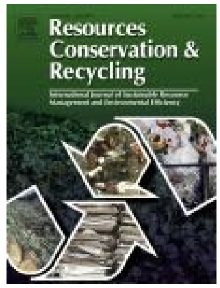

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Integrating durability-based service-life predictions with environmental impact assessments of natural fiber–reinforced composite materials

Highlights

- Durability must be considered in selecting and comparing novel materials.

- Environmental impact and durability are concurrently examined in material analysis.

- Material service-life is application and site specific.

- Bio-based composites have the potential to offer low impact material alternatives.

Abstract

As concern about resource conservation has grown, research efforts have increased to develop materials out of rapidly renewable constituents, to assess their life cycle environmental impacts, and to predict their service-life performance. Assessing time-dependent material property deterioration, often a concern for polymers and their composites, is essential to evaluating the viability of novel materials to serve as lower environmental impact replacements for conventional materials. However, research in methods to combine environmental impacts from production and material deterioration is limited. In this research, a durability-based service-life model was used to assess and incorporate composite deterioration into life cycle environmental impact analyses. The inclusion of composite deterioration under differing temperature and moisture conditions in these analyses typically resulted in higher volumes of material needed to serve the desired function compared to volumes needed to satisfy initial design requirements, leading to a change in environmental impact.

While this concept falls in line with the classic definition of material efficiency, namely improving mass yield for materials, the results of the life cycle impact assessment showed with certain process modifications lower environmental impacts could be achieved even in cases where more material was being used. These findings indicate that design decisions must account for application-specific requirements and consider environmental impacts concurrently with material deterioration.

Keywords

Life cycle assessment

Service-life

Bio-based composite

Wood flour

Moisture-induced deterioration

Durability

1. Introduction

As concern for resource conservation has grown, so has interest in the use of life cycle assessment (LCA) to measure environmental impacts of products in the building and construction sector (Shohet and Paciuk, 2004). Research suggests that in order to address resource depletion and environmental impact, LCAs should be incorporated into the design of materials and products (Ortiz et al., 2009). Material behavior and maintenance during use can increase the environmental impacts associated with a material and, in some cases, exceed the environmental impacts associated with production (Jönsson, 1999). Therefore, to reduce environmental burdens associated with material production and use, LCA and service-life performance should be concurrently incorporated into material design procedures.

Along with stimulating interest in reducing environmental impacts of conventional materials, our understanding of anthropogenic effects on the environment has lead to developing novel materials, such as natural-fiber composites (George et al., 2001, Akil et al., 2011, Wang and Huang, 2009). Natural fibers are abundant, inexpensive, recyclable, and biodegradable, unlike common synthetic reinforcing fibers (e.g., glass, aramid, carbon). Due to their similar specific stiffness relative to glass fibers, natural fibers are considered an environmentally preferable alternative to synthetic fiber reinforcement (George et al., 2001). Several LCAs confirm that inclusion of natural fibers in composites can reduce environmental impacts, such as greenhouse gas emissions, of a composite relative to using the neat polymeric material (Pietrini et al., 2007, Xu et al., 2008, Miller et al., 2013a). Additionally, fully bio-based composites of natural fibers in a biopolymer matrix have been shown to have lower environmental impacts than some petrochemical-based composites for certain applications (Pietrini et al., 2007, Miller et al., 2013a). While biopolymers alone have not been shown to have consistently lower environmental impacts than their petrochemical counterparts in mass and volume comparisons (Yates and Barlow, 2013), several authors have suggested methods for improving environmental impacts associated with biopolymer production through use of byproducts or waste flows for carbon feedstock (Koller et al., 2013, Kendall, 2012).

While there are apparent benefits to using natural fibers, the hydrophilic nature of natural fibers and the hydrophobic nature of most polymers often result in poor interfacial adhesion between the fiber and matrix. This incompatibility can lead to poor dispersion of fibers, non-perfect adhesion between the fiber and the matrix, and low mechanical properties (Nuñez et al., 2004). Additionally, moisture sorption into natural fibers can lead to hydroexpansion. When there is moisture sorption in natural fibers bound in a polymeric matrix, this hydroexpansion of the fibers can lead to stiffness and strength reductions, matrix cracking, and mass loss over time associated with water ingress (Stark, 2001, Chow et al., 2007, Srubar et al., 2012a). In turn, these effects lead to reduced durability of natural fiber-reinforced materials. Anticipation of such reductions necessitates the consideration of their long-term performance into their LCAs.

For novel materials, such as bio-based composites and bioplastics, LCAs are commonly performed on a volume or mass basis (i.e., cradle-to-gate production of the material) and compared to assessments of existing materials (Xu et al., 2008, Yates and Barlow, 2013). Because the material properties of novel materials are not necessarily consistent with existing materials, constant volume and mass comparisons are not an accurate basis of comparison. Furthermore, service-life is rarely accounted for given the lack of knowledge of material in-service behavior. Therefore, even studies that incorporate initial material properties into analyses do not capture material degradation during service or region-specific influences on material deterioration (Pietrini et al., 2007, Xu et al., 2008). Current knowledge gaps, such as deterioration properties for novel materials, result in either comparisons with large levels of uncertainty or comparisons that neglect consideration of durability completely. This issue speaks to the need to develop and apply material durability models that can capture time-dependent changes in properties and integrate these predictions into environmental impact analyses.

To address this need, this study integrates predictions of time-dependent and location-dependent in-service moisture-induced deterioration into LCAs. This research signifies the importance of providing more comprehensive functional units for LCAs of materials that can degrade during service by considering necessary in-service conditions. The role of material durability in material selection for building design is discussed. Additionally, implications of alternative processing methods and constituent selection for composites on material efficiency, defined as "providing material services with less material production and processing" (Allwood et al., 2011), is considered herein.

2. Objectives

The intent of this research is to analyze the effect of integrating the expected in-service moisture-induced degradation of natural-fiber composites into environmental impact analyses to guide design and selection of these composites. To conduct this research, LCAs are conducted. LCA is a tool for quantifying environmental impacts associated with a product's entire life from raw material acquisition through final disposal. To predict the service-life (in-use degradation) of these materials, a stochastic moisture-induced deterioration model for natural-fiber composites is employed.

Through integrating the moisture-deterioration model into the LCA, the susceptibility of the composites to environmental and time-dependent material degradation was considered in the environmental impacts.

3. Methodology

3.1. Materials

This research focuses on eleven formulations of wood-polymer composites (WPCs). Composite specimen nomenclature is given in Table 1. The variables considered in this study included different polymer matrices, wood fiber weight fractions, the addition of maleic anhydride (for improved moisture resistance), process improvements, and different sources of carbon feedstock. Nine of the eleven composites examined contained a poly(β-hydroxybutyrate)-*co*-(β-hydroxyvalerate) (PHBV) matrix and two contained polypropylene (PP) matrices. Three of the nine PHBV composites were modeled using a simple carbohydrate carbon feedstock for the production of PHBV. This PHBV production method was modeled based on average data presented in the literature (Miller et al., 2013b). These three composites contained: (a) 20% by weight wood flour filler; (b) 40% by weight wood flour filler; and (c) maleic anhydride-treated PHBV with 20% wood flour by weight. Three samples of the nine PHBV composites were also modeled using a simple carbohydrate carbon feedstock for the production of PHBV with process improvement (to lower environmental impacts) based on a previously published analysis by Miller et al. (2013c). The same three composite permutations were considered again: (a) 20% by weight wood flour filler; (b) 40% by weight wood flour filler; and (c) maleic anhydride-treated PHBV with 20% wood flour by weight. The final three of the nine PHBV composites were modeled as having a biogas carbon feedstock for the PHBV with idealized processing conditions using landfill biogas as a fuel source for production. This analysis is based on results published by Rostkowski et al. (2012). The same composite permutations were considered again: (a) 20% by weight wood flour filler; (b) use of 40% by weight wood flour filler; and (c) maleic anhydride-treated PHBV with 20% wood flour by weight. Maleic anhydride, the compatibilizing agent used to improve fiber–matrix adhesion in natural-fiber composites, was considered in this research to assess the value of utilizing this agent to reduce material deterioration and associated environmental impacts. Variation in polymer feedstock and production methods was assumed to impart no difference in composite material properties. Composite production methods and material characterization were based on Srubar et al. (2012b). In addition to the PHBV composites, two wood flour-filled polypropylene (PP) composites with 20% and 40% wood fiber weight fraction were considered based on production methods and material characterization by Stark (2001), which allowed for comparison of biopolymeric PHBV composites to petrochemical-derived (PP) polymer composites.

Table 1. Composites considered and naming conventions applied: values indicate weight fraction of constituent materials.

Abbreviation	PHBV	PHBV with processing changes	PHBV from biogas	Maleic anhydride grafted PHBV	Maleic anhydride grafted PHBV with processing changes	Maleic anhydride grafted PHBV from biogas	PP	Wood flour
P20	80							20
P40	60							40
M20				80				20
P20i		80						20
P40i		60						40
M20i					80			20
P20b			80					20
P40b			60					40
M20b						80		20
PP20							80	20
PP40							60	40

3.2. Determination of service-life

To predict differences in the service-life performance of the composites in a variety of geographic locations, a stochastic deterioration model for moisture-induced deterioration in wood-polymer composites developed by Srubar et al. (2014) was implemented in this analysis. Specifically, the model predicts moisture-induced deterioration in the natural fiber composites. It is implemented to analyze the tradeoffs between improved sustainability (e.g., lower environmental impact achieved via higher fiber contents) and reduced resilience (e.g., degradation due to moisture ingress, fiber swelling, and corresponding deterioration). Higher fiber contents result in more swelling, and corresponding lower polymer contents result in less resistance to this swelling. Thus, there exist tradeoffs between lowering the environmental impacts and expected lifetime. Complete details of the numerical model have been published in Srubar et al. (2014). The parameters required for the numerical service-life model necessitated accelerated aging of the composite samples (Srubar et al., 2014). More specifically, the liquid water and water vapor transport kinetic constants were empirically characterized, along with moisture-induced reductions in mechanical properties.

The eleven candidate materials were considered for use in an outdoor decking application in three cities with different climates and exposure conditions: Seattle, WA (marine climate); Lihue, HI (humid climate); and Phoenix, AZ (dry climate). In the model, initial material properties of strength and stiffness of the eleven candidate materials were used to design the original cross-sections of decking planks using strength and serviceability criteria typically used in structural design. A finite element implementation was used to simulate fluctuating temperature and moisture boundary conditions, which were generated stochastically using data from the National Weather Service (N.C.D. Center, 2013). Simulations incorporated fluctuations in exposure conditions with respect to temperature, relative humidity, and wet-day statistics for the three cities considered.

Using these data based on national weather patterns, moisture absorption and time-dependent moisture concentrations were tracked through the cross-section of the material using a numerical diffusion-based transport model. At each time-step, the moisture concentration profile was correlated with degrees of deterioration in terms of composite stiffness and strength through the thickness of the material. The model captured the bulk reduction in material properties over time due to heat and moisture exposure for all composites considered herein.

3.3. Life cycle assessment modeling

3.3.1. Goal and scope

As previously discussed, the goal of this research is to provide a method for incorporating material deterioration into environmental impact comparisons. In this research, the focus is on novel bio-based composites to determine the influence deterioration may have on cumulative environmental impacts. The life cycle environmental impacts of WPCs analyzed here include: resource consumption during cultivation of wood and carbon feedstock for polymers; energy and material flows during biosynthesized or synthetic polymerization; refinement processes resulting in the wood by-product and the polymer; manufacturing of composites; and end-of-life disposal (concept displayed in Fig. 1). These data constitute the basis of the life cycle inventory (LCI) and provide means to identify relationships between material and energy flows. End-of-life approximations were based on stoichiometric predictions for anaerobic decomposition. The LCIs for the composites considered, as well as the range and distribution of inputs, can be found in Appendix A and incorporate inventory inputs from several sources including Thiriez (2006), Althaus et al. (2007), Frischknecht and Jungbluth (2004), and Spielmann et al. (2007), among others. LCIs were developed to represent production of 1 kg of composite material for each of the eleven WPC composites analyzed. Manual labor and packaging were not included in the LCA. Data were not available on packaging for composite constituents and was assumed to be negligible relative to the constituent mass. Production of machinery and depreciation of machinery from use were considered to be minimal and excluded from the assessment according to the common practice (Heijungs et al., 1992).

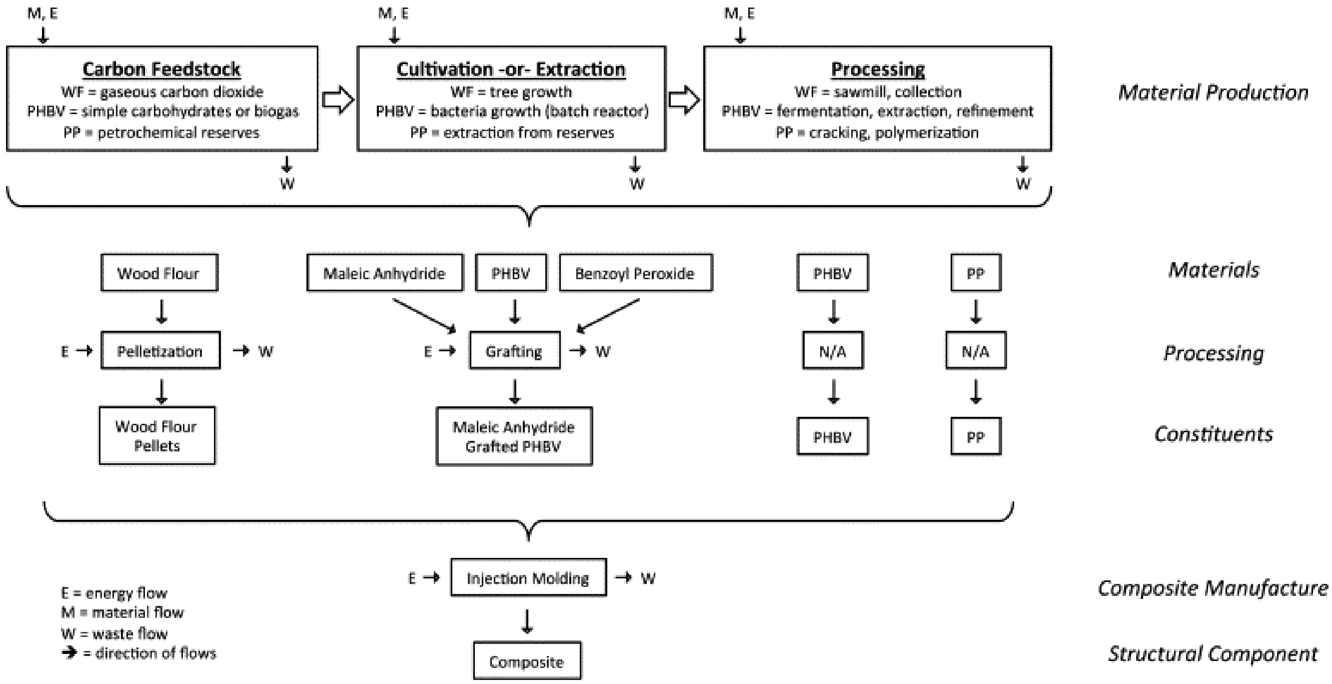

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Fig. 1. LCA scope diagram for composite cradle-to-gate production; transportation of material considered between sites.

Environmental impacts were assessed based on four environmental impact categories: global warming potential (GWP) (based on the IPCC weighting scheme (Bernstein et al., 2007)), fossil fuel demand (FFD) (based on the Eco-Indicator '99 weighting scheme (Goedkoop et al., 2000)), acidification and eutrophication (both based on the BEES weighting scheme (Lippiatt, 2007)). Monte Carlo simulations were conducted to incorporate input quantity variability and environmental impact uncertainty (n = 10,000) based on uncertainty methods developed by Weidema and Wesnaes (1996) and expanded upon by Frischknecht et al. (2005). A brief description of the input distributions and uncertainties considered in the Monte Carlo simulations, as well as the LCI tables can be found in the Supplementary material in Appendix A.

3.3.2. Functional unit for comparison

The functional unit for this comparison was based on the volumetric amount of material required to safely resist structural design loads. It is recognized that an alternate approach to the functional unit would have been to design each composite to last a given number of years (service-life equivalency). However, the latter approach would require an iterative design process and is less similar to current priorities in conventional engineering design. For the moisture material degradation simulations, the eleven composite formulations were sized based on initial mechanical properties, as mentioned above. The width and span length of the materials were set at 115 mm and 1030 mm, respectively, and the thickness was determined based on the thickness required to satisfy both strength and deflection criteria.

For calculation of both member dimensions and exceedance of service limit states, Euler–Bernoulli beam theory for a simply supported beam under a uniform load was applied. The loading for the decking application was taken as a uniform dead load of 479 Pa and live load of 1915 Pa according to ASCE 7-10 (ASCE, 2011). In terms of strength criterion, a factor of safety of 1.0 was applied. For the deflection criterion, the thickness was chosen so initial deflection was below the maximum allowable elastic deflection, taken as the member length divided by 360 ("$l/360$"). The design thickness for the member cross-sections used in this analysis was the minimum thickness that satisfied both design criteria. The composite mechanical properties, design dimensions, and densities can be found in Table 2.

Table 2. Initial design mechanical properties, dimensions, and composite densities.

Material	Strength (MPa)	Modulus (GPa)	Span Length (mm)	Width (mm)	Depth (mm)	Density (g/cm^3)
P20	52.9	3.80	1030	115	34	1.22*
P40	38.5	4.10	1030	115	33	1.24*
M20	48.5	3.90	1030	115	34	1.24*
PP20	44.8	2.13	1030	115	42	0.98**
PP40	46.6	3.68	1030	115	35	1.07**

*

Densities from Srubar et al. (2012b).

**

Densities calculated based on wood fiber density of 1.44 g/cm^3 (Srubar et al., 2012b) and polypropylene density of 0.91 g/cm^3 (Nuñez et al., 2003).

Moisture absorption, property degradation, and deflection, were considered to determine time-dependent exceedance of service-lifespan limits states. For moisture absorption, the limit state was reached when moisture absorption caused a 15% reduction in strength, the wet service design factor used in wood strength design. This reduction criterion was applied because the polymer composites considered in this analysis exhibit a similar strength reduction to moisture content ratio as wood (based on results presented by Stark, 2001, Srubar et al., 2012a, Srubar and Billington, 2013, Wilson, 1932). For deflection, the suggested loading combination of dead load + 50% of live load from ASCE 7-10 (ASCE, 2011) for long-term effects was applied. Exceedance of the deflection limit state was considered when the modulus was reduced to the point at which beam deflection exceeded $l/360$. For the total service-lifespan, it was assumed that there was a 20yr maximum desirability of the decking components and exceedance of this 20yr service-life span was considered to not have any continued functional value (decks are expected to have a service-life value of 20yr (Seiders et al., 2007)). For the purposes of this analysis, fractional replacements of composites were considered when a replacement of a composite would exceed the 20yr life span. Fractional replacement values were based on a linear correlation between material serviceability and time.

Due to differences in densities and mechanical properties, LCAs were made based on both volume of material needed to meet initial design criteria as well as volume of material needed to meet serviceability design criteria assuming replacement of material upon exceedance of the serviceability limit states.

3.3.3. Composite material inputs

For this analysis, the primary material constituents of the composites were the polymer matrices, wood flour, and the additives used in producing maleated PHBV. PHBV is cultivated in certain strains of bacteria, such as *Alcaligenes latus* and recombinant *Escheria coli*, as well as others, when they are put under specific environmental stresses, such as phosphorus deprivation (Anderson and Dawes, 1990, Akiyama et al., 2003, Lu et al., 2008, Valappil et al., 2007). The LCI of PHBV included resources consumed and the emissions discharged into the environment during cultivation of renewable carbon feedstock (in this case, simple carbohydrates), bacterial growth, bacterial fermentation, extraction, and purification (Miller et al., 2013b). The LCI of PHBV with processing improvements was built off of the LCI of the first PHBV by incorporating additional considerations for recycling process heat through heat exchangers and for incinerating waste biomass to provide an additional fuel source for manufacture (Miller et al., 2013c). The LCI of PHBV from a biogas carbon feedstock was modeled as synthesized in methanotrophic bacteria using biogas as the carbon feedstock for both the bacteria and the energy needed to cultivate, extract, and purify the polymer (Rostkowski et al., 2012).

Polypropylene is formed by the polymerization of propylene. In this research, propylene was modeled as a by-product of the petroleum refining industry and as co-product of ethylene production. While it is a by-product, environmental impacts were allocated to the production of polypropylene from the petrochemical industry. This analysis considered extraction of petrochemical carbon feedstock, cracking liquid feedstock, polymerization of the monomer, and refinement (Hischier, 2007).

The LCI of wood flour composite filler was considered to be a by-product of lumber production: when timber is cut using a sawmill, the teeth of the saws rip the wood leaving small wood flour particles that are captured in a gullet (Werner et al., 2007).

3.3.4. Processing techniques

The composites considered in this analysis were fabricated via injection molding. Prior to the injection molding, the wood flour was first pelletized. The pelletization process was modeled as an initial extrusion of the wood flour (representative of pelletization via extruder with an attached pelletizer). Along with the pelletization of the wood flour, the grafting of maleic anhydride to PHBV required additional processing. To graft the maleic anhydride to the neat PHBV, maleic anhydride, a grafting reagent (benzoyl peroxide), and neat PHBV were extruded together in a ratio of 1:1:20 to achieve a 1.32% graft (Wright, 2013). This grafted PHBV and maleic anhydride was then injection molded with the neat PHBV in a ratio of 1:49 of grafted polymer to neat polymer.

3.3.5. Transportation modeling

Transportation estimates for the materials applied in this analysis was based on an analysis of the largest global producers of each constituent and applying the weighted averages of the distances (for sources, see Supplementary material Table A.2; note: distances for maleic anhydride were based on the largest US producers). Because PHBV can be produced from renewable feedstock (e.g., biogas) wherever an appropriate bioreactor can be installed (Rostkowski et al., 2012), it was assumed that this polymer could be obtained from local landfills and ground transportation of this polymer was based on average transportation distances to regional landfills for each considered location (USEPA, 1996). A sensitivity analysis was conducted considering the same transportation distances for PHBV and PP; however, this analysis is not shown in the results due to the similarities in GWP, FFD, acidification, and eutrophication using either transportation methods.

3.3.6. End of life

The end-of-life scenario considered for these composite materials was anaerobic decomposition, as would occur if the materials were disposed in a landfill with methane capture capabilities. Although modeling materials as biodegradable ideally requires identification of a rate of degradation that coincides with specific disposal pathway (van der Zee, 2003), the rate of degradation was not examined in this analysis because the degradation was considered to be on a long enough time scale such that all biodegradable material would decompose. The methane from the biodegradable constituents was modeled based on 47% methane oxidation efficiency (Powelson et al., 2006). Non-biodegradable constituents were modeled as having permanent residence time in a landfill. Anaerobic decomposition of PHBV was calculated using stoichiometric balance of equations and a factor for cell synthesis of 0.13 (Budwill et al., 1992). Degradation of cellulose was based on empirical gas recovery data from the literature (Micales and Skog, 1997). Degradation of the wood flour filler in petrochemical-based polymer matrices was considered to occur based on a review of biological deterioration conducted by Morrell et al. (2010).

4. Results

4.1. Service-life modeling

Using the stochastic degradation model to predict moisture-related reduction in mechanical properties, service-life predictions were made for three limit states: allowable deflection, allowable strength reduction with elapsed time, and a limit state of 20yr of service-life. Fig. 2 shows the time to failure for the composites considered with an intended design life of 20yr. As expected, when the composites were exposed to higher (and more consistent) moisture levels, such as the humidity in Lihue or the rain in Seattle, they exhibited shorter service lives than the composites in the more arid climate of Phoenix. The results demonstrate the exacerbating effect temperature has on moisture movement through materials. This effect is shown in the relative time-to-failure for the P20, M20, and PP20 composites, in which the samples were robust enough to exhibit equivalent service-lives in Seattle and Phoenix but were predicted to exhibit shorter lifespans in Lihue. High average temperatures and high humidity make Hawaii a particularly aggressive hygrothermal environment for natural-fiber composites.

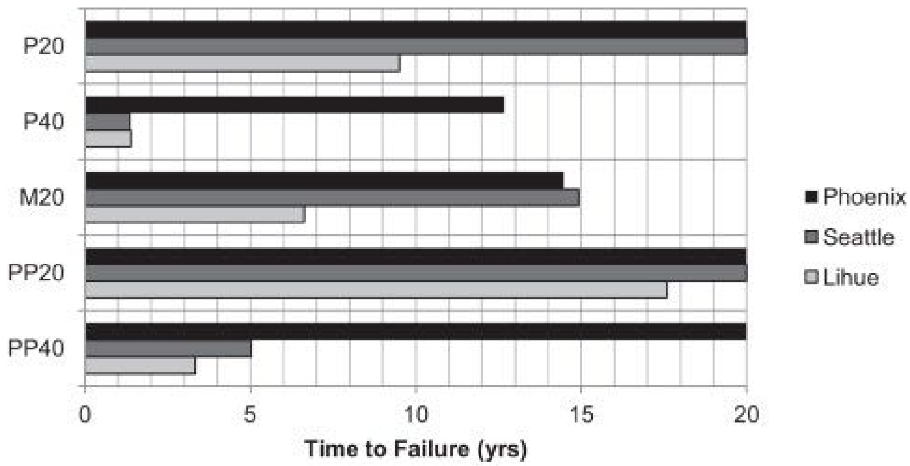

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Fig. 2. Time to failure for set design criteria for composites in Lihue, HI, Seattle, WA, and Phoenix, AZ (note: process improved (P20i, P40i, M20i) and biogas feedstock biopolymer (P20b, P40b, M20b) composites are considered to have the same deterioration properties as the P20, P40, and M20 composites, respectively).

The most common failure mode was exceedance of the allowable reduction in strength during the design life. For the majority of composites, the moisture absorption resulted in a reduction in strength that exceeded the design criteria associated with wood design before the reduction in elastic modulus resulted in exceeding the allowable time-dependent deflection.

4.2. Life cycle impacts

While the eleven composites all have similar constituents, the relative impacts associated with the polymer, wood flour, transportation, and treatment varied. Fig. 3 shows the relative fossil fuel demand (FFD) associated with the 20% fiber weight fraction composites by component for Seattle, WA. For the non-biogas carbon feedstock composites, regardless of whether polymer treatments or polymer processing improvements were incorporated, over 50% of the FFD was attributed to the polymer matrix. However, the total composite FFD associated with the biogas carbon feedstock PHBV composites was primarily a result of the composite molding. Higher FFD was found for the PP composites, a result of: (1) the greater FFD per kg needed to produce PP than PHBV, which was a result of the petrochemical carbon feedstock required for the production of PP; and (2) the transportation of PP, which was based on quantities of regional production unlike PHBV, which was assessed as being produced locally. For the three types of PHBV, the use of process improvements reduced the relative contribution of the polymer to the overall composite FFD from ~65% to ~55%. Use of the biogas carbon feedstock reduced the polymer contribution further to ~25%. Due to the relatively small mass associated with the additives, additional processing and material demands required for the maleic anhydride matrix grafting resulted in negligible addition to the overall impact for the treated PHBV composites. While the PP was modeled as requiring greater transportation than the PHBV, if the same transportation distance were assumed, the PHBV composites without improvements or biogas as the carbon feedstock would still exhibit a ~15% lower FFD than the PP20 composite. As would be expected, if the same transportation distance were assumed for the PHBV as the PP, the relative contribution of the transportation to the FFD would grow to be a greater contributor to the total impact than was noted in the PP20 composite (not shown).

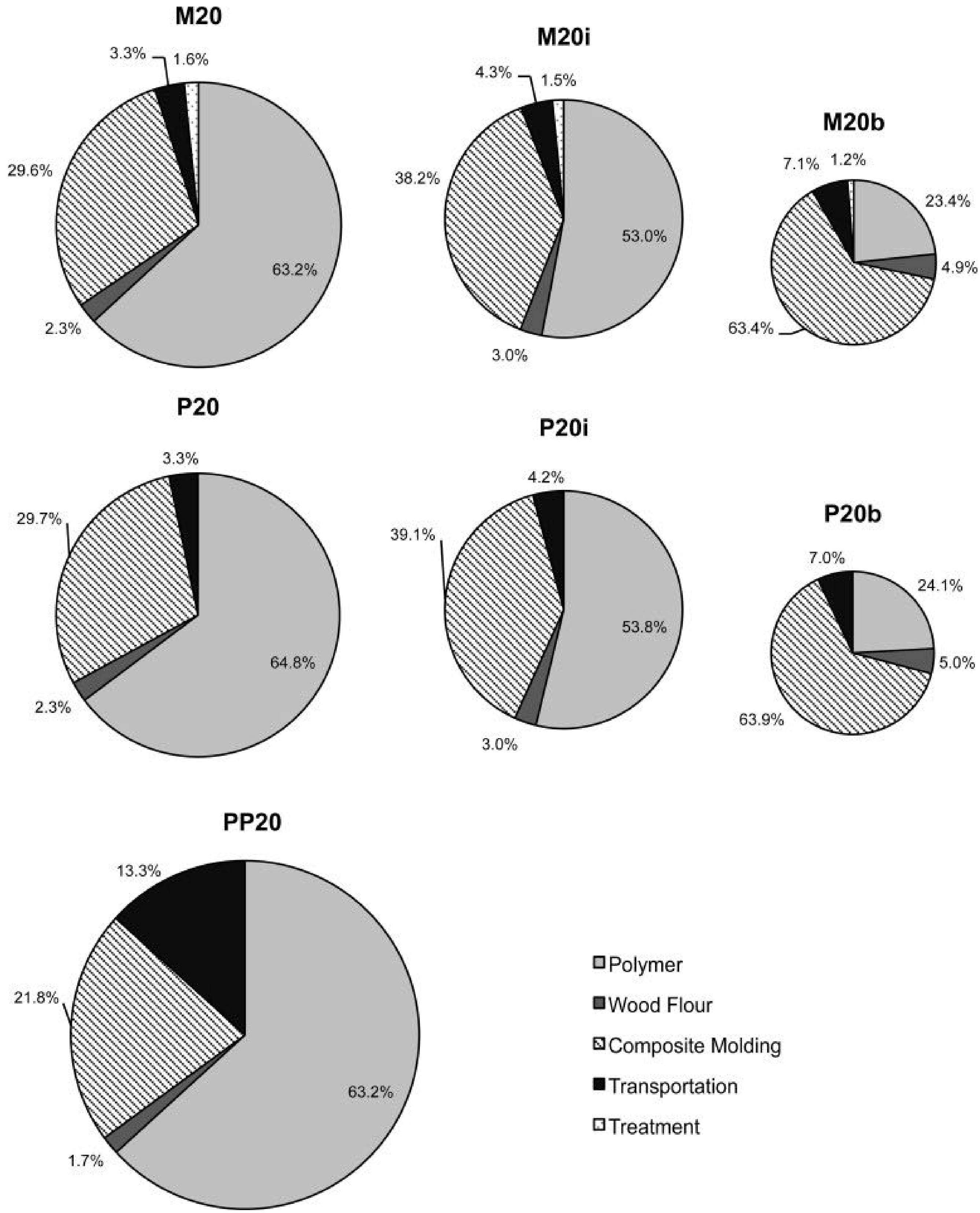

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Fig. 3. Relative cradle-to-gate fossil fuel demand and percent contributions for 20% fiber filled composites in Seattle.

While FFD and GWP are related to one another, these environmental impact categories can differ. The biogas carbon feedstock PHBV composites still offered the lowest impact in terms of GWP. In fact, using the scope and assumptions applied in this research, for the biogas feedstock PHBV composites, the polymer contributed an improved GWP to the composites, outweighing the other components, resulting in an overall lower GWP. Unlike the biogas feedstock PHBV, the simple carbohydrate carbon feedstock PHBV composites displayed greater GWP than the PP composites contrary to findings for FFD. Differences in GWP versus FFD associated with composite constituents resulted in different relative contributions to the overall composite impact; however, as was noted with FFD, the largest contributor to GWP was typically from the composite matrix.

In terms of acidification, the majority of the impacts for the PHBV composites were associated with the production of the polymer, whereas for the PP composites, impacts were nearly equivalent from the polymer, transportation, and composite molding. For the simple carbohydrate carbon feedstock PHBV composites, the use of processing improvements had little influence on acidification. For these composites, the large impact of the polymer (~70%) relative to the other constituents and manufacture of the composites was a result of the acidification from processing the simple carbohydrate feedstock. For the biogas carbon feedstock PHBV composites, the relative impact from the PHBV (~60%) was predominantly a result of the emissions during combustion of the fuel source (landfill biogas): the acidification resulting from combustion of landfill biogas resulted in higher acidification than the U.S. energy mix modeled for the simple carbohydrate carbon feedstock PHBV.

When considering eutrophication, trends were similar to acidification. The application of processing improvements did not significantly alter the relative impacts of the simple carbohydrate carbon feedstock PHBV composites. For these composites, the simple carbohydrate has byproducts during the refinement phase that can offset production of more intensive animal feedstock products. Therefore, the use of the simple carbohydrate as a carbon feedstock resulted in a beneficial eutrophication impact. The use of landfill biogas resulted in a lower relative contribution to the eutrophication impact from the PHBV (~60% relative to ~90% of the overall impact for the simple carbohydrate carbon feedstock PHBV), but using biogas did not offset production of high eutrophication impact products. Therefore, there was no reduction in eutrophication from the polymer. For the PP composites, the polymer contributed ~40% to eutrophication. Composite molding and transportation were responsible for most of the remaining eutrophication contributing ~30% each.

4.3. Integrating composite durability with environmental impact

Fig. 4, Fig. 5, Fig. 6, Fig. 7 show the relative GWP, FFD, acidification, and eutrophication of the eleven candidate materials in three different locations, respectively. Each figure shows the environmental impacts associated with the volume of material to meet initial deflection requirements and with the calculated replacement material needed to meet the 20yr target service design-life. Due to comparable flexural moduli and strength for the composites, the quantities of material needed based on initial design criteria were similar (between 2.15 kg and 2.42 kg per span length) relative to the material quantities needed when composite deterioration and member replacement was considered (between 2.15 kg and 181 kg of material needed per span length).

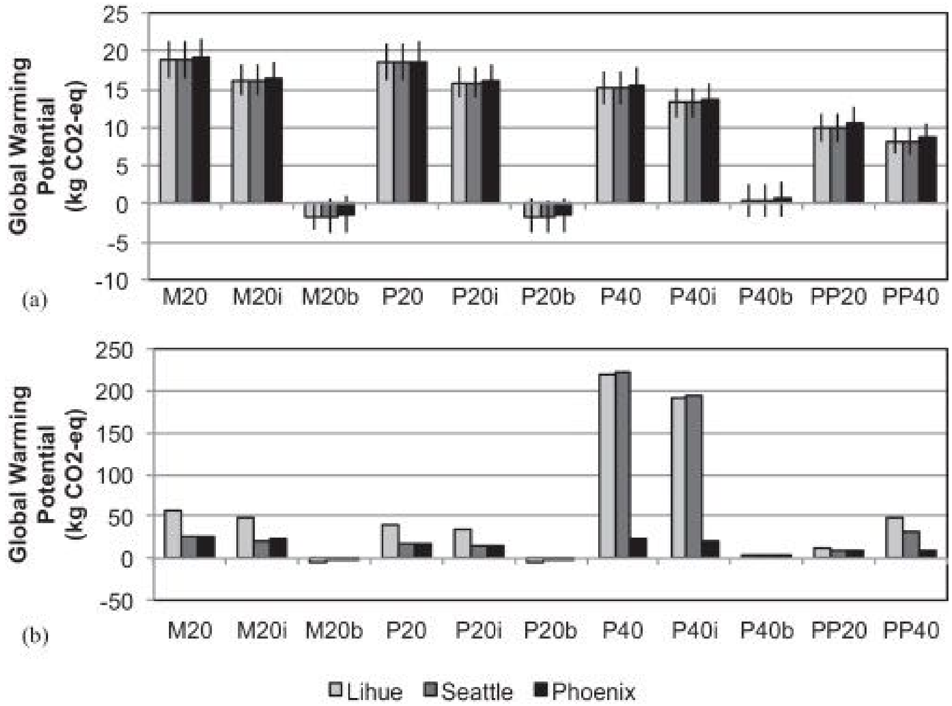

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Fig. 4. Global warming potential for (a) design quantity of composite material needed and for (b) design quantity of composite with requisite number of replacements based on limit criteria.

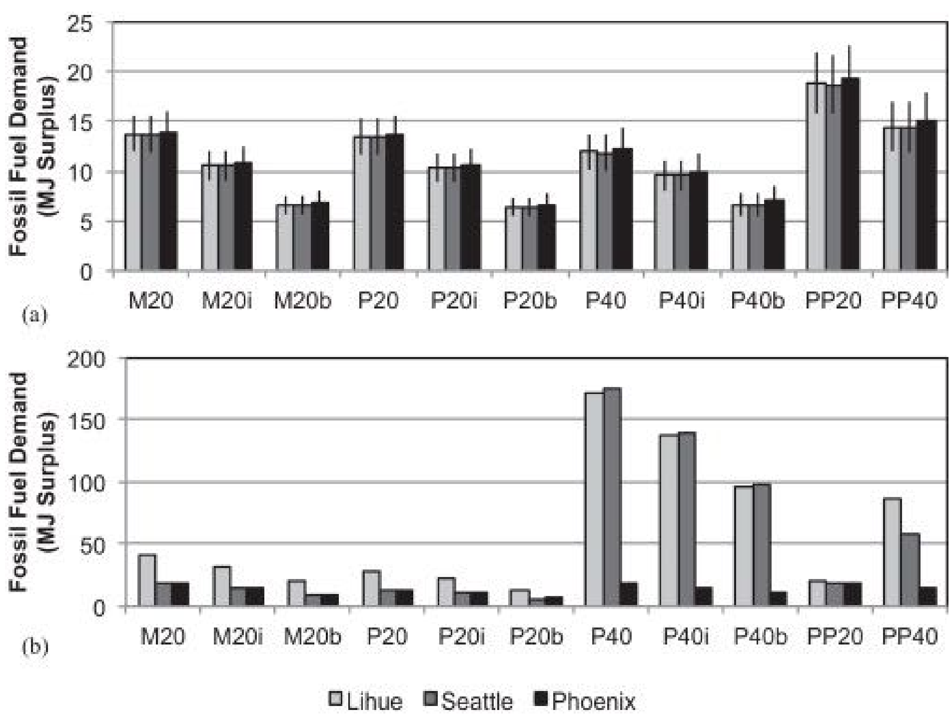

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Fig. 5. Fossil fuel demand for (a) design quantity of composite material needed and for (b) design quantity of composite with requisite number of replacements based on limit criteria.

quantity of composite with requisite number of replacements based on limit criteria.

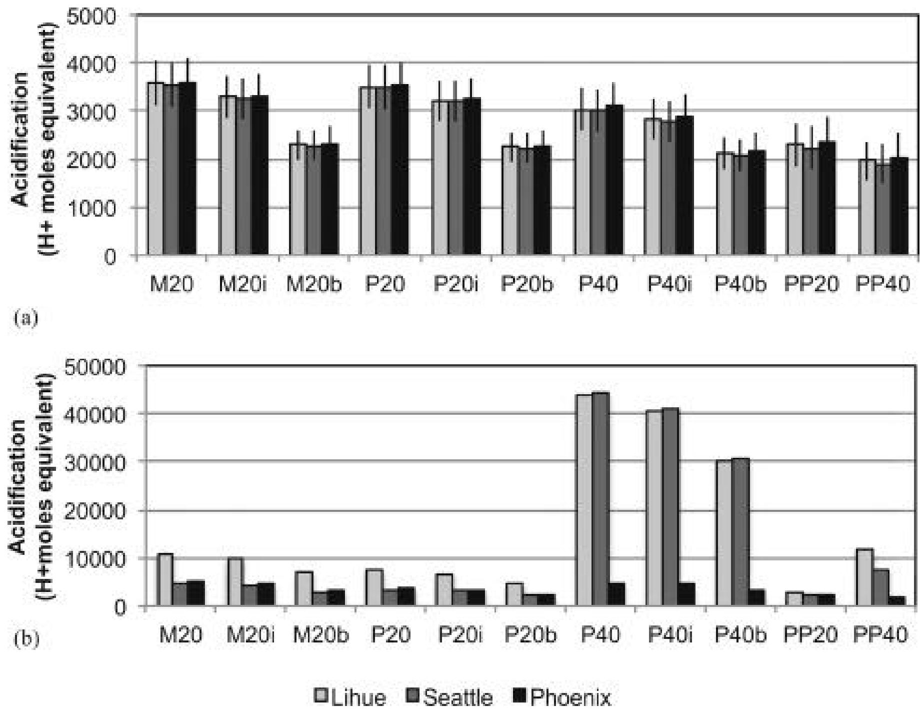

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Fig. 6. Fossil fuel demand for (a) design quantity of composite material needed and for (b) design quantity of composite with requisite number of replacements based on limit criteria.

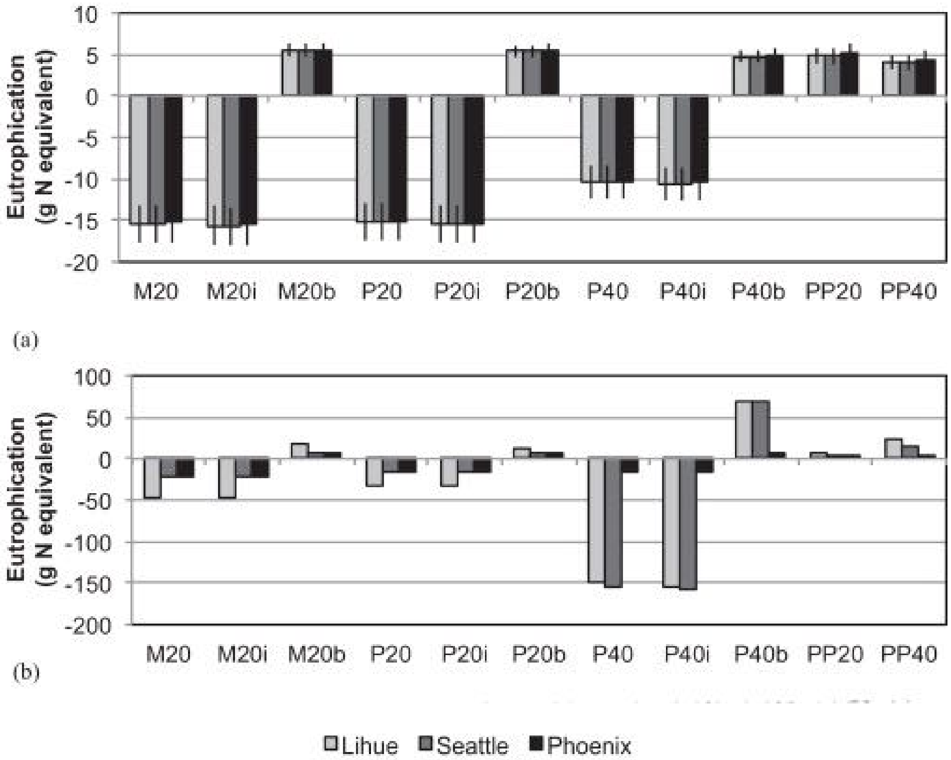

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Fig. 7. Fossil fuel demand for (a) design quantity of composite material needed and for (b) design quantity of composite with requisite number of replacements based on limit criteria.

Based on comparisons drawn on material quantities required for initial deflection criteria (Figs. 4a, 5a, 6a and 7a), the biogas carbon feedstock PHBV composites had lower GWP and FFD relative to the other composites: over 10–25 times lower GWP and 1.5–3 times lower FFD. In terms of GWP, the PP composites had the next lowest GWP with 50–120% lower impact than the simple carbohydrate carbon feedstock PHBV composites, regardless of whether processing improvements were applied. However, due to the petrochemical carbon feedstock needed for the PP composites, all of the PHBV composites provided a statistically significant lower FFD. Yet, for acidification, the biogas carbon feedstock PHBV composites fell in the same 66% confidence interval as the comparably filled PP composites with the PP composites having on average 1–1.8 times lower acidification than the other composites assessed. When transportation distances for the polymer were considered to be the same for each type of polymer, the lower acidification impact from the PP composites was more exaggerated. For eutrophication, the byproducts associated with production of feedstock resulted in the simple carbohydrate carbon feedstock having on average 3.5–4 times lower eutrophication than the other composites.

When incorporating composite material property deterioration (Figs. 4b, 5b, 6b, and 7b), the replacement requirements necessary to achieve a 20yr design life resulted in a shift in the total volume of material required and, thus, the environmental impacts associated with each composite's formulation. Due to higher deterioration rates for the 40% by weight wood-flour filled composites in Lihue and Seattle, the 20% filled composites offered lower GWP, FFD, and acidification. Because of the significant decrease in eutrophication associated with the use of simple carbohydrate carbon feedstock PHBV, the greater deterioration rates for the 40% fiber filled composites resulted in the P40 and P40i composites having the lowest eutrophication for Lihue and Seattle. For both GWP and FFD, the P20b composites were favorable regardless of whether material deterioration and replacement were considered or not. The relative differences between the P20b composites and the non-biogas carbon feedstock polymer composites ranged between 1.5–25 times lower impact based on initial design comparisons and 12–40 times lower impact when deterioration and replacements were incorporated into the analysis in Seattle and Lihue. When considering the influence of deterioration for each of the composites on acidification, the PP composites maintained the lowest average impact ranging from 1 to 20 times lower acidification than the PHBV composites in Seattle and Lihue. In terms of eutrophication, the high level of replacement acted in favor of the P40 and P40i composites, which resulted in 3 to 30 times lower eutrophication relative to the other composites.

In Phoenix, where the composites were less prone to moisture-induced deterioration, smaller shifts were seen in environmental impact categories examined. These results were a function of decreased board replacement relative to the moister climates. For Phoenix, the PP composites remained more desirable than the simple carbohydrate carbon feedstock composites in terms of GWP. However, the P20b was the most desirable composite for both GWP and FFD with 1.5–15 times lower impact based on initial design criteria and 3–27 times lower impact with consideration for deterioration and replacements. For acidification, the PP40 composite offered the lowest impact before and after deterioration was taken into consideration because this member has a low level of associated acidification and was predicted to not require replacements in Phoenix. In terms of eutrophication, the 20% fiber filled simple carbohydrate carbon feedstock PHBV composites had slightly lower impact than the 40% filled composite because few members require replacement in Phoenix. The extra use of polymer relative to fiber in the 20% composites made them more desirable: ranging from 1.5 to 5 lower impact than the other composites formulations.

Logically, the number of board replacements directly influences the total environmental impact of the composites considered. In certain cases, a lower level of deterioration resulted in a composite that was originally undesirable based on initial design criteria eventually becoming more desirable when long-term deterioration and replacements were considered, such as with the PP20 composite relative to the P40 and P40i composites in terms of FFD. The influence of the inclusion of composite deterioration on environmental impacts – and the range of environmental impacts associated with Lihue and Seattle relative to Phoenix – demonstrate the significance of serviceability design criteria in the LCAs of materials susceptible to deterioration.

5. Material durability in material selection

From the results presented here, it is clear that the influence of material durability can change a material's overall environmental impact. Impact of service-life property deterioration on environmental performance should be considered in the design and application of novel materials. Constituents for novel composites should be selected based both on their ability to lower environmental impacts of the composites and their ability for prolonged use. From the cases presented here, while the use of 40% wood fiber weight fraction often resulted in a lower per panel GWP, FFD & acidification than the use of 20% wood fiber weight fraction, the 40% filled composites were less durable in conditions with moisture exposure, resulting in their having to be replaced more frequently and, thus, their typically having a higher cumulative environmental impact for the prescribed service-life.

In the current definition of life cycle environmental impact assessment, use-phase induced impacts are to be taken into account. However, the concept of including durability in sustainable material selection is not yet common practice. For example, the Leadership in Energy and Environmental Design (LEED) rating system developed by the United States Green Building Council awards points for green materials with no regard for how long they will last (USGBC, 2015). The LEED point-rating system awards points to materials that contain recycled content (such as the wood flour in these composites, which could be considered a pre-consumer diverted material flow), as well as to using locally sourced materials (USGBC, 2015), such as the PHBV in the above examples. Yet, the results presented here show that the benefits of lower transportation distances and recycled material content were far exceeded by the impacts associated with necessary board replacement in most cases. The LEED rating system provides points for material reuse and extending the life cycle of building materials, suggesting recognition of the importance of using durable materials to offset environmental impacts. Yet, these points are not considered in conjunction with the locally sourced materials or materials with recycled content. As this research demonstrated, material durability can overwhelm the desirability of any of these other efficiency measures, thus emphasizing the importance of considering not only upfront environmental costs and benefits in material selection, but also the longevity of the materials. While criteria such as LEED certification aid builders and designers in considering potential environmental impacts, they do not incorporate an adequate assessment of factors that could influence desirable material selection for buildings. The case presented in this research emphasizes the effects incorporating material deterioration under different conditions (moisture and temperature in this analysis) could have in comparison of seemingly similar materials and the effects that incorporation could bare on selection of desirable building materials for low environmental impact.

6. Material durability in considering material efficiency

In addition to concerns related to sustainable building material selection, the issue of addressing material efficiency in early stages of design and selection should incorporate decisions regarding material durability. Recent studies have shown humans currently consume 10.5 ton/cap of resources exceeding the available limit, suggested to be 8 ton/cap by 2030 (Hoekstra and Wiedmann, 2014, Dittrich et al., 2012). Use of new, sustainable material technologies, such as the wood flour composites analyzed in this research, has been a proposed method for reducing environmental impacts (George et al., 2001). However, just as the deterioration of material properties influenced relative environmental impacts, they shift considerations for material efficiency.

Material efficiency is classically defined as the ratio of material used to the material supplied (Lifset and Eckelman, 2013); however, as discussed in more recent publications, material efficiency is motivated by environmental impact concerns, not just resource scarcity (e.g. Allwood et al., 2011, Lifset and Eckelman, 2013, Söderholm and Tilton, 2012). In light of this broader concern, it has been argued that material efficiency based solely on material mass "should be integrated with other strategies that explicitly consider [environmental] impacts" (Lifset and Eckelman, 2013). In this discussion, material demand was linked with the life cycle environmental impact results.

Incorporating LCA in early design stages can allow for greater leverage in reducing environmental impacts while there are higher degrees of freedom in material selection (Hellweg and Milà i Canals, 2014).

6.1. Resource consumption considering material deterioration and replacement

Including material yield loss during production, the composites considered in this analysis have similar material demand to produce 1 kg of composite. The similarities arise from the composites being formed using similar manufacturing methods and the similar densities of the constituents. Due to the additional material loss during the pelletization process of the wood flour prior to composite injection molding, the composites with 40% fiber weight fraction had approximately 5% greater yield loss than the composites with 20% fiber weight fraction. The use of maleic anhydride with benzoyl peroxide resulted in a negligible increase in material demand relative to the P20 composites. While not a main focus of this research, for the PHBV composites all material mass was from biogenic sources, with the exception of the mass contribution of maleic anhydride and benzoyl peroxide for the maleated PHBV composites. For the PP composites, the non-biogenic mass accounted for approximately 75% of the mass for the 20% filled composite and 55% of the mass for the 40% filled composites when yield loss was included in the material demand.

As shown in Fig. 8, the initial material demands for the composites are nearly equivalent (±5%). The quantity of material needed can be misleading without considering long-term deterioration. By examining the same figure, it can be seen that in regions with high moisture and correlated increase in material replacement, the material demand to meet the same function increases. However, the material demand was highly regionally dependent: in Phoenix the material demand was far lower than in the moist climates of Lihue and Seattle. Therefore, the efficiency of using a certain material over another is highly dependent on the deterioration properties, exposure conditions, and service requirements, such as limit-criteria and functional time-period of the material.

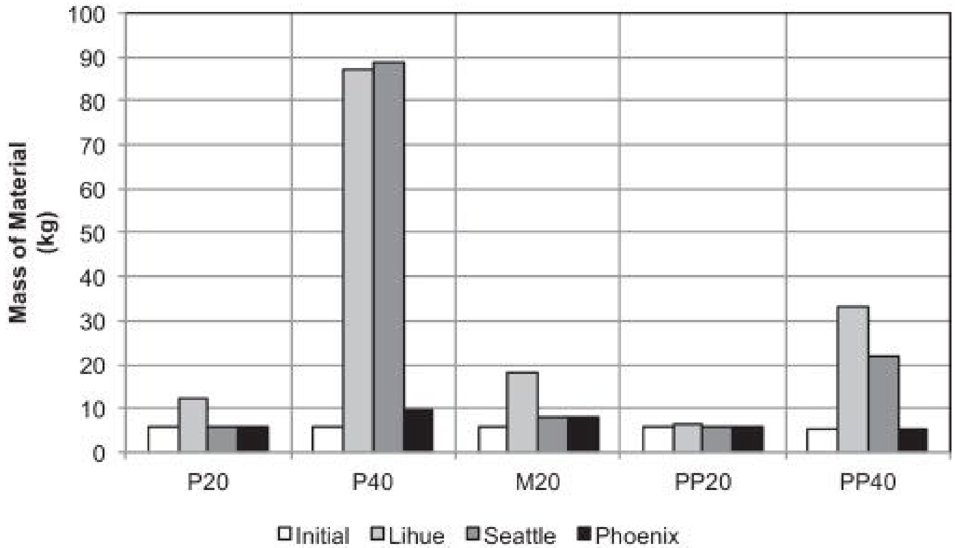

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Fig. 8. Material requirements based on initial design for one board versus design to meet 20 year service period with material deterioration including yield loss from manufacture.

6.2. Material demand and life cycle environmental impact assessment

As was shown with the GWP, FFD, acidification, and eutrophication of these composites, the environmental footprints of the composites assuming the same unit of product (a deck board needed to last 20yr) were highly dependent on the levels of time-dependent moisture-induced deterioration in the various case-study locations. For several cases, the relative material demand for the composites matched these environmental impacts. For example, (a) high FFD for the P40 and PP40 composites was similar to the relative material demand for these composites and (b) trends in GWP were similar in trends to material demand for the PP composites and the PHBV composites made with simple carbohydrate carbon feedstock.

While increased material demand from replacements inherently implies increased material production, some relative differences in composite material demand were not reflected in the environmental impacts examined. For example, (a) there was equivalent (or lower) PP20 material demand relative to the P20 for the three locations considered, but higher FFD of the PP20 composite relative to the P20i and P20b composites and (b) there was lower GWP of the M20b, P20b, and P40b relative to the other composites compared to the material demand relative to the other composites. For these composites, the higher or lower material longevity did not lead to an associated higher or lower FFD or GWP, respectively, relative to the other composites analyzed. In these cases, the use of processing improvements and an alternative carbon feedstock proved to be of greater value than a longer-lasting composite. These findings verify recommendations from previous researchers: material efficiency strategies should be integrated with methods to explicitly consider other related impacts (Lifset and Eckelman, 2013).

7. Conclusions

In this research, the use of degradation models as a service-life prediction technique was applied to provide a complete LCA of several natural fiber filled composites. Environmental impacts were considered based on global warming potential, fossil fuel demand, acidification, and eutrophication. Life cycle models were developed using Monte Carlo simulations based on the likelihood of quantities of material, processing, and transportation distance needed for each composite. Models were developed for three cities with different thermal and moisture conditions: Lihue, HI, Seattle, WA, and Phoenix, AZ.

The inclusion of service-life through deterioration modeling in a decking application exhibited how service conditions can influence a material's associated environmental impact. Differences in which composites were favorable with and without service-life considerations were found in this analysis, emphasizing the need to concurrently design for both longevity and environmental impact. Additionally, this analysis demonstrated how the environmental impact category investigated could influence which material or processing method is ideal for any given application. While the biogas carbon feedstock biopolymer composites were consistently favorable for the global warming potential and fossil fuel demand, this was not the case for the acidification and eutrophication impacts. Furthermore, the decision to use a certain fiber content or polymer matrix varied depending on both impact category and location.

The differences in environmental impact associated with the initially designed composite materials and the volume of composite material needed to meet serviceability limit states emphasizes the need to incorporate both life cycle impact as well as material durability in composite design. Current sustainable material selection methods are often based on sustainability criteria that do not adequately capture serviceability and can result in misleading design decisions. Additionally, considering only the material demand may provide an inadequate basis of comparison. Greater longevity or changed processing conditions to lower environmental impact cannot be used alone to reduce environmental impacts. To truly improve material efficiency, concurrent analysis of material performance properties and environmental impact must be conducted. Future work will expand on these design methodologies that can be employed to perform such concurrent analyses.

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Appendix A. Supplementary data

The following are the supplementary data to this article:

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  Composite preparation was modeled as occurring in Sacramento, California with PLA produced in and transported by truck from Nebraska, the production facility location for NatureWorks®, and with WF produced in and transported by truck from Wisconsin. Energy demands for extruding wood pellets, polymer composite pellets, and injection molding were captured using the same methods detailed by Miller et al. [60] for the production of WPC composites. Because environmental impact assessments by mass or by volume do not capture material behavior, comparisons in this work use an extension of comparison indices developed by Ashby [61].

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  Citation Excerpt :

  Moreover, residential areas generate high levels of air pollution with particulate matter (due to the biomass use to heat the homes), which according to the World Health Organization brings about adverse effects in the health of people [36]; Ministry of Environment [31,47]. In this context, the use of natural fibers for the development of insulation materials has become an essential alternative in order to achieve a sustainable development with less environmental negative impacts [3,21,30]. In this way, the use of synthetic insulation probably will be avoided to maintain comfortable conditions in buildings [12,27,44,45].

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