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Assessment of Potential Environmental Impact: Synthetic and Natural Binders

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***Abstract* – Binders are important construction materials, especially with plant-based granulates and fibers. A binder is chosen for its physical and chemical properties to be compatible with some construction requirements. New market trends show that green binders meet global sustainability targets, which is a step towards greener buildings and a greener environment. This study presents a cradle-to-gate comparative life cycle assessment (LCA) of synthetic binders (Polyvinyl Acetate (PVA) and Carboxymethyl Cellulose (CMC)) and agriculture starch-based binders made from cassava, wheat, and corn. The LCA was conducted using SimaPro software based on ISO 14040/14044 standards using the ReCiPe Midpoint and CML IA Baseline method. The assessment is cradle-to-gate with a binder production function unit of 1 kg. Key environmental sustainability metrics like Global Warming Potential (GWP) and Acidification Potential (AP) are assessed to rank the binder sustainability against each other. The results show that synthetic binder PVA has the highest environmental impact in almost all impact categories, especially GWP (6.55 kg CO_2 eq in ReCiPe and 6.37 kg CO_2 eq in CML) and AP (0.012 kg SO_2 eq in ReCiPe and 0.015 kg SO_2 eq in CML). Among natural binders, Corn Starch shows the lowest environmental impact with GWP values of 0.930 kg CO_2 eq (ReCiPe) and 0.896 kg CO_2 eq (CML) and AP values of 0.010 kg SO_2 eq (ReCiPe) and 0.016 kg SO_2 eq (CML). The agricultural binders (Cassava Starch, Wheat Starch, and Corn Starch) are environmentally friendlier than the synthetic binders (PVA and CMC). Although agricultural binders carry environmental costs associated with farming operations, they have lower environmental impacts than synthetic alternatives, demonstrating their sustainability potential in binder applications.**

***Keywords* - Environmental impacts; Life Cycle Assessment (LCA); sustainable binders; synthetic binders; starch-based binders.**

1. INTRODUCTION

For centuries, construction has defined human civilization as how infrastructure was built, and society progressed. Construction methods have adapted to technological advancements and changing social needs over time. Construction has been changing in the past years with environmental issues becoming a top priority in developing countries. This change is accompanied by a global sustainability agenda [1], [2]. More and more attention is being paid to integrating environmental management practices, resource conservation, and greener building materials. This green building movement isn't only fueled by technological advances but also by a growing recognition of the environmental effects of traditional construction

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practices [3], [4]. Material choice is one of the main sustainability factors in construction projects. Industry stakeholders now understand that critical material selection can reduce environmental impact and improve long-term performance [4]. One such group of materials is adhesives called binders that hold construction materials together. Binders are used to make cement, mortar, concrete, and coatings and they have a fundamental function in structural integrity. Based on their chemical properties and reaction mode, binders are divided into hydraulic (setting and hardening with water exposure) and nonhydraulic (hardening without water exposure) types [5], [6].

Construction is among the biggest contributors to the worldwide degradation of the environment. It contributes significantly to greenhouse gas (GHG) emissions, resource depletion, and the production of waste [7]. Buildings, from material extraction to demolition, contribute almost 37 % of global CO_2 emissions [8]. The construction industry accounts for almost half of all waste generated (30 %), water consumed (15 % worldwide), and energy consumed (almost 50 %) compared to other industries. While 50 % of all material extractions around the world are associated with building activities, materials extraction, construction product manufacture, construction and rehabilitation of buildings contribute an estimated 5–12 % to total national GHG emissions [9]. Binders are used in many construction processes, but synthetic binders have been criticized for their environmental impact. Excessive use of synthetic binders increases atmospheric carbon dioxide concentration and damages human health [10]. The Paris Agreement, the UNFCCC's treaty on CO_2 emissions, these Agreements states that "all states shall agree to reduce dangerous greenhouse gas emissions to the environment and also never to raise temperatures over two degrees Celsius," regardless of economic development [7]. The EU's ambitious target is to cut greenhouse gas emissions by 80–95 % by 2050 through the adoption of regulatory policies including the Construction Products Regulation (CPR) creating a common condition for the marketing of Construction Products, repealing Regulation (EU) 2019 / 1020 and repealing Regulation (EU) No (EU) No. 305/2011. This regulation aims to facilitate the green transformation of the construction industry.

Conventional synthetic binders such as PVA and CMC have been widely used, but their production processes lead to significant greenhouse gas emissions and other environmental damages [12], [13]. With the high emission level associated with the manufacturing of synthetic binders, the plant-based binders from agricultural sources like cassava, wheat, and corn starch have shown potential as an alternative to the synthetic alternative by utilizing renewable resources and having lower life cycle impacts [13].

PVA is a strong adhesive but performs poorly in wet conditions and degrades under heat, affecting its long-term use [14]. CMC improves compressive strength in biomass pellets and has potential in construction, though more durability data is needed [15]. Cassava starch has been shown to improve the durability of construction materials, such as by reducing water absorption in sandcrete blocks [16]. Wheat starch-based binders (WSB) demonstrate promising mechanical properties as sustainable alternatives. Corn starch, used in materials like "CoRncrete," offers rapid hardening but may be limited to non-structural applications due to durability issues [17].

Cassava and wheat starch binders are renewable and biodegradable, with potentially lower environmental impacts than synthetic binders [18]. Corn starch has shown lower environmental impacts but raises concerns over energy use and food resource competition [19]. PVA, made from non-renewables, has high environmental costs, including GWP. CMC, while biodegradable, involves environmentally impactful chemical processing.

The trend of green buildings in the construction industry demonstrates that greener materials that are in line with global sustainability goals should be adopted. This change is driven by regulatory requirements as well as societal demand for environmentally sustainable buildings and infrastructure construction. Comparative LCA of different binder types is important to know their environmental footprints and to guide material choice during construction projects. Based on LCA approaches, stakeholders can assess the environmental performance of different binders to make sustainable decisions [20].

This study presents a cradle-to-gate comparative LCA of synthetic binders – namely PVA and CMC and agriculture starch-based binders made from cassava, wheat, and corn. Utilizing SimaPro software based on ISO 14040/14044 standards, this research assesses key environmental metrics, including Global Warming Potential (GWP), Human Toxicity, and Acidification Potential (AP), to provide a comprehensive comparison of the sustainability profiles of these binders and valuable insights for agriculture-based binders selection in the construction industry.

2. METHODOLOGY

LCA is a standard approach for estimating the environmental impact of material and product selection. This approach can also be used to identify emission types and sources from a material or product. For this effect, carbon footprint has emerged as one of the main environmental protection measures, carbon footprint measurement is based on LCA methodology. Carbon footprint is the sum of direct and indirect greenhouse gas emissions from the production process within the chosen system boundary [21]. According to ISO standards 14040/14044, the LCA study consists of four steps: goal and scope definition, life cycle inventory analysis, life cycle impact assessment, and interpretation [22].

2.1. Goal and Scope of the Study

The objective of the study is to present potential environmental impacts by an LCA analysis in conformity with the ISO 14040 and ISO 14044 standards for the synthetic binders (PVA and CMC) and natural binders from plants (Cassava Starch, Wheat Starch, and Corn Starch). The analysis boundaries run from cradle to gate, from the raw materials processing to the end of the manufacturing industry. All the phases regarding distribution, use, and end of life have been excluded because they are irrelevant to the analysis. The Life Cycle Impact Assessment (LCIA) methodologies are ReCiPe Midpoint and CML-IA Baseline. The ReCiPe Midpoint method provides a detailed, scientific, and comparative global assessment of selected environmental mechanisms, whereas the CML-IA Baseline method provides process-level environmental assessment compliant with European standards. By combining the two approaches, a global and European-specific comparison of the environmental performance of binders is possible. The result will shed light on the possible use of these binders in construction.

2.2. Functional Unit and System Boundary

The product results are analyzed using a functional unit, which defines the function of the investigated system and is used as a reference unit for relating inventory data [23]. In this study, the functional unit is 1 kg of binder production, which is the minimum quantity required in SimaPro and sufficient for a full impact assessment. The system boundaries define the bounds of the Life Cycle Assessment and are defined as follows: Raw Material Extraction: Gathering binder Raw materials, transportation produce products, production: Energy and resources used in manufacturing, Usage: application Emissions and impacts, End-of-Life: Disposal recycling or degradation. This LCA study adopts a cradle-to-gate approach to system boundary. Cradle of the system boundary in raw material extraction and production / synthesis of materials and fuels. The system's gate is the manufacturing of binders (starch or synthetic binders).

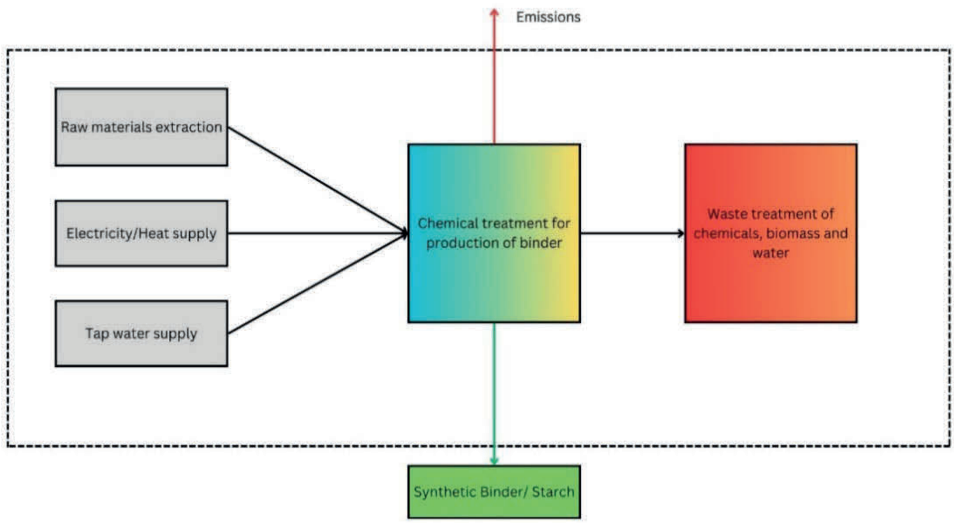

Fig. 1. System boundary of life cycle of binders production from Cradle to gate (made by the authors).

2.3. Life Cycle Inventory

An important component of LCA analysis is the inventory model, which links all unit processes of the study to the finished product. In this phase, we aim to gather all quantities required to develop product/waste flows and elementary flows dividing them between inputs and outputs within selected system boundaries [24]. The input is the materials, energy, and resources that enter the unit process while the outputs are the products, waste, and emissions from the process. In this LCA study, data from manufacturing companies are used to model and analyze the life cycle impact assessment of a product or a system. Data Sources: primary data from Ecoinvent V9 (Ecoinvent database) and secondary data from literature [20]–[27]. Life Cycle Inventory for 1 kilogram of five different binders is shown in Table 1.

2.4. Life Cycle Impact Assessment

In the third stage of LCA, the Life Cycle Impact Assessment (LCIA) is conducted by translating the elementary flows from the LCI into environmental impacts. ISO 14040/14044 standards require LCIA to perform three steps: (i) choice of the characterization model, (ii) category of impact categories, and (iii) characterization of environmental effects.

The ReCiPe 2016 Midpoint model evaluates four major environmental impacts. Climate change and atmospheric impacts include Global warming potential, Stratospheric Ozone depletion, Ionizing radiation, and ozone formation (for Human health and Terrestrial ecosystems). Fine particulate matter formation (FPMG), human carcinogenic toxicity, along with human non-carcinogenic toxicity are human health and air quality indicators, respectively. Terrestrial and aquatic ecosystem impacts consist of Terrestrial acidification, Terrestrial ecotoxicity, Marine eutrophication, Freshwater eutrophication, Freshwater ecotoxicity, and Marine ecotoxicity. Land use, Mineral resource scarcity, Fossil resource scarcity, and Water consumption are the three indicators of resource use and Land transformation. These indicators offer a holistic picture of environmental and societal health effects related to climate change, pollution, toxicity, resource depletion, and ecosystem damage, allowing scientifically informed sustainable decision-making [28], [29].

TABLE 1. LIFE CYCLE INVENTORY DATA FOR 1 KG OF BINDER PRODUCTION: (A) CASSAVA STARCH; (B) CORN STARCH; (C) WHEAT STARCH; (D) CARBOXYMETHYL CELLULOSE; AND (E) POLYVINYL ACETATE (ON THE NEXT PAGE)

(a)

Input/emissions	**Unit**	**Volume**
Cassava root	kg	3.421
Tap water	kg	14.75
Sulfur	kg	0.00005
Hydrogen peroxide	kg	0.00001
Phosphoric acid	kg	0.00001
Sodium hydrogen sulfate	kg	0.00006
Soda ash, dense	kg	0.00031
Petrol, unleaded	kg	0.00004
Diesel	kg	0.00264
Heavy fuel oil	kg	0.01033
Biogas	m^3	0.04185
Electricity, medium voltage	kWh	0.17116
Carbon dioxide, fossil	kg	0.095493
Wastewater, average	L	14.75

(b)

Input/emissions	**Unit**	**Volume**
Tap water	kg	0.2
Maize starch and gluten slurry	kg	3.7
Electricity, medium voltage	kWh	0.45
Diesel	MJ	1.78
Wastewater	L	2.68
Biowaste	kg	0.01

(c)

Input/ emissions	**Unit**	**Volume**
Tap water	kg	4
Wheat grain	kg	1.85
Electricity, medium voltage	kWh	2.3
Heat, district, or industrial	MJ	7
Wastewater	L	3.32

(d)

Input/ emissions	**Unit**	**Volume**
Sodium hydroxide	kg	0.31
Chloroacetic acid	kg	0.33
Hydrochloric acid	kg	0.022
Chemical Organics	p	4E-10
Sulfate pulp, bleached	kg	0.4275
Sulfate pulp, unbleached	kg	0.0225
Electricity, medium voltage	kWh	1.47
Heat, district, or industrial	MJ	25.112
NMVOC, non-methane volatile organic compounds	kg	0.0001
Particulates, > 10 μm	kg	0.0003

(e)		
Input/ emissions	**Unit**	**Volume**
Vinyl acetate	kg	0.8
Hydrogen peroxide	kg	0.03
Non-ionic surfactant	kg	0.02
Tap water	kg	12.5
Electricity, medium voltage	kWh	3.61
VOC, volatile organic compounds	kg	0.02
Carbon dioxide, fossil	kg	1.5
Spent solvent mixture	kg	0.075
Wastewater	L	12.5
Hazardous waste, for incineration	kg	0.02

The CML IA Baseline model considers environmental pressures grouped into four major impact categories. Abiotic depletion (fossil fuels) measures resource depletion by assessing nonrenewable materials and energy use. Global warming, Ozone layer depletion (ODP), and Photochemical oxidation are the major climate and atmospheric indicators that measure contributions to Global climate change and air pollution. Toxicity and ecosystem health parameters such as human toxicity, Freshwater aquatic ecotoxicity, Marine aquatic ecotoxicity, and Terrestrial ecotoxicity are measures of pollutants' effects on Human and ecological health. Acidification and Eutrophication are Acidification and nutrient pollution indicators assessing disturbances of soil and water chemistry that may degrade ecosystems. These indicators allow systematic assessment of environmental burdens, thereby forming a scientifically valid basis for sustainability assessments and environmental impact reduction measures [33].

3. RESULTS AND DISCUSSION

The section presents a comprehensive report on the LCA for synthetic binders (PVA and CMC), and agriculture starch-based binders made from cassava, wheat, and corn using the ReCiPe 2016 Midpoint and CML IA Baseline methods. The analysis of the results provides insight into the environmental impact of each binder across the impact categories outlined in the methodology.

3.1. CML-IA Baseline Impact Assessment Results

As shown in Fig. 2, all environmental impact scores have been converted to a common reference or maximum value (set to 100 %) for comparison across multiple impact categories and materials; the LCA results using the CML-IA baseline method show significant environmental impact differences among the five binders analyzed: CMC, Cassava Starch, Corn Starch, PVA, and Wheat Starch. PVA (79.27 MJ fossil fuels / kg) and CMC (50.79 MJ fossil fuels / kg) show the highest fossil fuel depletion indicating high non-renewable energy use. On the other hand, Corn Starch (9.82 MJ fossil fuels / kg) and Cassava Starch (12.12 MJ fossil fuels / kg) are the least fossil fuel-intensive alternatives. Likewise, CMC (2.40E05 kg Sb eq) and PVA (2.39E05 kg Sb eq) have the highest abiotic mineral and metallic depletion while Cassava Starch (6.13E06 kg Sb eq) and Wheat Starch (9.81E06 kg Sb eq) use up the lowest resource.

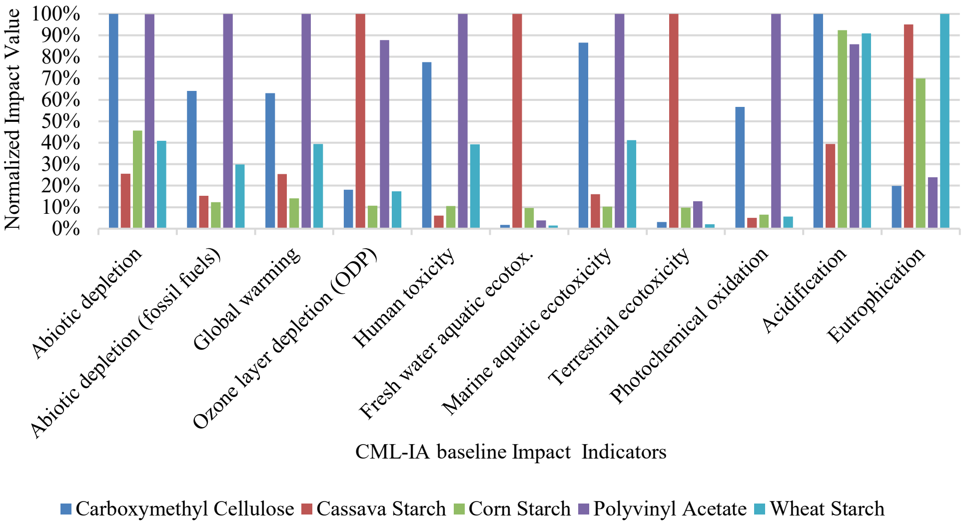

Fig. 2. CML-IA baseline Impact Assessment Results.

PVA (6.37 kg CO_2 eq) and CMC (4.02 kg CO_2 eq) are the largest emitters of greenhouse gases for Climate change potential due to their energy-intensive production methods. On the flip side, Corn Starch (0.89 kg CO_2 eq) and Cassava Starch (1.62 kg CO_2 eq) possess the smallest CO_2 footprints and are thus preferred to lessen the impact of the climate. Toxicity impacts show significant differences between materials; PVA (10.56 kg 1.4-DCB eq human toxicity) and CMC (8.18 kg 1.4-DCB eq) present the highest risks to human health, while Cassava Starch (0.64 kg 1.4-DCB eq) and Corn Starch (1.10 kg 1.4-DCB eq) have the lowest impacts. Ecotoxicity, Cassava Starch (27.66 kg 1.4 DCB eq freshwater ecotoxicity) is particularly harmful to aquatic environments, whereas CMC (0.47 kg 1.4 DCB eq freshwater ecotoxicity) and Wheat Starch (0.41 kg 1.4 DCB eq freshwater ecotoxicity) possess the least impact. The most damaging are PVA (4385.05 kg 1.4-DCB eq marine aquatic ecotoxicity) and CMC (33 800.35 kg 1.4-DCB eq marine aquatic ecotoxicity), which have the highest marine toxicity.

Key indicators of ecosystem degradation include acidification and eutrophication. CMC (0.017 kg SO_2 eq acidification) and Corn Starch (0.0157 kg SO_2 eq acidification) have the highest impact on acid rain formation, which damages soils and aquatic habitats. Meanwhile, Cassava Starch (0.0067 kg SO_2 eq acidification) has the lowest impact in this category. Wheat Starch (0.0091 kg PO_4 eq eutrophication) and Cassava Starch (0.0087 kg PO_4 eq eutrophication) show the highest eutrophication leading to excess nutrient buildup in water bodies, perhaps causing water pollution and algae blooms.

On the other hand, CMC (0.0018 kg PO_4 eq eutrophication) contributes the least to eutrophication and is therefore not harmful here. Polyvinyl Acetate (0.00196 kg C_2H_4 eq) and CMC (0.0011 kg C_2H_4 eq) have the highest photochemical oxidation (smog formation potential) impact, and Cassava Starch (9.82E05 kg C_2H_4 eq) the lowest. These findings demonstrate that synthetic material's smog formation and acidification are stronger than bio-based starch materials.

3.2. ReCiPe 2016 Midpoint Impact Assessment Results

As shown in Fig. 3, all environmental impact scores have been converted to a common reference or maximum value (set to 100 %) for comparison across multiple impact categories and materials, the ReCiPe 2016 Midpoint method LCA results highlight significant environmental differences. For global warming and atmosphere impact, PVA (6.55 kg CO_2 eq) and CMC (4.15 kg CO_2 eq) contribute the highest to global warming, whereas Corn Starch (0.93 kg CO_2 eq) and Cassava Starch (1.73 kg CO_2 eq) would be the more climate-friendly alternatives. The highest stratospheric ozone depletion potential is Wheat Starch (1.57E05 kg CFC 11 eq) and Cassava Starch (1.32E05 kg CFC 11 eq), while PVA (2.12E06 kg CFC 11 eq) emits the very least ozone-depleting compounds.

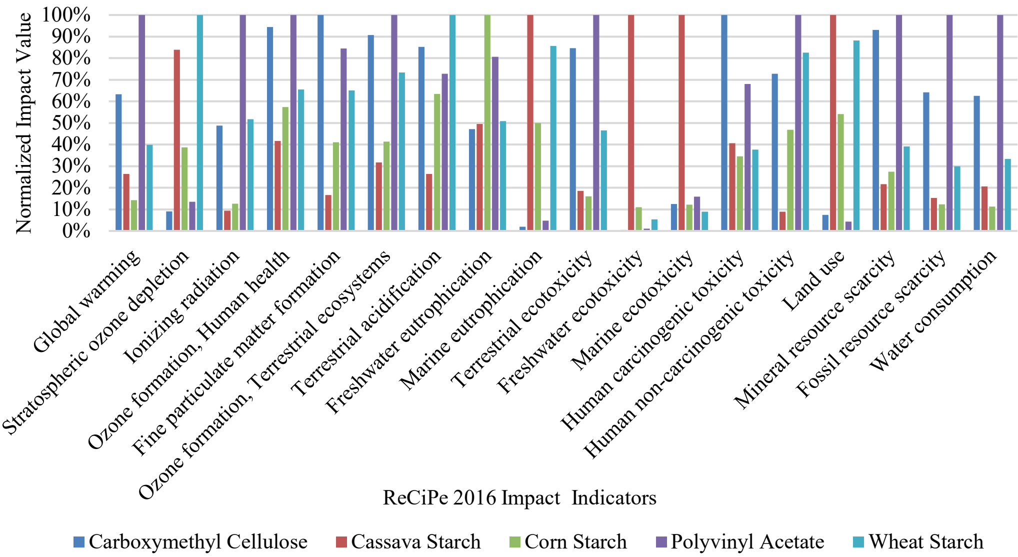

Fig. 3. ReCiPe 2016 Midpoint Impact Assessment Results.

In the human toxicity and ecotoxicity categories PVA (1.12 kg 1.4 DCB eq non-carcinogenic toxicity) and CMC (0.82 kg 1.4 DCB eq non-carcinogenic toxicity) have the highest health risk, whereas Cassava Starch (0.10 kg 1.4 DCB eq) and Corn Starch (0.53 kg 1.4-DCB eq). Cassava Starch (0.66 kg 1.4 DCB eq freshwater ecotoxicity) has a high effect on freshwater biomes, while PVA (0.04 kg 1.4 DCB eq marine ecotoxicity) and Cassava Starch (0.26 kg 1.4 DCB eq marine ecotoxicity) have the highest marine toxicity. Moreover, PVA (34.57 kg 1.4-DCB eq terrestrial ecotoxicity) and CMC (29.27 kg 1.4-DCB eq terrestrial ecotoxicity) damage the terrestrial biomes. Across all impact categories, Corn Starch is the least toxic material and thus the safest option for minimizing human and environmental health risks.

Ecosystem degradation as a function of acidification, eutrophication, and smog development suggests that Wheat Starch (0.0163 kg SO_2 eq) has the highest acidification potential and Cassava Starch (0.0043 kg SO_2 eq) the very least. The most significant source of nutrient pollution in marine environments is Cassava Starch (0.0042 kg PO_4 eq marine eutrophication) followed by CMC (0.00008 kg PO_4 eq). In terms of ozone formation (smog potential), PVA (0.0097 kg NO_x eq human health smog) and CMC (0.0092 kg NO_x eq human health smog) contribute the most to poor air quality, while Cassava Starch (0.0041 kg NO_x eq human health smog) has the lowest impact. These findings suggest that although starch-based materials perform well in general, Cassava Starch poses a serious marine eutrophication risk while PVA is a major source of air pollution and ecosystem degradation.

In terms of resource use and land transformation, Cassava Starch (4.25 m^2a crop eq) and Wheat Starch (3.75 m^2a crop eq) require the most land area, while PVA (0.18 m^2a crop eq) has the lowest land use due to its synthetic nature. PVA (0.0121 kg Cu eq) and CMC (0.0113 kg Cu eq) are the highest contributors to mineral resource scarcity, whereas Cassava Starch (0.0026 kg Cu eq) and Wheat Starch (0.0048 kg Cu eq) show minimal depletion. PVA (1.88 kg oil eq) and CMC (1.21 kg oil eq) exhibit the highest fossil resource depletion, while Corn Starch (0.23 kg oil eq) and Cassava Starch (0.29 kg oil eq) show significantly lower dependency on fossil fuels. In water consumption, PVA (0.0485 m^3 water eq) has the highest footprint, while Corn Starch (0.0055 m^3 water eq) and Cassava Starch (0.01 m^3 water eq) are the most water-efficient options.

3.3. Comparison of CML-IA Baseline and ReCiPe 2016 Midpoint Impact Assessment Results

A graphical comparison of Global Warming Potential and Terrestrial Acidification impact results of CML-IA and ReCiPe 2016 are presented in Fig. 4 and Fig. 5, the methods are similar due to standardized, universally accepted scientific models and similar characterization factors applied for these impact categories by the two methodologies. The CML-IA Baseline versus ReCiPe 2016 Midpoint comparison demonstrates significant differences in environmental impact assessment methods. The closest comparison is in global warming potential, where ReCiPe 2016 estimates are 2.8 % higher than CML-IA. This suggests that ReCiPe 2016 may incorporate a more comprehensive global greenhouse gas emission assessment or a different weighting of global warming factors as seen in Fig. 4. Similarly, ReCiPe 2016 estimates of terrestrial acidification are slightly lower (−4.1%) due to small methodological differences in modeling acidification impacts between the two approaches (Fig. 5). However, ReCiPe 2016 calculates much lower marine eutrophication values (−58.6 %) than CML-IA for freshwater and marine eutrophication, indicating a different characterization model for nutrient pollution in aquatic systems.

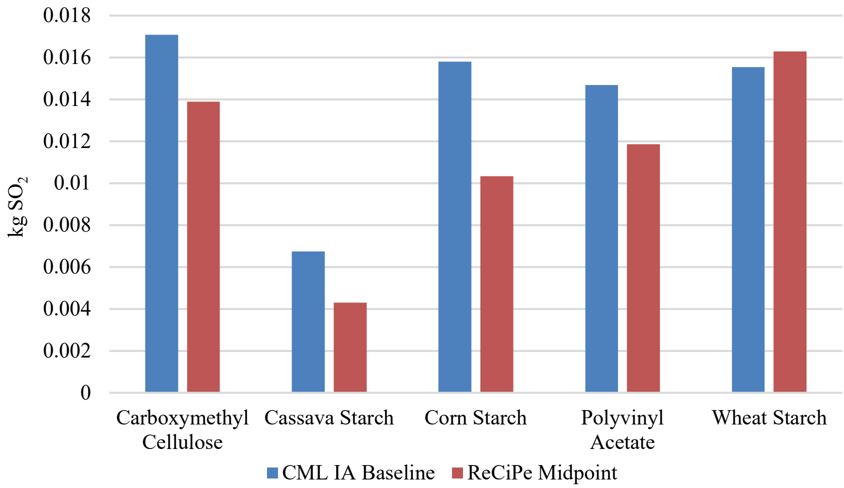

Fig. 4. Comparison of CML-IA baseline and ReCiPe 2016 Midpoint GWP Impact Assessment Results.

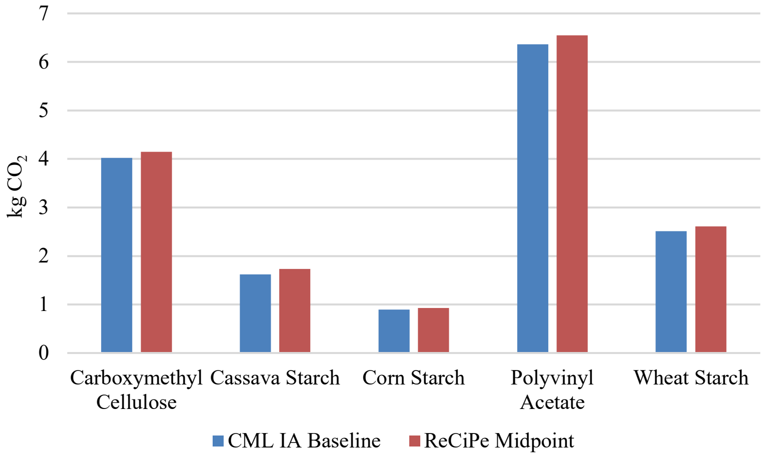

Fig. 5. Comparison of CML-IA baseline and ReCiPe 2016 Midpoint Acidification Impact Assessment Results Comparison.

A significant difference is found for abiotic depletion (fossil fuels), where ReCiPe 2016 reports 97.6 % lower than CML-IA. This large difference indicates that CML-IA may use a more general or conservative measure of fossil fuel depletion, while ReCiPe 2016 uses a restricted model. On the other hand, ReCiPe 2016 reports 50.3 % higher values than CML-IA for abiotic depletion (minerals), demonstrating a fundamentally different approach to mineral resource scarcity assessment. This large difference indicates that ReCiPe 2016 may use a broader mineral depletion factor range or higher weighting for critical raw materials, while CML-IA may use a more limited range.

ReCiPe 2016 generally reports lower environmental burdens than CML-IA Baseline for toxicity and ecotoxicity, especially for terrestrial and marine ecotoxicity. This could be due to differences in chemical fate, exposure models, or impact pathway assumptions between the two methodologies. For example, terrestrial ecotoxicity values in ReCiPe 2016 are much lower compared to those in CML-IA, implying a more stringent or refined classification system. Similarly, marine ecotoxicity impacts are also significantly decreased in ReCiPe 2016, suggesting a possible recalibration of toxicity weighting in oceans.

The methodological differences between the two approaches create substantial variations in certain impact categories, particularly in resource depletion and toxicity-related indicators. While Recipe 2016 provides a more detailed assessment of mineral scarcity, CML-IA presents higher estimates for fossil fuel depletion and overall environmental toxicity. These findings suggest that when selecting an impact assessment method, it is crucial to consider which environmental aspects are most relevant to the study's objectives, as the choice of methodology can significantly influence the interpretation of sustainability and environmental impacts.

4. Conclusion

The cradle-to-gate LCA study examines the environmental impact of synthetic (PVA, CMC) and natural binders (cassava, wheat, and corn starch). The study utilized the ISO 14040/14044 standards, ReCiPe Midpoint, and CML-IA Baseline impact assessment method to evaluate key environmental indicators including GWP, Acidification Potential (AP), and fossil fuel depletion.

The results demonstrate that synthetic binders, especially PVA, have a significantly higher environmental impact across all impact categories. The highest GWP (6.55 kg CO_2 eq in ReCiPe and 6.37 kg CO_2 eq in CML) for PVA, with elevated fossil fuel consumption and toxicity indicators. In contrast, among the natural binders, corn starch presented the most sustainable profile with the lowest GWP (0.930 kg CO_2 eq in ReCiPe and 0.896 kg CO_2 eq in CML) and lowest toxicity. Natural binders still have eutrophication and land use impacts because of agricultural production processes, but in comparison to synthetic binders, their total environmental footprint is still much smaller.

A comparison of the two-impact assessment methods ReCiPe Midpoint and CML-IA Baseline reveals slight differences in results due to differences in characterization models. For example, ReCiPe calculated slightly higher GWP values for all binders (an average difference of about 2.8 %). On the other hand, CML-IA calculated higher acidification potential (AP) values, with average increases of 4.1 % over ReCiPe, reflecting its more conservative sulfur dioxide emission policy. Abiotic depletion (fossil fuels) values were also significantly higher in CML-IA (97.6 % greater fossil fuel depletion than ReCiPe) the ReCiPe reported 50.3 % greater mineral depletion than CML-IA, indicating its more refined approach to resource use estimation. These differences underscore the need to select appropriate impact assessment tools based on the specific environmental issues a study addresses.

These findings underscore the need to migrate to bio-based binders as an alternative for the construction industry. The use of agricultural starch binders aligns with global sustainability targets and regulations such as the EU's Construction Products Regulation and the Paris Agreement commitments. However, further research is needed to optimize the performance and durability of natural binders, ensuring their practical feasibility across various construction applications. In the future, sustainable binder alternatives and green material technologies should be a top priority for industry stakeholders, including policymakers, manufacturers, and construction professionals. Additionally, circular economy principles such as using agricultural wastes for binder production and increasing material recyclability can further reduce environmental impacts. Further studies should systematically explore and clarify the methodological differences between ReCiPe Midpoint and CML-IA Baseline based on the significant differences in abiotic depletion indicators (fossil fuels and minerals) to increase transparency and guide the choice of impact assessment tools based on specific sustainability objectives in construction applications.

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