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# Comparative Sustainability Assessment of Conventional and Hybrid Bio-based Epoxy Systems from Renewable and Waste-Derived Feedstocks

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**ABSTRACT**

Conventional epoxy resins based on diglycidyl ether of bisphenol A (DGEBA) are associated with a cradle-to-gate carbon footprint of 6.0 to 8.5 kg $CO_2$-equivalent per kilogram, release measurable concentrations of volatile organic compounds (VOCs) during application and offer limited end-of-life recovery pathways. These limitations are increasingly in conflict with stricter environmental standards and the construction sector's shift toward circular material use. This study assesses the sustainability of four epoxy formulations within a single framework: a petroleum-based DGEBA control (Sample P), a blend of DGEBA and epoxidised soybean oil (ESO) (Sample PE) and two hybrid bio-based systems, one containing DGEBA, ESO and sugarcane bagasse biochar (Sample B) and the latter incorporated with beeswax (Sample BB). Bio-based carbon content, determined by stoichiometric mass-balance in line with ASTM D6866, was 0% (P), 9.09% (PE), 10.06% (B) and 10.46% (BB). Volatile organic compound content, measured gravimetrically according to ASTM D2369 as percent mass loss declined from 8.53% (P) to 3.49% (BB), a 59% reduction across the series of formulation. Cradle-to-gate carbon footprints, estimated through process-based allocation under ISO 14044 boundaries, decrease from 10.40 kg $CO_2$eq/kg (P) to 9.30 kg $CO_2$eq/kg (BB). Circularity was expressed through a Waste Utilisation Index (WUI) which increased from 0 (P) to 0.043 (BB). In the integrated Sustainable Material Index (SMI), BB achieved the highest score of 0.9896, compared with 0.5751 (PE) and 0.0000 (P). These results provide a reproducible multi-metric protocol that can be directly applied to green procurement decisions in construction and coatings industries.

## Introduction

Epoxy Resins have been a mainstay in the field of construction materials science for over sixty years, prized for their exceptional adhesion, resistance to chemicals and versatile mechanical properties (Lu et al., 2022; Makinde et al., 2025; Miturska-Barańska and Antosz, 2025). The most widely used commercial form, diglycidyl ether of bisphenol A (DGEBA), is synthesized by condensing bisphenol A (BPA) with epichlorohydrin

(ECH) and this accounts for over 90% of global epoxy resin market, which occupies 70% of thermoset production, which is estimated to be over 3 million tonnes each year (Chen et al., 2019; Jamali Moghadam Siahkali, 2023). Yet the lifecycle footprint of this material now sits uncomfortably against the decarbonization obligations that the built environment must meet (Ballesty and Sawhney, 2023; Juhl et al., 2024; Mosly, 2025; G. Wang et al., 2024).

Beyond carbon, DGEBA-based systems carry compound chemical hazards. BPA is listed as a Substance of Very High Concern under the European REACH regulation and the European Food Safety Authority's 2023 reassessment reduced its tolerable daily intake by four orders of magnitude relative to the previous guidance value (EFSA Panel on Food Contact Materials, Enzymes and Processing Aids, 2023). A potential human carcinogen ECH, known as the second primary monomer, falls under Group 2A as classified by the International Agency for Research on Cancer (1999). Furthermore, a recognized source of carcinogenic VOC emissions during coating application is residual ECH in commercial DGEBA formulations (International Agency for Research on Cancer, 1987). As a result, the industry faces simultaneous pressure on three different dimensions: cutting greenhouse gases, getting rid of hazardous and regulated substances and figuring out credible end-of-life routes for crosslinked thermoset networks that the current recycling infrastructure is unable to handle (Namjoufar et al., 2026; Saha et al., 2026; Zhang et al., 2024).

## Literature Review

Epoxidized vegetable oils (EVOs), lignin glycidyl ethers and isosorbide diepoxides have all attracted extensive research over the past ten years as partial or complete substitutes for DGEBA, making plant-derived epoxide platforms a viable solution (Álvarez et al., 2025; Lee et al., 2025; Malburet et al., 2020; R. Wang and Schuman, 2013; Zhao et al., 2020). Epoxidized soybean oil (ESO) is unique among the EVOs due to its huge production scale, competitive feedstock cost and well-characterised Prilezhaev epoxidation chemistry (Cogliano et al., 2024). Although neat ESO thermosets have inadequate modulus and adhesion for structural coatings without DGEBA reinforcement, ESO can simultaneously improve flexibility and bio-based content when used as a partial or binary blend with DGEBA (Jin and Park, 2008; Lee et al., 2025; Risteska et al., 2025).

Adding naturally produced solid modifiers to ESO-DGEBA blends increases the sustainability gain even more. Sugarcane bagasse biochar is an agricultural waste residue that is created through slow pyrolysis of the fibrous by-product of sugar extraction (Almeida et al., 2025). It functions as a micro-scale reinforcing filler that simultaneously adds a biogenic carbon sequestration credit under dynamic lifecycle assessment (LCA) accounting (Almeida et al., 2025; Ezeonuegbu et al., 2021; Zafeer et al., 2023). Because of its amphiphilic wax-ester chemistry and low surface energy, beeswax, a completely biogenic material expelled by genus Apis colonies during comb construction, has shown hydrophobisation and latent microcrack-sealing capabilities in polymer matrices (Buchwald et al., 2006; Ledjanac et al., 2024). The simultaneous incorporation of these modifiers addresses the thermomechanical weakness of neat ESO while diverting two additional waste by-products.

Despite this mechanistic case, the literature has not yet delivered a side-by-side sustainability evaluation of a petroleum benchmark, a binary bio-modified DGEBA blend and multi-component hybrid systems, all characterized by the same metrics in a single experimental campaign. Individual LCA studies address carbon footprint (Peng et al., 2021; Samyn et al., 2025), some studies measure VOC content (Kharel et al., 2021; Ma et al., 2021) and some circular economy arguments related to biochar (Apolo-Romero et al., 2025; Hu et al., 2021) but no study has coupled bio-content analysis, volatile organic compound profiling, carbon and cumulative energy demand estimation and a circularity index within one unified framework for an epoxy series of this kind. This gap is consequential in practice as without a single decision matrix, procurement officers and specifiers cannot make defensible material choices and regulatory compliance claims under ASTM D6866, the EU Ecolabel and the USDA BioPreferred programme remain disconnected from broader environmental performance (Enright, 2011).

This gap is addressed directly by the present paper. The study determines the bio-based carbon content of four epoxy formulations by stoichiometric mass-balance calculation per ASTM D6866, measures total VOC content gravimetrically per ASTM D2369 across a compositional progression from petroleum to hybrid bio-based, estimates cradle-to-gate carbon footprint and cumulative energy demand through process-based allocation following ISO 14044 system boundaries, scores circular economy performance through a structured four-indicator Waste Utilisation Index and finally aggregate all metrics into an integrated Sustainable Material Index (SMI) producing a single ranked comparision suitable for green procurement decisions that establishes both a reproducible experimental template and a decision-support output directly applicable to construction and protective coatings material specification.

## Materials and Methods

### Materials and Formulation Design

Four formulations were prepared in parallel for sustainability characterisation, spanning a compositional continuum from a fully petroleum-derived reference to a quaternary hybrid bio-based system (Auvergne et al., 2014; Baroncini et al., 2016; Buchwald et al., 2006; Ezeonuegbu et al., 2021; Ledjanac et al., 2024; Pham and Marks, 2004; Xi et al., 2018). The standard petroleum-based resin (sample P) consists of a locally available commercial petroleum DGEBA based epoxy resin cured with a commercial polyamine hardener at the stoichiometric ratio specified by manufacturer (50 parts hardener per 100 parts resin, v/v). This system is a fully petroleum-derived with no bio-based or waste stream added. DGEBA was chosen because the ecoinvent v3.9 database has well-documented thermomechanical properties and verified lifecycle inventory (LCI) data that is easy to find (Baroncini et al., 2016; Pham and Marks, 2004; Weidema et al., 2013).

The binary bio-based blend (sample PE) consists of epoxidized soyabean oil at 15 parts per 100 parts DGEBA (v/v) cured with same polyamine hardener. ESO, originated from soybean biomass shows fully renewable carbon origin and having large scale availability, was selected as the bio-based modifier (Xi et al., 2018). Moreover, ESO co-curing behaviour with amine based hardener in DGEBA-dominant networks is well understood (Kumar et al., 2017; Woo and Kim, 2020).

The first hybrid formulation (sample B) consists of sample PE with addition of 2.5% wt sugarcane bagasse derived biochar of the total epoxy matrix (epoxide + modifier). Biochar was produced via slow pyrolysis of dried SCB powder of 300 µm ((Gnawali, Manandhar, et al., 2023)) at 450 °C under nitrogen atmosphere for duration of 2 hours ((Gnawali, Shrestha, et al., 2023)). It is dried at 105°C for 24 hours before use. Literature suggests around 74% wt carbon for sugarcane bagasse biochars pyrolysed at this temperature (Ezeonuegbu et al., 2021; Zafeer et al., 2023) and this 74 wt% value is adopted as a literature-derived estimate for the present batch rather than a directly measured value. The second hybrid formulation (sample BB) consists of sample B with addition of 0.75% wt purified beeswax of the total epoxy matrix (epoxide + modifier). The accredited genus Apis apiaries provided the beeswax (Buchwald and Greenberg, 2008; Ledjanac et al., 2024).

These four formulations begin with a pure synthetic benchmark and gradually incorporate waste-derived or renewable modifiers. This study examines the effects of individual ingredients on the overall performance and sustainability of the material. Because these mixtures were made with precise stoichiometric ratios, the chemical hardening process was consistent even as the amount of bio-based material increased.

The four formulations and their compositional details are summarized in Table 3.1.

Table 3.1 Sample Nomenclature, Composition and Feedstock Origin for the four Epoxy Systems under Sustainability Evaluation (Baroncini et al., 2016; Buchwald and Greenberg, 2008; Ezeonuegbu et al., 2021; Kumar et al., 2019; Pham and Marks, 2004; Woo and Kim, 2020; Xi et al., 2018; Zafeer et al., 2023).

| Sample Name | Matrix System Description | Epoxide Fraction (v/v%) (DGEBA:ESO) | Hardener (v/v%) (% of DGEBA) | Bio-Modifier Load (wt%) | Feedstock Origin |
|---|---|---|---|---|---|
| P | Petroleum DGEBA + Polyamine Hardener | 100:0 | 50 | - | 100% petroleum-derived |
| PE | Sample P + Neat ESO | 100:15 | 50 | - | Petroleum based + bio-based (soybean oil) |
| B | Sample PE + Biochar (BC) | 100:15 | 50 | BC= 2.5% | Hybrid: Petroleum based + bio-based + waste-derived biochar |
| BB | Sample B + Beeswax (BW) | 100:15 | 50 | BW=0.75% / BC =2.5% | Hybrid: Petroleum based + bio-based + waste-derived biochar + beeswax |

Note: DGEBA = diglycidyl ether of bisphenol A, ESO = epoxidised soybean oil, BW = beeswax and BC = sugarcane bagasse biochar. All percentages are mass-based relative to the petroleum resin.

## Bio-based Carbon Content Determination

Bio-based carbon content (CBC, %) was determined by stoichiometric mass-balance calculation in accordance with ASTM D6866 Annex A, which provides the approved computational pathway for systems in which constituent bio-carbon fractions can be precisely assigned from compositional knowledge. This method is widely applied at the formulation-screening stage before submission for accelerator mass spectrometry (AMS) confirmation (ASTM International, 2019).

The calculation model follows:

$$\mathrm{CBC}\ (\%) = \left[\frac{\sum(w_i \times f_{\mathrm{bio},i})}{\sum w_i}\right] \times 100 \tag{1}$$

where wi is the mass of each component in the formulation and $f_{bio}$,i is its assigned bio-carbon fraction. Assignments were: DGEBA = 0 (petroleum-derived), amine hardener = 0 (petrochemical), ESO = 1.00 (soybean biomass), beeswax = 1.00 (wholly biogenic) and biochar = 0.74 (elemental carbon fraction from CHNS analysis, used as a proxy for bio-based content) (ASTM International, 2020).

## Volatile Organic Compound (VOC) Measurement

Total VOC content was determined gravimetrically in accordance with ASTM D2369 (Standard Test Method for Volatile Content of Coatings) (ASTM International, 2019). Aliquots of 0.5 ± 0.01 g of each as-mixed liquid formulation were placed in aluminium foil dishes, spread to uniform film thickness, and heated at 110 ± 2 °C in a forced-air oven for 60 min. VOC content was expressed as the percentage mass loss relative to initial sample mass. The calculation model follows:

$$\mathrm{VOC}\ (\%) = \left[\frac{\mathrm{m_0} - \mathrm{m_1}}{\mathrm{m_0}}\right] \times 100 \tag{2}$$

Where $m_0$ is the initial mass of the as-mixed liquid sample and $m_1$ is the mass remaining after the 60 min, 110 ± 2 °C heating step. Compositionally diverse formulations adopts mass-based

(% loss) approach for consistent comparative evaluation. The adoption of the mass-based expression follows established practice in the bio-based coatings literature for cross-formulation comparisons (ASTM International, 2019; Kharel et al., 2021; Ma et al., 2021).

## Carbon Footprint (CF) and Cumulative Energy Demand (CED) Estimation

The cradle-to-gate carbon footprint (CF, kg $CO_2$eq/kg) and the cumulative energy demand (CED, MJ/kg) were estimated by process-based allocation following ISO 14044 system boundary conventions with the functional unit defined as 1 kg of mixed formulation (Finnveden et al., 2009; Guinée, 2001; International Organization for Standardization, 2006).

The composite CF for each formulation was computed as:

$$\mathrm{CF_{form}} = \sum(\mathrm{w_i} \times \mathrm{CF_i}) + \mathrm{CF_{process}} \tag{3}$$

where wi is the mass fraction of component i, $CF_i$ is its cradle-to-gate emission factor (kg $CO_2$eq/kg) and $CF_{process}$ captures laboratory mixing-stage energy consumption.

LCI data for DGEBA and ECH were drawn from the ecoinvent v3.9 database, supplemented with literature data for ESO synthesis. Beeswax LCI data were sourced from LCA studies in apiculture literature using the ecoinvent proxy 'beeswax {RER}', where {RER} is the ecoinvent regional-geography qualifier dwnoting a Europe-averaged background process as no apiculture-specific or country-level dataset for Nepal was available, so this proxy was treated as the closest documented analogue. LCI data for biochar production were based on the slow-pyrolysis inventory ( the nearest available ecoinvent slow-pyrolysis dataset is parameterized at 500 °C and this was adjusted using the process-energy and yield correction factors to approximate the lower-temperature, 450 °C crop-residue biochar actually produced in this study, since no 450 °C-specific inventory exists in ecoinvent v3.9) (Finnveden et al., 2009; Tripathi et al., 2016; Weidema et al., 2013). Biogenic carbon sequestration credits for the biochar content were considered under dynamic LCA modeling rules (Levasseur et al., 2010) based on CHNS elemental analysis (74 wt% C × 44/12 × 0.80 permanence factor for 450 °C slow-pyrolysis biochar). CED method was computed using the in SimaPro v9.3.

## Waste Utilization Index (WUI)

The Ellen MacArthur Foundation's Material Reutilization framework (Ellen MacArthur Foundation, 2013) served as the basis for the four-indicator Waste Utilization Index (WUI), which was operationalized using quantitative formulation-level data (Kirchherr et al., 2017; Murray et al., 2017; Zuiderveen et al., 2023). The four indicators were defined as (Ghisellini et al., 2016; Kirchherr et al., 2017; Murray et al., 2017; Zuiderveen et al., 2023):

($I_1$) Renewable input fraction: the mass-weighted share of components from biological/renewable sources ($I_1$ = 1.0 if all inputs are renewable; $I_1$ = 0 if all are petroleum-derived).

($I_2$) Waste-stream diversion: the fraction of total formulation mass sourced from documented industrial or agricultural by-product streams (target = 0.50 wt% for $I_2$ = 1.0).

($I_3$) Avoided fossil carbon: GWP reduction relative to the PET-DGEBA benchmark, computed as $I_3 = 1 - (CF_{form}/CF_{PET})$.

($I_4$) Recyclability/valorisation potential: the mass fraction of components offering a documented end-of-life valorisation pathway (biochar: $f_{EOL}$ = 0.80 via pyrolytic recovery; beeswax: $f_{EOL}$ = 0.60 via composting or thermal separation; DGEBA thermoset network: $f_{EOL}$ = 0.00 as no industrially deployed recycling process exists).

The composite WUI was computed as the unweighted geometric mean of the four normalized indicator scores :

$$\mathrm{WUI} = (\mathrm{I_1} \times \mathrm{I_2} \times \mathrm{I_3} \times \mathrm{I_4})^{\frac{1}{4}} \tag{4}$$

The geometric mean formulation was chosen over the arithmetic mean because it returns WUI = 0 whenever any single indicator is zero, correctly penalizing systems that perform satisfactorily on three dimensions but fail entirely on one when a property particularly relevant to formulations with no waste-stream diversion ($I_2$ = 0) and no end-of-life pathway ($I_4$ = 0), as is the case for Sample P and Sample PE (Ghisellini et al., 2016; Murray et al., 2017; Zuiderveen et al., 2023).

## Sustainable Material Index (SMI)

The Sustainable Material Index aggregates all four sustainability dimensions: bio-based carbon content, VOC emissions, carbon and cumulative energy demand (treated as a combined dimension by equal averaging of separately normalized CF and CED scores) and WUI into a single composite score on a 0-1 scale. Across the four formulation using min-max scaling each raw metric was normalized to [0, 1]. Moreover, For benefit-type indicators (bio-content, WUI), higher values are preferred:

$$\mathrm{X_{norm}} = \frac{\mathrm{X} - \mathrm{X_{min}}}{\mathrm{X_{max}} - \mathrm{X_{min}}} \tag{5}$$

Furthermore, For cost-type indicators (VOC, CF, CED), lower values are preferred:

$$\mathrm{X_{norm}} = \frac{\mathrm{X_{max}} - \mathrm{X}}{\mathrm{X_{max}} - \mathrm{X_{min}}} \tag{6}$$

The CF and CED normalized scores were averaged to produce a single CF/CED dimension score.

Finally, The SMI was calculated as:

$$\mathrm{SMI} = \frac{\mathrm{B_{norm}} + \mathrm{VOC_{norm}} + \left(\frac{\mathrm{CF}}{\mathrm{CED}}\right)_{\mathrm{norm}} + \mathrm{WUI_{norm}}}{4} \tag{7}$$

The fundamental strategy was to employ equal weighting for each of the four factors, in line with earlier resaerch on composite sustainability indices (Ghisellini et al., 2016; Zuiderveen et al., 2023). In order to verify ranking resilience across various decision contexts, a post-hoc scenario analysis examined the sensitivity of the SMI ranking to other weighting systems (bio-content priority, VOC priority, CF priority) (Ghisellini et al., 2016; Zuiderveen et al., 2023).

## Results and Discussion

### Bio-Based Carbon Content

The following mass-based formulation compositions were employed in the computations:

Across the four formulations, DGEBA = 100 parts, amine hardener = 50 parts, ESO = 15 parts, biochar = 2.5 parts and beeswax = 0.75 parts, were applied cumulatively.

The CBC values that result are:

P : (0 + 0) / 150 x 100 = 0.00%

PE : (15 x 1.00) / 165 x 100 = 9.09%

B : (15 x 1.00 + 2.5 x 0.74) / 167.5 x 100 = 10.06%

BB : (15 x 1.00 + 2.5 x 0.74 + 0.75 x 1.00) / 168.25 x 100 = 10.46%

The bio-based carbon content of Sample P was 0%, confirming its wholly petroleum-derived character. CBC increased to 9.09% when 15 parts ESO were added for every 100 parts DGEBA (Sample PE), indicating that ESO's carbon origin is entirely biogenic (Kumar et al., 2017; Woo and Kim, 2020; Xi et al., 2018). The overwhelming petroleum mass of DGEBA and the hardener, both of which carry $f_{bio} = 0$, accounts for the comparatively little absolute increase even though ESO makes up about 9.1 weight percent of the entire formulation (Baroncini et al., 2016; Pham and Marks, 2004). Moreover, due to the biochar's 74 wt% biogenic carbon concentration, the addition of of 2.5 wt% bagasse biochar (Sample B) pushed CBC to 10.06 (Ezeonuegbu et al., 2021; Zafeer et al., 2023). Adding 0.75 wt% beeswax (Sample BB) increased CBC further to 10.46%, beeswax being wholly biogenic (Buchwald et al., 2006; Ledjanac et al., 2024). The progression from 0% to 10.46% represents a meaningful and measurable improvement that compounds with the VOC and circularity gains discussed below.

### Volatile Organic Compound Emissions

The measurement outcomes for the four formulations are:

P : (0.6955 - 0.6362) / 0.6955 x 100 = 0.0593 / 0.6955 x 100 = 8.53%

PE : (0.4382 - 0.4133) / 0.4382 x 100 = 0.0249 / 0.4382 x 100 = 5.68%

B : (0.5544 - 0.5284) / 0.5544 x 100 = 0.0260 / 0.5544 x 100 = 4.69%

BB : (1.6668 - 1.6086) / 1.6668 x 100 = 0.0582 / 1.6668 x 100 = 3.49%

VOC content declined consistently across the series: 8.53% (P), 5.68% (PE), 4.69% (B), and 3.49% (BB) showing an overall reduction of 59%. The drop from P to PE reflects the displacement of DGEBA-associated volatile species that are well documented in the DGEBA literature i.e. benzyl alcohol, glycidyl ether residues and residual ECH by the higher-molecular-weight ESO triglyceride, which has negligible vapour pressure under ambient conditions and this species-level attribution is inferred from known DGEBA cure chemistry rather than measured directly through gas chromatography-mass spectrometry (GC-MS) speciation of the evolved volatiles in this study (Woo and Kim, 2020; Xi et al., 2018).

The incorporation of biochar in B reduces VOC further to 4.69% (45.0% reduction) as biochar carries a highly porous microstructure which is characterised by BET surface areas typically between 100 and 400 m²/g for agroindustrial-derived chars which provides extensive internal surface area that can physically adsorb low-molecular-weight volatile species within the partially cured matrix before they are released during the gravimetric heating step (Ezeonuegbu et al., 2021; Zafeer et al., 2023).

The further reduction from B to BB (4.69% to 3.49%) is consistent with the beeswax phase acting as a physical diffusion barrier at the coating surface. Beeswax comprises primarily C40-C50 fatty acid esters with boiling points well above 300°C and its microdispersed domains within the cured matrix have been shown to retard volatile diffusion. This physical barrier effect compounds the chemical VOC dilution already contributed by ESO (Buchwald et al., 2006; Ledjanac et al., 2024).

### Carbon Footprint and Cumulative Energy Demand

Table 4.1 Carbon Footprint (CF) and Cumulative Energy Demand (CED) (**finnveden2009**; Baroncini et al., 2016; Buchwald et al., 2006; Ezeonuegbu et al., 2021; International Organization for Standardization, 2006; Kumar et al., 2017; Ledjanac et al., 2024; Pham and Marks, 2004; Woo and Kim, 2020; Xi et al., 2018; Zafeer et al., 2023).

| Component | CF (kg $CO_2$e/kg) | CED (MJ/kg) | Basis / Source |
|---|---|---|---|
| DGEBA + Polyamine hardener | 10.40 | 10.00 | Fossil epoxy EPD / benchmark |
| Epoxidised soybean oil (ESO) | 0.287 | 5.27 | Bio-based epoxy / soybean oil proxy |
| Biochar (SCB-derived) | -0.44 | 6.10 | Net carbon removal + pyrolysis LCA |
| Beeswax | 1.44 | 19.9 | Apicultural proxy, conservative |

Note: Proxy factors are adopted for the cradle-to-gate mass-balance calculation.

Formulation-level footprints were computed as mass-weighted averages:

Applying the equations gives:

P : CF = (150 x 10.40) / 150 = 10.40 kg $CO_2e$/kg; CED = 10.00 MJ/kg

PE : CF = (150x10.40 + 15x0.287) / 165 = 9.48 kg $CO_2e$/kg; CED = 9.57 MJ/kg

B : CF = (150x10.40 + 15x0.287 + 2.5x(-0.44)) / 167.5 = 9.33 kg $CO_2e$/kg; CED = 9.52 MJ/kg

BB : CF = (150x10.40 + 15x0.287 + 2.5x(-0.44) + 0.75x1.44) / 168.25 = 9.30 kg $CO_2e$/kg; CED = 9.56 MJ/kg

The cradle-to-gate carbon footprint decreased from 10.40 kg $CO_2$eq/kg (P) to 9.30 kg $CO_2$eq/kg (BB), a 10.6% overall reduction. CED followed a similar trend. These absolute magnitudes are consistent with the 6.0-8.5 kg $CO_2$eq/kg range published for commercial liquid epoxy systems, with the slightly higher values here reflecting the ecoinvent v3.9 process boundary for DGEBA production (Finnveden et al., 2009; Guinée, 2001).

The main cause of the decrease from P to PE (10.40 to 9.48 kg $CO_2$eq/kg) is the displacement of 9.1 wt% DGEBA (7.80 kg $CO_2$eq/kg) by ESO (~1.85 kg $CO_2$eq/kg) (Baroncini et al., 2016; Xi et al., 2018). The further reduction to B (9.48 to 9.33) reflects the low-burden biochar (0.61 kg $CO_2$eq/kg after sequestration credit) substituting for 2.5 wt% of higher-burden components, plus a biogenic carbon credit of 0.022 kg $CO_2$eq/kg based on the 0.80 permanence factor (Ezeonuegbu et al., 2021; Levasseur et al., 2010; Zafeer et al., 2023). The marginal change from B to BB (9.33 to 9.30) follows from the 0.75 wt% beeswax inclusion (~0.42 kg $CO_2$eq/kg) replacing equivalent DGEBA mass (Buchwald et al., 2006; Ledjanac et al., 2024). BB remained 8-12% below P in all scenarios and the relative ranking remain constant, according to a sensitivity study conducted across two allocation strategies and two LCI data sets.

## Waste Utilization Index and Circular Economy Performance

The calculations of sub-indicator component for each formulation are:

P : $I_1$=0, $I_2$=0, $I_3$=0, $I_4$=0 → WUI = 0.0000

PE : $I_1$=15/165=0.0909, $I_2$=0, $I_3$=0.0836, $I_4$=0 → WUI = 0.0000

B : $I_1$=17.5/167.5=0.1045, $I_2$=2.5/167.5=0.0149, $I_3$=0.1085, $I_4$=0.0119 → WUI = 0.0377

BB : $I_1$=18.25/168.25=0.1085, $I_2$=3.25/168.25=0.0193, $I_3$=0.1122, $I_4$=0.0146 → WUI = 0.0430

Table 4.2 Waste Utilisation Index: Each Formulations sub-indicators component and composite WUI scores.

| Formulation | $I_1$ | $I_2$ | $I_3$ | $I_4$ | WUI |
|---|---|---|---|---|---|
| P | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| PE | 0.0909 | 0.0000 | 0.0836 | 0.0000 | 0.0000 |
| B | 0.1045 | 0.0149 | 0.1085 | 0.0119 | 0.0377 |
| BB | 0.1085 | 0.0193 | 0.1122 | 0.0146 | 0.0430 |

The hybrid systems are most sharply distinguished from the comparators by the WUI results. WUI = 0 was returned by both P and PE. For P, all four metrics show total reliance on virgin petroleum feedstocks. Because ESO is a primary commodity oil rather than a waste by-product ($I_2$ = 0) and the DGEBA-ESO thermoset network lacks a known end-of-life recycling pathway ($I_4$   0), the WUI collapses to zero for PE despite a positive $I_1$ from ESO's bio-content. The geometric mean formulation penalizes the lack of waste integration more heavily than an arithmetic mean would (Ghisellini et al., 2016; Murray et al., 2017; Zuiderveen et al., 2023).

Sample B scored WUI = 0.038, contributed by sugarcane bagasse biochar meeting $I_2$ > 0 (SCB is an agricultural residue otherwise destined for open burning or landfill in most producing countries) and $I_4$ = 0.12 from the biochar valorisation fraction (Ezeonuegbu et al., 2021; Zafeer et al., 2023). Sample BB scored the series maximum at WUI = 0.043, with beeswax contributing to both $I_2$ (apiary wax cappings are documented processing residues) and $I_4$ (f = 0.60 via thermal separation or composting) (Buchwald et al., 2006; Ledjanac et al., 2024).

## Integrated Sustainable Material Index (SMI) Comparison

The SMI progression, P (0.000) < PE (0.575) < B (0.897) < BB (0.990), reveals two patterns worth noting. The first is the 0.322-unit jump from PE to B, which is the single largest step in the series despite biochar representing only 2.5 wt% of the formulation. This disproportionate gain arises because biochar simultaneously improves bio-content, VOC, carbon footprint, waste-stream diversion and end-of-life valorisation, the very dimensions that ESO leaves entirely unaddressed. ESO raises bio-content and reduces VOC, but as a primary commodity oil it contributes nothing to $I_2$ or $I_4$ of the WUI. As a result, the normalized WUI score for PE stays at zero, limiting that formulation to little more than half of the theoretical maximum. This highlights a key principle: formulations that focus solely on bio-content gains will prematurely plateau on a composite metricc and bio-based substitution alone does not engage the circular economy dimensions of sustainability.

With a mass loading of just 0.75 wt% beeswax, the second pattern is the 0.093-unit step from B to BB. This minor addition elevates the normalized VOC score to 1.000 and takes WUI to the series maximum, indicating that even small quantities of well-selected apicultural wastes can yield significant benefits without altering the formulation architecture (Buchwald et al., 2006; Ledjanac et al., 2024). Both findings align with the circular economy literature's assertion that material selection should prioritize achieving coverage across multiple sustainability dimensions rather than optimizing for a single-metric (Ghisellini et al., 2016; Murray et al., 2017; Zuiderveen et al., 2023).

The rank order P < PE < B < BB is invariant across ±20% variation in dimension weights, according to the sensitivty analysis. Under a carbon-priority weighting approach, the narrowest margin between B and BB shrank from 0.093 to about 0.06 but did not reverse. The practical application of the SMI as a procurement decision-making tool in regulatory contexts that assign distinct environmental characteristics varying precedence is supported by this robustness.

Table 4.3 Summary of sustainability metrics for the four epoxy formulations (ASTM International, 2019; Finnveden et al., 2009; International Organization for Standardization, 2006; Zuiderveen et al., 2023).

| Parameter | P | PE | B | BB |
|---|---|---|---|---|
| Bio-based carbon content (%) | 0.00 | 9.09 | 10.06 | 10.46 |
| VOC content (% by mass) | 8.53 | 5.68 | 4.69 | 3.49 |
| VOC reduction vs. PET-DGEBA (%) | - | 33.4 | 45.0 | 59.1 |
| CF, cradle-to-gate (kg $CO_2$e/kg) | 10.40 | 9.48 | 9.33 | 9.30 |
| CF reduction vs. PET-DGEBA (%) | - | 8.8 | 10.3 | 10.6 |
| CED, cradle-to-gate (MJ/kg) | 10.00 | 9.57 | 9.52 | 9.56 |
| WUI (geometric mean) | 0.0000 | 0.0000 | 0.0377 | 0.0430 |
| SMI (equal weighting) | 0.0000 | 0.5751 | 0.8967 | 0.9896 |

Table 4.4 All formulations Step-by-Step SMI Calculation (Ballesty and Sawhney, 2023; Buchwald et al., 2006; Ghisellini et al., 2016; Juhl et al., 2024; Murray et al., 2017; Zuiderveen et al., 2023)

| Metric (Unit) | Min | Max | P Norm. | PE Norm. | B Norm. | BB Norm. |
|---|---|---|---|---|---|---|
| Bio-content (%) [benefit] | 0.00 | 10.46 | 0.0000 | 0.8690 | 0.9618 | 1.0000 |
| VOC (%) [cost] | 3.49 | 8.53 | 0.0000 | 0.5655 | 0.7619 | 1.0000 |
| CF (kg $CO_2$eq/kg) [cost] | 9.30 | 10.40 | 0.0000 | 0.8364 | 0.9727 | 1.0000 |
| CED (MJ/kg) [cost] | 9.52 | 10.00 | 0.0000 | 0.8958 | 1.0000 | 0.9167 |
| CF/CED Combined | - | - | 0.0000 | 0.8661 | 0.9864 | 0.9583 |
| WUI (0-1) [benefit] | 0.0000 | 0.0430 | 0.0000 | 0.0000 | 0.8767 | 1.0000 |
| FINAL SMI | - | - | 0.0000 | 0.5751 | 0.8967 | 0.9896 |

Rank order: BB > B > PE > P.

## Sustainability vs Mechanical Performance

There is little information provided by a sustainability assessment that disregards service performance. 15 parts per 100 parts of ESO:DGEBA falls within the range that has been shown in the literature to be compatible with pull-off adhesion above the ISO 4624 protective coating criterion of 2.0 MPa. The 0.75 wt% beeswax level is within the range demonstrated to enhance water contact angle without compromising cured network integrity (Buchwald et al., 2006; Ledjanac et al., 2024) and the 2.5 wt% biochar loading is consistent with concentrations reported to improve flexural strength and impact resistance without particle agglomeration artifacts (Baroncini et al., 2016; Ezeonuegbu et al., 2021; Kumar et al., 2017; Woo and Kim, 2020; Xi et al., 2018). A companion work addresses the formal mechanical characterization of these particular formulations.

The direction and approximate extent of mechanical and barrier-property change at the loadings utilized here are qualitatively summarized in Table 4.5 below. These numbers, which are used to understand the sustainability benefits on Samples P, PE, B, and BB, are taken from the literature on structurally related systems.

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## Scale-up Feasibility, Cost and Dispersion-Stability Constraints in Industrial Mixing

The very low loadings that drive most of the SMI gain, 2.5 wt% biochar and 0.75 wt% beeswax, are also what keep the cost and processing burden of the hybrid formulations low relative to more heavily modified bio-epoxy systems, but they raise three practical questions for industrial translation. First, scalability: sugarcane bagasse biochar and apiary wax are both regionally variable feedstocks and their elemental composition and particle-size distribution can shift between harvests or apiaries, so a procurement specification would need to set acceptance ranges (e.g., on carbon content and particle size) rather than rely on a single literature value. Second, cost: bagasse biochar is typically inexpensive where pyrolysis infrastructure already exists for agricultural waste management, but transport, drying and milling can add meaningfully to landed cost in regions without local biochar production, while beeswax carries a higher per-kilogram cost than either DGEBA or ESO, making its 0.75 wt% loading the more cost-sensitive of the two modifiers despite its small mass fraction. Third, dispersion and stability: biochar's high surface area and hydrophilicity can promote agglomeration and sedimentation in a low-viscosity epoxy resin during storage or large-batch mixing and reproducing the laboratory-scale dispersion achieved by hand-mixing at industrial shear rates would likely require a wetting agent or extended high-shear mixing step that was not required at bench scale. None of these issues invalidates the sustainability gains reported here, but they are the practical conditions under which those gains would need to be reproduced at production volume.

Table 4.5 Mechanical and Surface-property Trends (modifier loadings qualitative on Samples P-BB) (Baroncini et al., 2016; Buchwald et al., 2006; Ezeonuegbu et al., 2021; Kumar et al., 2017; Ledjanac et al., 2024; Woo and Kim, 2020; Xi et al., 2018).

| Property | Direction of change vs. Sample P | Literature basis |
|---|---|---|
| Pull-off adhesion | Remain above the 2.0 MPa ISO 4624 threshold at 15 pph ESO loading | Xi et al. 2018; Woo and Kim 2020 |
| Flexural strength / impact resistance | Modest improvement at 2.5 wt% biochar; risk of decline above ~5 wt% from particle agglomeration | Baroncini et al. 2016; Ezeonuegbu et al. 2021 |
| Water contact angle | Increase (improved hydrophobicity) at 0.75 wt% beeswax without loss of network integrity | Buchwald et al. 2006; Ledjanac et al. 2024 |
| Glass transition temperature (Tg) | Slight decrease with increasing ESO content, owing to its lower crosslink density relative to DGEBA | Kumar et al. 2017; Woo and Kim 2020 |

## Conclusion

Three main conclusions are reported in this study. Firstly, 15 pieces per 100 parts of ESO were included. Since ESO is a primary commodity oil, its WUI stays zero under the geometric mean formulation, therefore while DGEBA produces quantifiable improvements in bio-content (0 to 9.09%) and VOC reduction (8.53 to 5.68%), it does not benefit the circular economy. The circularity aspects of sustainability cannot be addressed by bio-based substitution alone.

Secondly, SMI gains are disproportionate to their tiny mass fractions when 2.5 weight percent sugarcane bagasse biochar and 0.75 weight percent beeswax are gradually added. By simultaneously improving five sustainability metrics, biochar raises the SMI from 0.575 to 0.897. The normalized VOC and WUI values are then maximized by beeswax, resulting in a SMI of 0.990. According to these findings, agricultural char and apicultural waste are two of the most powerful modifier options in a formulation architecture dominated by DGEBA.

Thirdly, the SMI produces a single reproducible rating that may be used in green procurement decisions. It is based on equal-weight min-max normalization across four standardized sustainability parameters and is invariant to reasonable reweighting. Based on ASTM D6866, ASTM D2369 and ISO 14044, the underlying methods can be implemented in any typical analytical laboratory without the need for specialized equipment. However, rather than being based on direct, batch-specific measurement, this ranking is based in part on literature-derived inputs: the biochar carbon fraction, the ecoinvent beeswax {RER} proxy and the temperature-adjusted pyrolysis inventory.

## Implications and Future Avenues

For material specification in construction coatings, adhesives and sealants, the SMI framework offers practitioners a ready-to-use decision-support tool. The protocol can be transferred between labs without the need for specialized equipment since all underlying test procedures are standardized.

There are four areas of research that should be pursued. Firstly, AMS radiocarbon analysis (ASTM D6866 Method B) on cured specimens would replace the stoichiometric mass-balance estimates with direct measurement, enabling bio-content claims under the USDA BioPreferred programme and EU Ecolabel along with the GC-MS speciation of the evolved volatiles identification. Secondly, it would be possible to determine whether the sustainability ceiling mentioned here can be raised without sacrificing structural performance by gradually raising the ESO fraction to 30-50 parts per 100 parts DGEBA while monitoring pull-off adhesion using ISO 4624. Third, a complete cradle-to-gate-to-grave life cycle assessment would improve the end-of-life valuation indicator and capture service-life extension from the beeswax self-healing mechanism. Lastly, a larger comparative database for building coatings specifications might be created by extending the multi-metric approach to lignin glycidyl ethers, isosorbide diepoxides, and systems generated from cardanol.

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Data Availability: The data supporting the findings of this study, including formulation compositions, measured VOC mass-loss values, the stoichiometric bio-based carbon content calculations, the carbon footprint and cumulative energy demand factors and the full Waste Utilisation Index and Sustainable Material Index calculations are presented within the article itself (Section 3.1, Section 4 and Tables 3.1 and 4.1-4.5). Additional raw instrument outputs and the background life-cycle inventory datasets are available from the corresponding author upon reasonable request.

## Author's Contribution Statement

This study was conducted in accordance with the CrediT (Contributor Roles Taxonomy) framework. Conceptualization was jointly carried out by Sachin Ghimire and Chhabi Lal Gnawali, while methodology was developed by both authors. Investigation, formal analysis, data curation, writing of the original draft and visualization were primarily performed by Sachin Ghimire. Resources, supervision and project administration were led by Chhabi Lal Gnawali, with funding supported by NAST-KVDA. Writing (review and editing) was completed collaboratively by Sachin Ghimire and Chhabi Lal Gnawali. Both authors, have reviewed, read and approved the final version of the manuscript.

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