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Life cycle assessment of UV-Curable bio-based wood flooring coatings

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ABSTRACT

An important recent trend in the paints and coatings industry has been the use of bio-based alternatives to fossil-based building blocks in many applications. This trend is being driven in part by cleaner production and sustainability goals. As bio-based ingredients have been widely shown to present environmental trade-offs along their life cycle, new formulations should ideally be assessed for environmental preference before entering into full-scale production. In this paper, a bio-renewable content (BRC) formulation for wood flooring coating is analyzed using a life cycle assessment (LCA) framework and quantitatively compared to a conventional petrochemical formulation of similar performance across a range of impact categories. This BRC formulation has 50% bio-based ingredients and zero-to-low VOC emissions and was developed by PPG Industries, Inc. The scope of the analysis is cradle-to-gate and includes biomass cultivation and crude oil extraction and refining for renewable and non-renewable chemical inputs, formulation, transport, and application of 1 m^2 of each coating, followed by UV-curing. Comparative results show more than 30% reduction in six out of ten impact categories, using the USEPA TRACI 2.1 impact assessment method, with smog formation, acidification, eutrophication and respiratory effects showing increases in environmental impacts, largely due to burdens from bio-based components. Bisphenol A–epichlorohydrin resin and corn-derived itaconic acid are the most impactful chemicals in the composition of conventional and bio-renewable wood flooring coatings, respectively. Energy use from UV-curing does not appreciably contribute to impacts. The contribution of various building blocks to environmental impacts of both coatings are presented in detail, potentially guiding further formulation research and development. Modifying the BRC formulation to use corn stover instead of corn grain for synthesis of sugar-derived chemicals would improve the environmental profile of the BRC formulation, leading to reductions in all impact categories. The results underscore that meeting targets for bio-based content can have multiple secondary benefits to the environment and human health, but these depend on the particular biofeedstock and conversion processes as well as on the petrochemical components that are being replaced.

1. Introduction

Biomass from dedicated production or residues from forestry, agriculture, and aquaculture could serve as environmentally sustainable feedstocks for fuels and chemicals, provided that production routes offer reductions in energy and material use and emissions on a life cycle basis. Global production of bio-based chemicals (excluding biofuels) is estimated to be 50 million metric tons (De Jong et al., 2012), the largest category of which is synthetic bio-based polymers (~55%) (NNFCC, 2014). Renewable chemical building blocks have been targeted to substitute for petrochemicals in various applications (Holladay et al., 2007; Montazeri et al., 2016; Werpy et al., 2004), including paints and coatings, one of the major markets for chemicals and polymers. Active research and development in this sector has facilitated application of bio-based chemicals in products, such as the use of proteins as biopolymer binders, vegetable oils as binder constituents in coatings formulations (Derksen et al., 1996), non-drying oils including soybean, sunflower and linseed oils as automotive finishes (Athawale and Nimbalkar, 2011), and production of powder coatings and alkyd resins using bio-renewable ingredients (Van Haveren et al., 2007). Various biomass fractions have been utilized as feedstocks for renewable polymers (Gross and Kalra, 2002; Shakina et al., 2012), including polyesters, polyurethane, polyamides, epoxy resins and vinyl copolymers (Meier et al., 2007).

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In this paper, we investigate application of renewable building blocks in composition of wood flooring coatings. Wood coatings, with global market size of 100 million gallons (378 million liters) in 2005 (Davis, 2005), are applied on the surface of the wood in order to enhance its natural beauty, protect wood from abrasion and degradation, and provide a cleanable surface (Williams, 1999). Wood flooring is an important building product and many of the green building rating systems, including LEED, GBTool, Green Globes, and CASBEE, are supportive of coatings that minimize VOCs and other indoor air pollutants (Fowler, 2006), while LEED assigns a credit specifically for use of rapidly renewable materials in coating formulations (USGBC, 2006).

The chemistry and performance of renewable building blocks have been extensively investigated by formulators, as before the advent of modern petrochemicals, agricultural sources were used widely for ingredients in wood coating applications. Plant proteins, linseed oil and soybean oil were all used historically as building blocks in coating formulations (Derksen et al., 1996). With the widespread availability of synthetic polymers, polystyrene, polyurethane and polyvinyl chloride were introduced in coatings with customizable physical properties (Deaner et al., 1996; Meier-Westhues, 2007), while later on, acrylates combined with isocyanates and melamines added high UV durability and hardness to the coatings (Maldas and Kokta, 1991). However, in the late 1970s, the US Occupational Safety and Health Administration (OSHA) issued regulations to help control indoor emissions and maintain safe indoor air quality (IAQ) levels, primarily targeting volatile organic compounds (VOCs) (OSHA, 2015). Exposure to high concentrations of VOCs in indoor environments can trigger membrane irritation, liver and kidney disease and cancer, depending on the contaminant and the level of exposure (Niu and Burnett, 2001).

As a result of new standards, VOCs were targeted for substitution in the development of low-solvent and solvent-less adhesives and coatings (Linak, 2009). Such formulations may reduce VOC exposure for workers and building inhabitants and limit ambient emissions, reducing potential deleterious health effects. The inclusion of bio-renewable ingredients reduces the need for nonrenewable petrochemical inputs. In addition to these direct benefits, there are other types of hazards and potential life cycle environmental impacts to consider, such as total energy use for production and application or greenhouse gas (GHG) emissions. The goal is developing sustainable coating formulations that provide equivalent functionality as conventional formulations, while mitigating associated environmental impacts overall. In order to ensure that new formulations do not have unintended environmental or health impacts, either from emissions during production of novel ingredients, or during product use and eventual disposal, it is necessary to apply a holistic assessment tool that compares formulations on a life cycle basis. In addition to current efforts in decreasing fossil fuel inputs and addressing human health issues, there are various environmental programs that encourage enhancing ecosystem health through consumption of renewable building blocks.

Life Cycle Assessment (LCA) is a tool to assess the potential environmental impacts and resources used throughout a product's life cycle, considering all potentially hazardous emissions and multiple categories of health and environmental impacts that result from those emissions (ISO, 2006). By identifying the processes or materials in a product life cycle that contribute the most or the most hazardous emissions overall, LCA can be used to investigate the most important contributors to environmental impacts. Thus, it can deliver information for designers to guide material selection, assist in supply chain management efforts, compare alternate designs or formulations, and provide product-level assessments that can be used for technology development and marketing.

LCA has been used extensively in the chemicals and formulated products sectors, including coatings (Bidoki et al., 2006; Häkkinen et al., 1999; Hofland, 2012; Papasavva et al., 2001) Häkkinen et al. (1999) investigated environmental impacts of thirteen waterborne and solvent-borne commercial coatings for outdoor applications in Finland, using LCA framework. The cradle-to-grave analysis was framed in a 100-year period including maintenance and renewal, in addition to final disposal of the coatings. The results showed that water-born acrylic coatings had the lowest VOC emissions, as expected. Results for other environmental impact categories were mixed, as several formulations of water-born coatings were shown to have higher energy use and CO_2, NO_x and SO_x emissions when compared to the solvent-born counterparts. These results also highlighted that the manufacturing of coating components is a critical consideration in determining environmental impacts of a coating over its lifetime, and not just emissions that occur during product application.

The benefits of including renewable building blocks in coating formulations was examined in a comparative LCA study by Gustafsson and Börjesson (2007). Four different formulations, two wax-based and two lacquers using ultraviolet light for hardening (UV lacquers), were investigated. Wax-based coatings included one 100% fossil-based coating sourced from crude oil and one renewable wax ester produced from rapeseed oil, while UV lacquers consisted of one 100% solids and one water-based coating. The results of the cradle-to-grave LCA showed that the 100% UV coating is the most environmentally benign alternative followed by water-based UV. For global warming, the fossil wax had the highest contribution while acidification and eutrophication potential were mostly dominated by renewable wax. Application of pesticides and fertilizers during biomass cultivation played a key role in ecotoxicity, acidification, and eutrophication impacts of renewable wax, highlighting the importance of considering multiple impact categories, not just global warming, when evaluating bio-based products. As recommended by the authors, the UV coatings could be further improved by substituting epoxides and diacrylates with renewable building blocks.

Supporting the results of Gustaffson and Börjesson, several other comparative LCA studies between renewable building blocks and their fossil-based counterparts have shown that use of renewable alternatives can cause trade-offs in overall environmental impacts, lowering impacts in GHG emissions and nonrenewable energy use, while shifting burdens to other impact categories due to increased agricultural activities and inefficient or energy-intensive conversion methods (Huijbregts et al., 2006; Montazeri et al., 2016; Tabone et al., 2010). Therefore, minimizing these trade-offs through the choice of feedstock and conversion method is a key element in ongoing research. Previous work has shown that use of agricultural and forest residues as feedstock can decrease the impacts associated with agricultural activities (Cherubini et al., 2009; Vink et al., 2003), while process modifications such as less solvent use, recycling/substitution of hazardous input materials, and catalyzed reactions can result in more efficient conversions (Fernando et al., 2006).

The present study is a cradle-to-gate LCA study of a new 100% UV-cured wood flooring coating with 50% bio-renewable content (BRC) and zero-to-low VOC content. The environmental profile of this formulation is compared with the conventional low-VOC UV-cured wood flooring coating. The proposed formulation was developed by PPG Industries, Inc. Cradle-to-gate LCA results are compared across multiple impact categories in order to highlight potential environmental benefits or impacts of the new formulation and provide recommendations for further improvements.

2. Methods

As set forth in relevant ISO standards (14044:2006), **goal and scope definition**, **life cycle inventory**, **life cycle impact assessment** and **interpretation** are the four main stages in each LCA study (ISO, 2006).

2.1. Goal and scope

The goal of this study is to evaluate life cycle environmental impacts of a new UV-cured coating formulation for wood flooring applications with similar performance to the existing UV-cured control formulation. The proposed formula has 50% bio-renewable content (BRC) made up of three main renewable building blocks: corn-derived 1,3-propanediol, corn-derived itaconic acid, and soy-derived glycerin. These compounds and their derivatives replace conventional petroleum-based acrylates. The abrasion-resistant sealer, sanding sealer and topcoat are main layers of the coating, where the sealer layers prevent abrasion and seal the interior surface of the wood (Mireles et al., 2011), while the topcoat is the finishing layer applied in order to inhibit surface degradation of the wood (George et al., 2005). Typically, all of the three layers have urethane acrylate and epoxy acrylate as main components, as acrylate groups provide the functionality necessary for crosslinking (curing) of the coatings (Moore, 1990). Average densities of the control abrasion resistant sealer, sanding sealer and topcoat are 1.57, 1.29 and 1.23 (g/cm^3), respectively, with their average film thickness being between 0.3 and 1.1 mm.

In order to ensure equivalent functional unit, the proposed formula was tested upon standard protocols for hardwood flooring finishes. Two sets of tests were conducted, including 1) flooring performance tests and 2) required tests for acceptance by wood flooring industry. The first set included Cross Hatch Adhesion (ASTM D3359), Belmar Loop (ASTM D2197), Gloss Retention (ASTM 2486), Taber Adhesion Resistance (ASTM D4060) and Stain Resistance (ASTM D1308). The second set consisted of Hoffman Scratch (ASTM D5178), Coefficient of Friction (ensures proper floor safety), Impact Resistance (an in-house method accepted by flooring customers), Steel Wool Scratch Resistance (an in-house method accepted by flooring customers), and Cold Check Resistance (in-house method accepted by flooring customers that assesses coating flexibility and ensures no coating failure under variations in temperature and humidity). The new formulation has been determined from these tests to have similar characteristics and functionality during the coating use and maintenance phases. The functional unit of the study is thus set to 1 m^2 of coatings.

The LCA is scoped to account for impacts associated with raw material acquisition (including crude oil extraction and refining for fossil-based building blocks, and biomass cultivation, fractional extraction and conversion for renewable building blocks), intermediate chemicals synthesis, layer assembly and UV-curing processes, a cradle-to-gate assessment. The system boundary of this LCA is shown in Fig. 1 for both BRC and control coatings. Use phase and end-of-life considerations were excluded for several reasons. First, this product has not entered commercial application, and so there are no field data for chemical releases during use, refinishing, incineration/landfilling. Second, differences in the chemical composition of particulate matter generated during refinishing would not be captured in current life cycle impact assessment methods, and no characterization factors exist for the types of isocyanates used in the conventional coating. Third, previous studies from the VTT research center in Finland, Häkkinen et al. (1999) and Gustafsson and Börjesson (2007) have shown that manufacturing energy use and emissions and the durability of coatings are the key factors in the life cycle environmental impacts for UV-cured coatings, while impacts stemming from end-of-life treatment and disposal are relatively insignificant. Equivalent durability has been verified through the testing procedures described above.

2.2. Life cycle inventory

Life cycle inventories are compiled based on formulation components and energy consumption data. Composition and thickness of layers as well as energy required for UV-curing were given by PPG, shown in Table 1. Integration of the input parameters and life cycle inventories of the coatings are modeled in the commercial LCA software package SimaPro v8.1 (Amersfoort, the Netherlands). The inventories are developed using ecoinvent life cycle inventory database adjusted for the US energy system (US-EI database, Earthshift, Huntington, VT).

In most cases, the exact chemical/compounds specified in the formulations are not available in the database, so either closely related unit processes are used or new unit processes are created. For the purpose of this project, ~40 new unit processes are created, including both intermediate and final compounds, using ecoinvent unit processes for background data in order to ensure consistency. SDS (Safety Data Sheet) is one of the primary sources for developing a new unit processes. SDSs typically specify CAS number, chemical structure and properties, and hazards associated with the target compound. Additional literature sources (Hess et al., 1995; Sienel et al., 2000) are used alongside the MSDSs for certain compounds. Target chemicals and their upstream processes are modeled up to the point where the precursors are available in ecoinvent. Detailed descriptions for modeling of all new unit processes are included in the Supporting Information (SI), Tables S1-S9. Due to business confidentiality concerns, the exact input quantities used in each formulation were not included.

The proposed bio-renewable oligomers substitute for petroleum-based oligomers of acrylate resins. Three bio-based compounds of 1,3-propanediol, itaconic acid, and succinic acid (the precursor for production of itaconic acid) are modeled based on data from literature (Cok et al., 2014; Hogle et al., 2002; Urban and Bakshi, 2009; Dunn et al. 2015), while soy-based epoxy is modeled using the existing unit process from ecoinvent: "soy-based resin". As the coating is partially bio-based, non-renewable compounds are handled using approximate unit processes, substituting target compounds, or creating new ones. In addition to the main formulations, control and BRC coatings, an alternative scenario was modeled for the BRC coating, substituting corn-derived chemicals with identical counterparts obtained from corn stover, detailed in Table S10 and Table S11 in the SI. The density and film thickness values are used to convert mass-based inventories to fraction of each content in unit area covered by the coatings. Final LCI data are all scaled based on 1 m^2 of each coating.

2.3. Life cycle impact assessment

Ten environmental impact categories are considered in the life cycle comparison, including (with equivalent units in parentheses) global warming (kg CO_2 eq.), ozone depletion (kg CFC-11 eq.), smog formation (kg O_3 eq.), acidification (kg SO_2 eq.), eutrophication (kg N eq), carcinogenics (CTUh), non-carcinogenics (CTUh), respiratory effect (kg PM2.5 eq.), ecotoxicity (CTUe) and fossil fuel depletion (MJ surplus), following the US EPA's Tool for the Reduction of Chemical and Other Environmental Impact (TRACI 2.1) life cycle impact assessment method (Bare, 2011). Impact assessment methods use coupled fate-exposure-effect models to connect each life cycle emission to environmental or health midpoints (physical changes) or endpoints (damages), considering a range of ecosystem

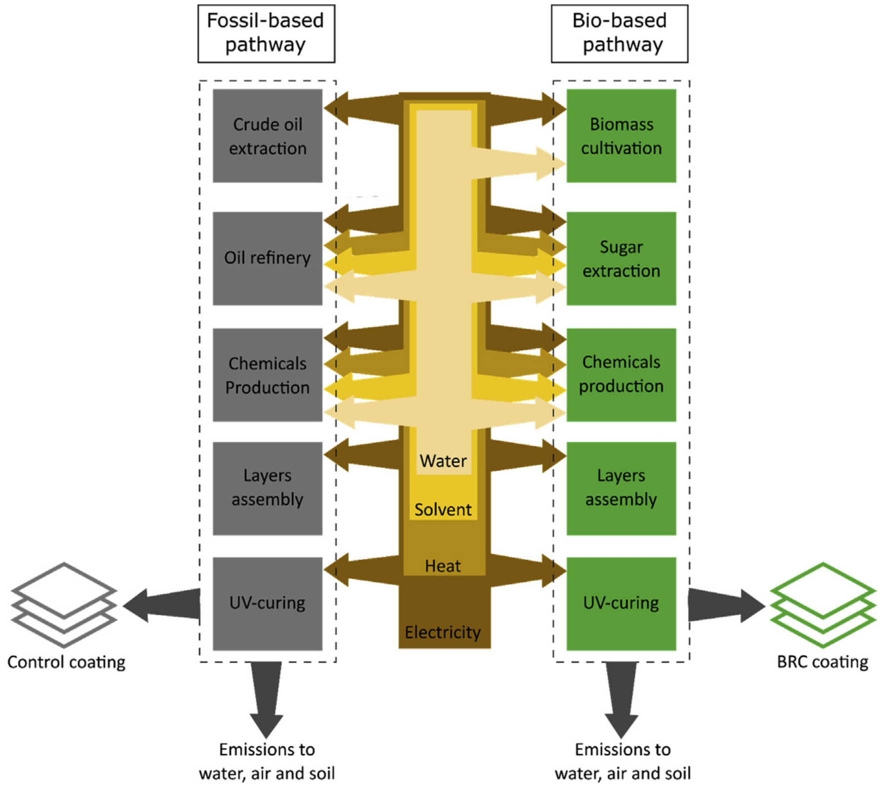

Fig. 1. System boundary for 1 m^2 of control and BRC coatings, US geography.

Table 1
Layers characteristics for BRC and control coatings.

Layer	Film thickness (mm)	Average density (g/cm^3)	UVA curing energy (J/m^2)
Abrasion resistant sealer	0.7–1.1	*Control*: 1.57 *BRC*: 1.71	2000–3000
Sanding sealer	0.4–0.5	*Control*: 1.29 *BRC*: 1.39	2000–3000
Topcoat	0.3–0.4	*Control*: 1.24 *BRC*: 1.1	1000–1500

and public health issues (Jolliet et al., 2003). The TRACI method was chosen as it reflects US conditions and thus matches the geographic region of the unit processes used in the LCI.

Following GHG accounting conventions for durable products (WBCSD, 2011), we assume that the entire carbon content of bio-based ingredients is supplied by atmospheric CO_2. The amount of sequestered carbon is calculated from the chemical formula of the bio-based components, while the carbon content of refined soy-oil is used as an approximation for the 12% soy content of the soy-based resin (Omni Tech International, 2011). Table 2 shows carbon sequestration quantities for each of the bio-renewable compounds considered in this study. Land use change (LUC) emissions are also accounted for, considering emissions from increasing corn and soy production scenarios based on the results of Dunn et al. (2013), using Argonne National Laboratory's Carbon Calculator for Land Use Change from Biofuels Production (CCLUB) module of the Greenhouse Gases, Regulated Emissions, and Energy use in Transportation (GREET) model. Their base case values are 7.6 g CO_2e/MJ corn ethanol (equivalent to 98 g CO_2e/kg corn grain) and 6.2 g CO_2e/MJ soy biodiesel (equivalent to 248 g CO_2e/kg soy oil), which have been applied to those biomass-derived compounds used in the BRC formulations, also shown in Table 2.

In order to account for the share of impacts attributed to co-products during chemical synthesis or processing, allocation is considered when co-products are present. For the simulation of corn-derived chemical building blocks, impacts of upstream processes of corn cultivation and wet milling are allocated between corn grain and corn stover using economic allocation, which proportions emissions and resource inputs based on the market value of each co-product (Luo et al., 2009). Economic allocation gives higher share of impacts to the corn grain compared to mass or energy allocation, but are typically employed in biofuel production systems and match the approach used in the ecoinvent datasets on bioenergy production (Muñoz et al., 2014). This approach also creates an upper bound for environmental impacts of corn-derived compounds. For the primary feedstock source of this study, corn grain, the share of emissions from agricultural and milling processes is ~88% while for the alternate source, corn stover, this fraction is ~12%.

Table 2
Carbon sequestered in the life cycle of bio-renewable compounds.

Bio-based compound	Formula	Mol. weight (g/mol)	C sequestration (kg CO_2/kg)	LUC emissions (kg CO_2e/kg)
Succinic acid	$C_4H_6O_4$	118.1	1.5	0.15
Itaconic acid	$C_5H_6O_4$	130.1	1.7	0.13
1,3-propanediol	$C_3H_8O_2$	76.1	1.7	0.33
Soy-based resin	–	–	0.35	0.03

3. Results and discussion

3.1. Formulation comparison

The comparative cradle to gate life cycle results showed lower impacts in six of the ten impact categories when renewable feedstocks (corn and soybeans) are used in the BRC coating formulation. However, environmental impacts of the BRC formulation were significantly higher in four impact categories of smog formation, acidification, eutrophication and respiratory effects, with acidification in particular showing more than 25 times higher impacts for the BRC coating compared to the control coating. Table 3 presents absolute and relative impacts for all categories of environmental impact. These mixed results can be partially explained given the substitution of industrial processes with agricultural processes that is occurring. Fewer energy-intensive petrochemicals are being used, leading to reductions in overall fossil energy use and GHG emissions. Some component substitutions also result in fewer releases of toxic substances during production, which reduces human toxicity and ecotoxicity. On the other hand, emissions from agricultural activities, particularly from sulfur-containing diesel burned in farm equipment and surface runoff of N and P compounds to local water bodies due to fertilizer use, degrade local air and water quality as reflected in the trade-offs in the overall results. The four categories with increased impacts are commonly affected by shifts to bio-based feedstocks, and have been highlighted in previous assessments of BRC formulations (Hill et al., 2006; Hottle et al., 2013).

3.2. Formulation contribution analysis

Fig. 2 shows the comparative results broken down by relative contributions of the three coating layers and the curing process. (Absolute results and the chemical composition of various layers are discussed in the next Section 3.3.) Green and gray bars represent BRC and control coatings, respectively. Fig. 2(a) shows the breakdown of results for the BRC coating and demonstrates that the abrasion-resistant sealer is the primary driver of negative impacts, contributing 58–83% of the total across impact categories, followed by the sanding sealer. This pattern can be partially explained by considering the mass fraction and the composition of each layer. The abrasion-resistant sealer has the highest mass fraction in the coating (1.5 kg/m^2), while the sanding sealer (0.6 kg/m^2) and topcoat (0.4 kg/m^2) are ranked second and third, and this order is reflected in the environmental impact results as well. Corn-derived itaconic acid, with the second highest mass fraction in the composition of both BRC abrasion-resistant sealer and BRC sanding sealer, contributes the most in overall environmental impacts. Electricity for UV-curing adds the least impact to the overall burden, less than 1%.

Fig. 2(b) shows the contribution of layers for the control coating. As for the BRC coating, the abrasion-resistant sealer again shows the highest contribution, 50–81% of overall impacts, mainly caused by the extensive use of epoxy acrylates resins in this layer. The mass fraction of acrylates in control abrasion resistant sealer is about 50%. The only exception is ozone depletion potential, where the sanding sealer is controlling the impacts, mainly due to the contributions of propylene glycol. Use of liquid chlorine in the synthesis of propylene oxide, a precursor for production of propylene glycol, plays the key role in contribution of this building block in ozone depletion category. The impacts of control sanding sealer is mostly controlled by Bisphenol A epichlorohydrin production, an epoxy resin with thermoplastic behaviors (Aouf et al., 2013). Again mirroring the BRC coating results, estimated impacts are mainly caused by the synthesis of intermediate chemicals and the production of each coating, while electricity use in the UV-curing process is shown to have <1% contribution to overall impacts.

3.3. Layer-by-layer comparison

Various layers of BRC and control coatings are compared in absolute terms in Fig. 3. Echoing the overall results, the BRC layers (green bars) have lower impacts compared to the fossil-based control formulations (gray bars), except for the impact categories of smog formation, acidification, eutrophication and respiratory effects. There are, however, exceptions to this pattern for the ozone depletion and eutrophication categories.

For ozone depletion, Fig. 3 shows that the BRC abrasion resistant

Table 3
Absolute and relative life cycle impacts of BRC wood flooring coating compared to control UV-cured coatings (per m^2 of coating).

Impact category	Unit	Control coating (absolute results)	BRC coating (absolute results)	% Change
Ozone depletion	kg CFC-11 eq.	1.30E-06	9.04E-07	−31%
Global warming	kg CO_2 eq.	1.17E+01	6.96E+00	−40%
Smog	kg O_3 eq.	9.81E-01	7.03E+00	617%
Acidification	kg SO_2 eq.	6.33E-02	1.82E+00	2771%
Eutrophication	kg N eq.	2.45E-02	3.30E-02	35%
Carcinogenics	CTUh	9.22E-07	6.57E-07	−29%
Non-carcinogenics	CTUh	1.52E-06	3.99E-07	−74%
Respiratory effects	kg PM2.5 eq.	7.59E-03	1.02E-01	1241%
Ecotoxicity	CTUe	2.24E+01	1.39E+01	−38%
Fossil fuel depletion	MJ surplus	2.69E+01	1.31E+01	−51%

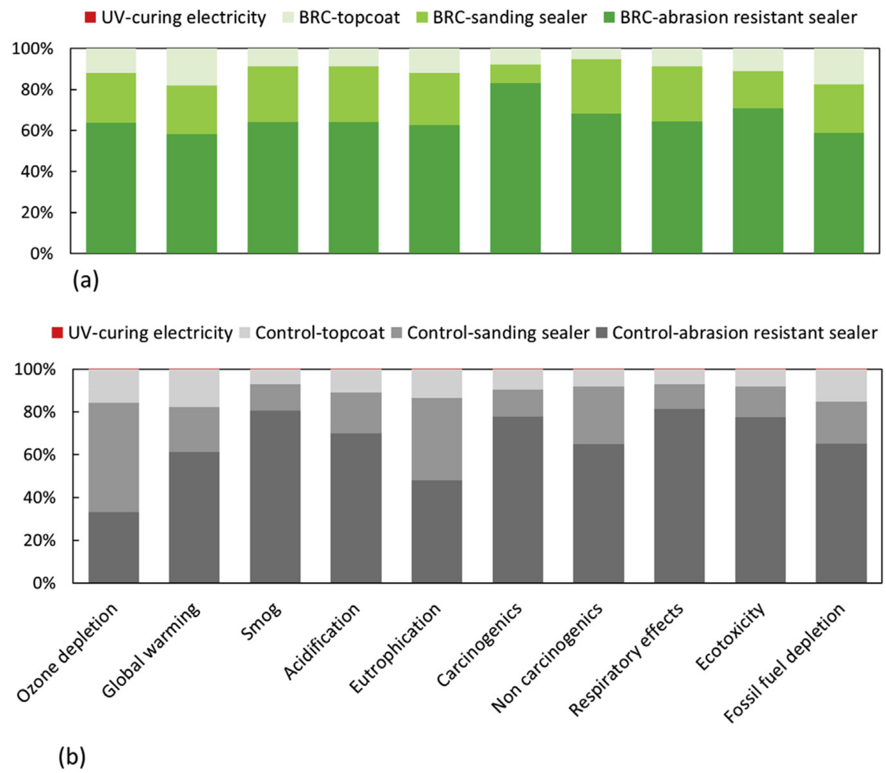

Fig. 2. Contribution of layers and UV-curing process in environmental impacts of (a) BRC and (b) control coatings.

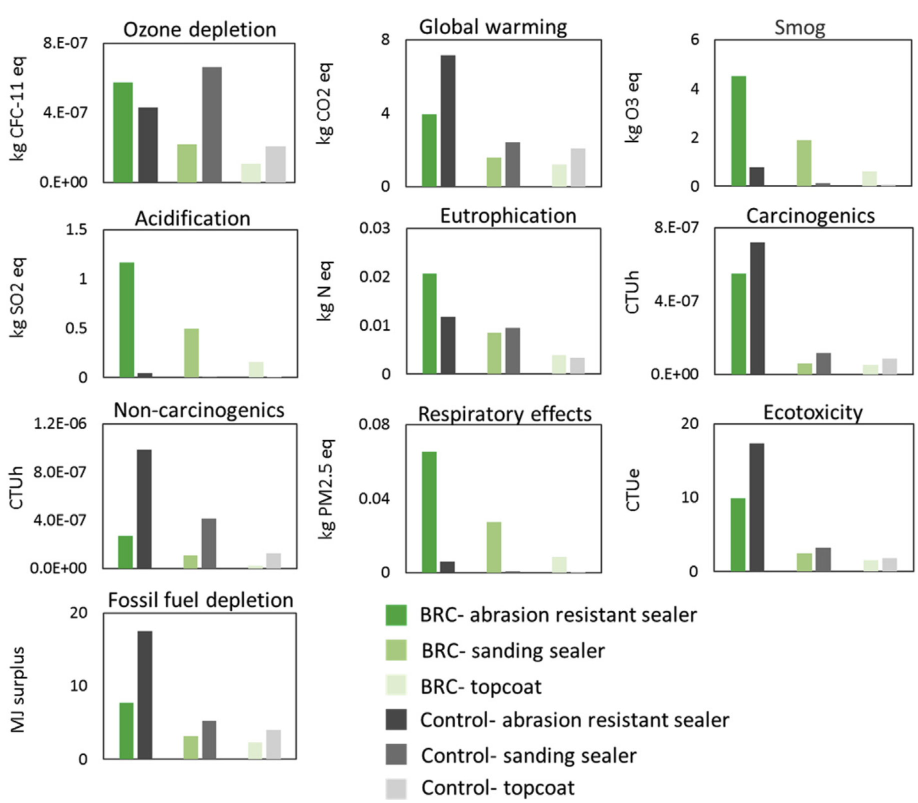

Fig. 3. Life cycle comparison between layers of BRC and control coatings.

sealer has higher life cycle emissions of ozone depleting substances compared to the control formulation, but that this increase is balanced by decreases in impacts for the BRC sanding sealer and topcoat layers. The primary contributor to ozone depletion in the abrasion resistant sealer is a diacrylate monomer, common to both BRC and control layer, but for the BRC formulation there are additional ozone depleting emissions from the production of corn-derived propanediol.

Eutrophication, on the other hand, is an impact category that commonly shows environmental trade-offs due to introduction of bio-based feedstock. It was expected that runoff from upstream agricultural activities would lead to higher eutrophication impacts in the BRC formulation compared to the control coating for all layers, but this was not the case for the sanding sealer. For this layer, high eutrophication impacts from emissions from power plants that supply energy for upstream processing of bisphenol A and acrylate derivatives in the control formulation outweighed the impacts from agriculture-related emissions from switching to BRC components.

For the BRC layers the greatest environmental improvements are for the categories of non-carcinogenics and fossil fuel depletion, with impact reduction of more than 50% for all three layers. Substitution of epoxy acrylate resin in the abrasion resistant sealer, propylene glycol and bisphenol A–epoxy resin in the sanding sealer, and diacrylate monomers in the control topcoat with alternate biorenewable components led to the significant environmental impact reductions.

The results of Figs. 2 and 3 highlight key points in understanding the cradle-to-gate environmental impacts of both coatings. Diacrylate monomer, corn-derived itaconic acid, and soy-based epoxy resin are shown to be major contributors to the environmental impacts of the BRC formulation, despite the fact that latter two are promoted as renewable materials with presumably better environmental profiles. Considering the synthesis of each of these components, diacrylate monomer is found in both the BRC and control coating formulations, and is synthesized using sodium hydroxide and chlorine, which are hazardous chemicals produced through the energy-intensive electrolysis of salt. Environmental impacts of corn-derived itaconic acid are mainly caused by emissions from diesel burned in agricultural equipment and fertilizer run off during cultivation of corn. Soy-based resin shows similar patterns of emissions from upstream processing. Fertilizer and pesticide use during cultivation, aromatic, aliphatic and chlorinated compounds added during soybean crushing and degumming, soy oil refining, and resin production all contribute to environmental impacts (Omni Tech International, 2011).

For the conventional coating formulation, bisphenol A and acrylate groups drive environmental impacts. Bisphenol A is known to be an endocrine-disrupting chemical, impacting developmental, metabolic, and reproductive systems (Flint et al., 2012). Some acrylate groups, on the other hand, are classified as mutagenic and/or carcinogenic compounds (Lithner et al., 2011) and even trace amount of these chemicals show significant contribution in overall impacts. Bisphenol A, with a 20% mass fraction in the control sanding sealer, contributes nearly half of the layer ecotoxicity. Acrylate groups are more common in both control and BRC layers. Between 40 and 75% of control layers are composed of acrylate derivatives which shows significant impacts in different categories, from 25% contribution to ozone depletion of the control sanding sealer up to 96% contribution to smog formation of the abrasion resistant sealer.

3.4. Alternate BRC formulation and sensitivity to feedstock choice

Further improvement in environmental performance of the BRC formulation can be achieved by using agricultural and forest residues as biomass sources, since these sources are mostly piled as waste or burnt on site to produce energy. In order to evaluate the sensitivity of the results to the primary choice of feedstock (corn), an alternate BRC formulation is modeled, substituting corn-derived chemicals with their identical counterparts from corn stover (Hong et al., 2015). The results show that if corn-derived chemicals were produced from corn stover, environmental impacts of BRC formulation would decrease significantly. The relative reduction between the proposed BRC formulation and control coating would be between 20 and 60% in nine out of ten categories, shown in Table S12 in the SI. Eutrophication is the only category that shows increase in impacts and even in that case, the relative value is 1% increase. Non-carcinogenic human health impact is the only impact category that shows more reduction when corn is used as main feedstock. The main reason is the upstream mercury use in the production of sodium hydroxide (from mercury cell electrolysis units still in use), a pretreatment solvent for separation of soluble and insoluble solids prior to enzymatic hydrolysis of corn stover. This complementary analysis highlights that further modification in feedstock choice can minimize expected environmental trade-offs and should be considered as next steps for development of the formulation.

3.5. Implications of cradle-to-gate scope

This cradle-to-gate study is focused on production of BRC and control coatings, which were designed to have similar coating performance and hence the same longevity. However, a larger scope could include more than one application of the coating and thus capture energy use and emissions associated with on-site curing and sanding (if wood flooring is refinished) or waste treatment and disposal (if flooring is replaced). Doing so would capture the difference in health effects from direct exposure via inhalation of emissions, which have been a major motivator of reformulation efforts. However, as mentioned in the Introduction section, the isocyanates used in this particular BRC formulation do not have existing human health characterization factors, so additional toxicity testing/modeling would have to be carried out in parallel. Future work could therefore benefit from empirical data through monitoring and characterization of emissions from sanding and re-application of coatings.

In summary, BRC formulations have been prioritized in research and development by PPG Industries, Inc. and many other chemical companies. This assessment demonstrates that the pursuit of higher bio-based content in formulations does not *a priori* lead to environmental benefits. Comparative LCA results for a 50%-BRC wood flooring coating show improvements in six impact categories including global warming, but worse life cycle environmental performance for four categories of smog formation, eutrophication, acidification and respiratory effects on a life cycle basis, compared to a conventional control coating with similar performance and durability. Replacing petrochemical components with renewable chemical substitutes in formulated products should ideally consider multiple environmental goals, not just the percentage of bio-based content. Specifying not just the bio-based target chemical but also the bio-feedstock choice and processing conditions can help ensure environmentally preferable formulations.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.jclepro.2018.04.209.

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