of mosquitoes" [70]. While this second type of waste may also be utilized for the production of biomaterials, there is not enough quantitative information to accurately estimate the environmental credits due to the avoided air pollution when the waste is collected for the production of biomaterials instead of burnt on site. As a result, the conservative assumption was made that the coconut coir boards under analysis here would be produced out of mature coconut husks only.

Processing of the coconut husks into coconut coir compressed boards entails the following steps:

(i) Manual crushing and decortication. Coconut pith, containing over 60% TDN (1,1,6,-trimethyl-1,2-dihydronapthalene), is also obtained as a byproduct, which can later be used as a binder [24];
(ii) Shredding of the fiber in a hammer mill;
(iii) Thermal pressing of the fiber, sprinkled with coconut pith or soy protein bio-binder in a hydraulic press;
(iv) Trimming of the boards using an electric table saw.

3. Results

Figures 5–9 illustrate the life-cycle impact assessment results for the four wall assemblies, broken down into their three main contributions, namely, the emissions due to the biomaterials (including associated manufacturing), the inorganic materials (including associated manufacturing), and end-of-life incineration and landfilling. For all four wall assemblies, alternative scenarios are provided in which selected parts thereof are designed for disassembly (DfD) and assumed to be reused once in a similar second-life application (see Tables 1–4 and Section 2.2). For the African case studies (bamboo and coconut options), additional scenarios are provided to investigate the effect of the expected future evolution of the regional electricity grid mix, as well as of a potential future switch to 100% dedicated RE procurement (see Section 2.2).

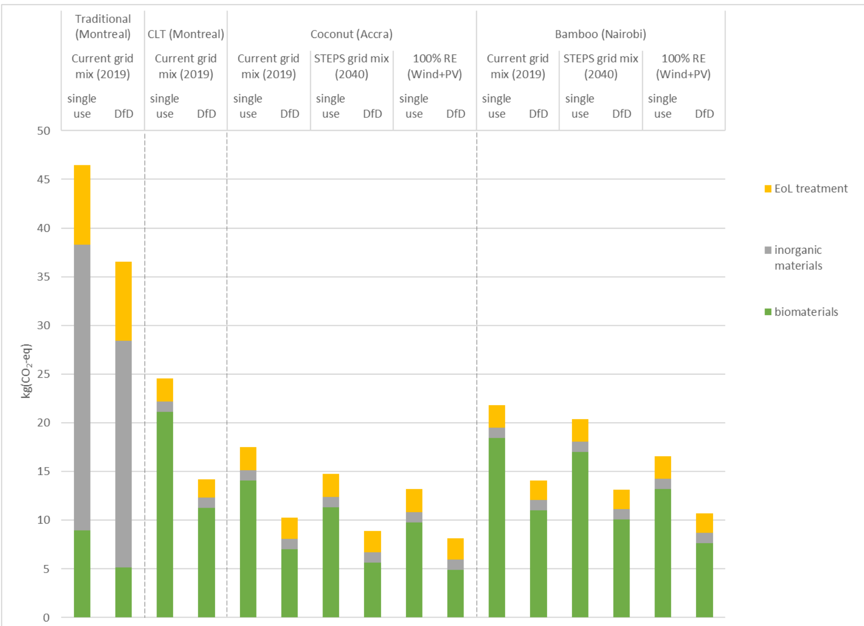

Figure 5. Global warming potential (fossil) results for the four wall assemblies and locations, with sensitivity analyses (FU = 1 m^2).

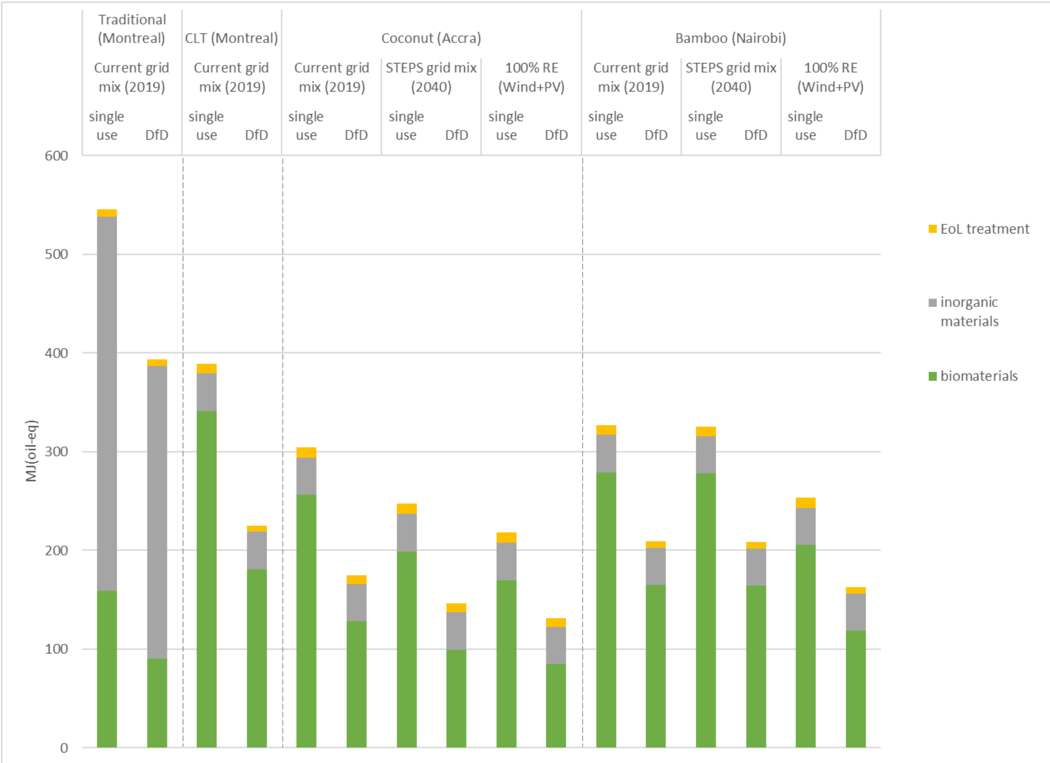

Figure 6. Nonrenewable cumulative energy demand results for the four wall assemblies and locations, with sensitivity analyses (FU = 1 m^2).

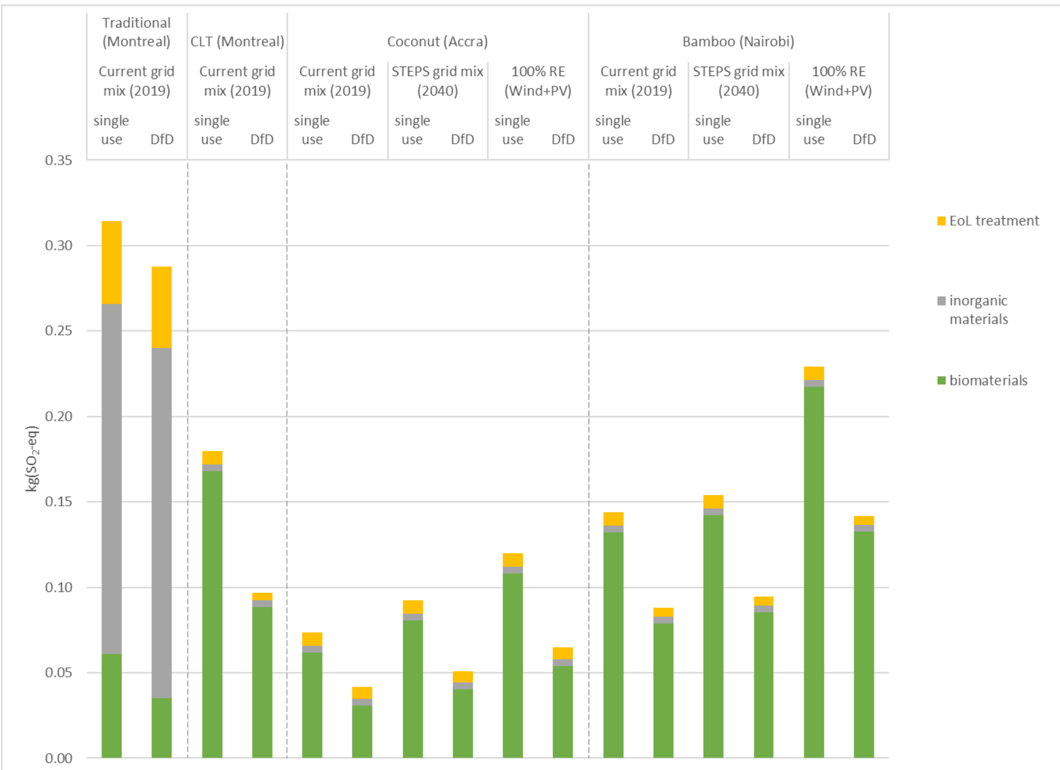

Figure 7. Acidification potential results for the three wall assemblies and locations, with sensitivity analyses (FU = 1 m^2).

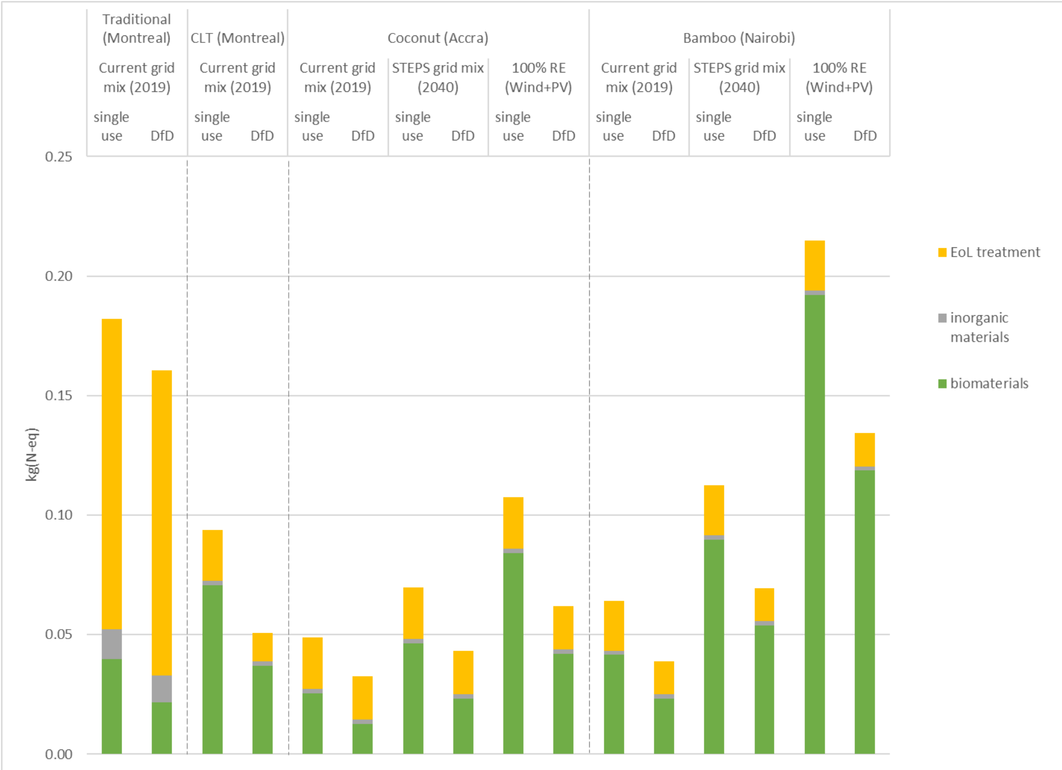

Figure 8. Eutrophication potential results for the three wall assemblies and locations, with sensitivity analyses (FU = 1 m^2).

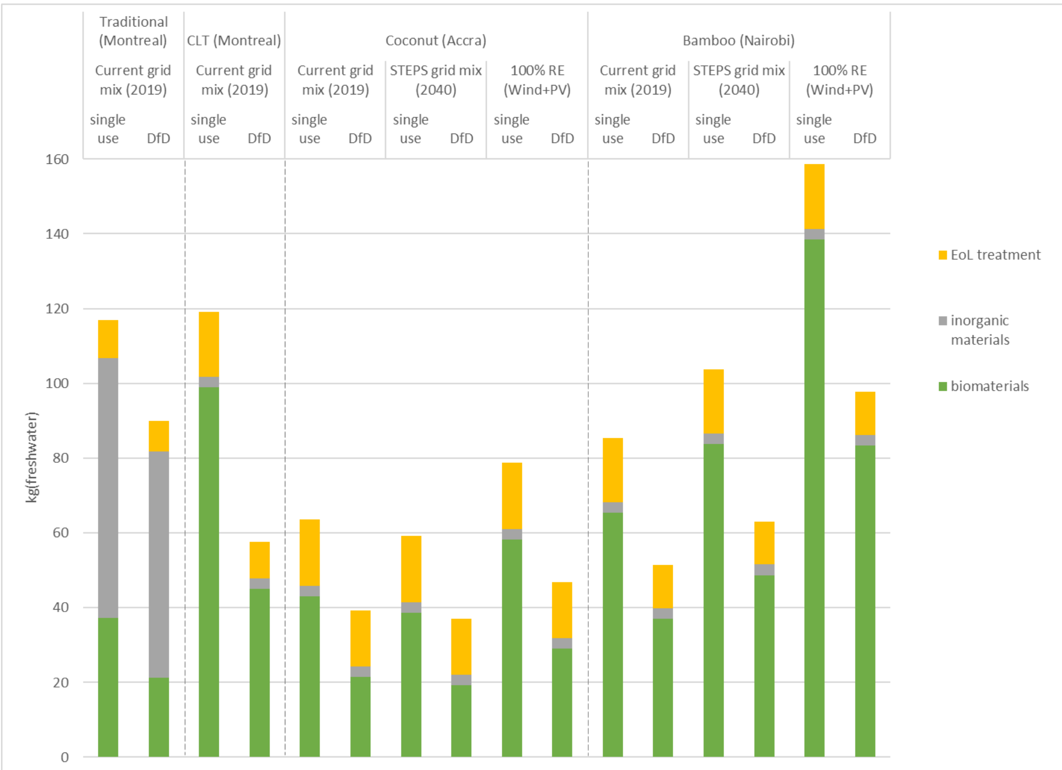

Figure 9. Freshwater consumption results for the three wall assemblies and locations, with sensitivity analyses (FU = 1 m^2).

Across most impact categories and metrics, the first striking result is the significantly higher impacts associated with the traditional wall assembly, which is included in the comparison as the "benchmark". The decomposition analysis clearly shows that the largest share of the impacts is due to the use of inorganic materials (specifically, gypsum boards and rockwool insulation).

Moreover, in very general terms, for all wall assemblies and all considered grid mix scenarios, and across all impact categories and metrics, the results confirm the effectiveness of DfD strategies, whereby selected parts of the assemblies are separated at end of life and reused in second-life applications. Consistently across all cases, the "DfD" scenarios result in significant (from −10% up to −50%) reductions in life-cycle impacts.

Looking more specifically at the results for global warming potential (GWP) and the closely related nonrenewable cumulative energy demand (nr-CED), respectively reported in Figures 5 and 6, several observations can be made. Firstly, the coconut-based option is characterized by the lowest impacts among the three considered biobased alternatives; this competitive advantage is in part due to the substrate material benefiting from being a waste flow to which zero embodied burdens are assigned. Secondly, the results point to a significant dependence on the assumed electricity grid mix used for manufacturing. While the expected evolution for the average grid mix compositions in Kenya and Ghana to 2040, based on currently state policies, only seem to entail relatively minor improvements in terms of overall decarbonization, the results for the 100% RE scenarios (corresponding to dedicated RE procurement for the manufacturing of these products) do point to significant potential margins for reductions in GWP and nr-CED (approximately −25%).

Furthermore, interestingly, the up-front GWP and nr-CED impacts associated with the production of inorganic materials required for the traditional wall assembly are so high that this option still ranks highest in all impact categories, even when its "DfD" scenario is compared to the "single-use" scenarios for the biobased alternatives (CLT, bamboo, and coconut).

The results for life-cycle acidification potential (AP) and eutrophication potential (EP), shown respectively in Figures 7 and 8, paint a different picture. On one hand, since the main contributions to the overall impact in these categories come from the biomass harvesting stage, the competitive advantage for the coconut-based wall assembly is confirmed, since this latter option benefits from not having such harvesting impacts (due to the husks being a zero-burden waste). On the other hand, however, a potential future shift to RE energy use in manufacturing risks increasing, rather than decreasing, the associated AP and EP impacts. In case of a lack of any DfD strategy, in the specific case of the bamboo-based wall assembly, a shift to 100% RE would even lead to worse EP results than the traditional alternative (although not if DfD is implemented). These unwelcome results are largely due to the increased demand for metals (specifically, copper and aluminum) per unit of electricity delivered that characterizes wind and solar PV generators; therefore, they are not directly transferable to other RE technologies. However, the fact remains that wind and PV are the most likely candidates for dedicated RE procurement when, critically, additionality is required (i.e., when the dedicated RE generation must add to the pre-existing grid mix capacity).

Additionally, the analysis indicated that a significant share of the EP impacts is due to the end-of-life waste management processes, specifically to the operation of the municipal solid landfill in the case of the inorganic materials used in the traditional wall assembly construction.

Lastly, results for total freshwater consumption (FWC), illustrated in Figure 9, confirm the competitive advantage of the coconut-based solution, mainly thanks to the zero-burden nature of the waste biomaterial substrate used in that case. Water consumption for the CLT and bamboo alternatives is instead in the same ballpark as for the traditional wall assembly but, importantly, with larger margins for improvement if DfD is implemented. As in the case of EP, in the case of the bamboo-based assembly, a shift to 100% RE in manufacturing risks increasing FWC beyond that for the traditional alternative, unless DfD is implemented.

4. Discussion

First and foremost, this study highlighted that the shift from traditional construction practices relying heavily on nonrenewable inorganic materials to biobased solutions using woody biomass substrates may hold a large potential for environmental impact reductions. These findings appear to be in line with some other early life-cycle studies of the use of biobased material alternatives in the building sector. For instance, Quintana-Gallardo et al. [71] found a 50% decrease in the amount of CO_2 equivalent emitted when replacing plasterboard with bio-composite boards. Other studies have produced less conclusive results (e.g., [72]). However, it is important to underline that each of these results only applies to the specific biomaterial solutions under assessment and are intimately dependent on the associated assumptions on their supply chains; the degree of direct comparability among the results produced by different studies is, therefore, limited.

Secondly, this study provided a clear, quantitative indication of the effectiveness of design-for-disassembly (DfD) strategies that enable the end-of-life recovery and reuse of materials in second-life applications. Thirdly, the study also evidenced the sensitivity of the overall environmental impacts of the biobased solutions to the specific grid mix supplying the electricity input for the associated production processes, as well as some potential tradeoffs between reduced greenhouse gas emissions and demand for nonrenewable primary energy, and increased acidification and eutrophication potentials. It was also noted that, while the grid mix composition is unlikely to change significantly in the foreseeable future in Québec, it may in fact do so in both African countries under consideration here. In the specific case of Ghana, over the past 10 years, the demand for electricity has increased so much that, while most of the electricity was formerly generated by hydroelectric dams, there is now a need to significantly supplement such resources with other energy fossil-based resources, and it appears unlikely that this trend will be significantly reversed in the near term. However, the potential remains for the installation of other renewables such as PV or wind, which would have a positive impact on reducing greenhouse gas emissions [73]. Furthermore, new biomaterial manufacturing may be supported by dedicated decentralized RE generation model using on-site solar or other renewable electricity systems. Additionally, in many African countries, such decentralized models often prove more reliable for the manufacturer than connection to a centralized electrical grid potentially susceptible to power outages.

The comparative nature of this study also highlighted the role that the use of an agricultural byproduct (e.g., coconut husks) as opposed to a virgin biobased material (as in the case of bamboo and CLT) has on the overall environmental impacts. The bamboo and CLT require energy for harvesting, which is not the case for the coconut husks, since these are assumed to be a readily available waste product (however, it is noted that other engineered wood and bamboo products also employ a non-negligible percentage of waste substrates).

One limitation of this study is that it did not include components for structural joints, which would be critical for a full LCA of building systems incorporating these materials, with respect to the requirements for structural integrity, as well as the EoL considerations. The three material sectors all present variable but substantial opportunities for innovation in DfD, which would substantially alter life-cycle considerations, although these aspects were not considered in the context of this comparison. However, future analysis is required to examine the tradeoffs between upfront embodied impacts in the production phase, and the potential downstream benefits of adaptability and reuse from DfD; for example, since the metals sector is so far advanced in EoL recycling methods, emerging DfD systems in CLT have favored the use of metal fasteners that are easy to disassemble, and the increasing predominance of metal fasteners is likely to impact the life-cycle impacts of these systems, in comparison to assemblies that seek to limit the use of carbon-intensive metal components through the use of biobased fasteners such as wooden dowels. However, the latter limit the adaptability of the structure for DfD, in comparison to the ease and flexibility of metal structural components.

One challenge encountered in this study, which future research may aim to overcome, was that of comparing fully optimized factory processes such as those for CLT manufacturing with emerging fabrication processes. This also raises the question of how best to quantify and gain an understanding of the impacts of emerging biomaterial processes whose widescale market take-up is not currently yet a reality.

The authors are also keenly aware of the issues related to the scale-up of these building materials, especially in the countries of the Global South, as a means to meet the growing demand for construction materials in the face of rapid urbanization and housing shortages. Being fully aware that the results presented here are only a snapshot of the current situation, the authors acknowledge that future, more consequential studies should consider the potential change in the land-use patterns that could be triggered by high demand and a wide-scale market take-up of these materials. Such future studies should aim to quantify the indirect emissions associated with induced land-use change (iLUC), as well as the potential for soil erosion and land degradation. However, accurately quantifying these impacts is a monumental challenge; in fact, this initial piece of research puts into stark relief how difficult it is to assess the potential environmental consequences of the long-term scale-up of biomaterials. Although these materials do appear to be sustainable in the short term, in the long term, the same results cannot be simply assumed to hold for scaled-up versions of the same processes and supply chains, which renders the accurate quantification of the long-term impacts of biobased construction materials elusive.

Lastly, further research will also have to focus on the potential social (as well as environmental) impacts of biobased materials intended as steppingstones toward a truly circular built environment. To this end, the use of complementary approaches such as that provided by social life-cycle assessment (S-LCA) may be employed, while acknowledging its many remaining limitations and sources of uncertainty.

Supplementary Materials: The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/en15197239/s1, complete bills of materials (BOMs) for all four considered wall assemblies (Tables S1–S4); R-value calculations for all four considered wall assemblies (Tables S5–S8).

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