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Life Cycle Assessment of Plasterboard Production: A UK Case Study

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Abstract: Plasterboard, which serves as a nonstructural building material, is widely employed for lightweight wall construction and surface finishing in walls and ceilings. Amid mounting concerns regarding product sustainability and the adoption of Net Zero strategies, evaluating the environmental performance of materials has become crucial. This study aims to conduct a comprehensive life cycle assessment (LCA) for wall gypsum plasterboard, aiming to pinpoint areas for potential environmental improvement. The LCA methodology, adhering to established guidelines and considering midpoint impact categories, was employed to quantify environmental impacts across various stages of the plasterboard life cycle—encompassing raw material extraction, plasterboard manufacturing, transportation during all stages, and end-of-life treatment of plasterboard waste. Primary data were sourced directly from a plasterboard manufacturer and recycler and supplemented with secondary data obtained from the Environmental Product Declaration (EPD) and the Ecoinvent 3.9 database. Among the identified impact categories, the human carcinogenic toxicity category emerged as the most affected category, primarily due to the raw material supply stage, followed by freshwater ecotoxicity, which was impacted due to the material supply stage.

Keywords: plasterboard; life cycle assessment; environmental impacts; sustainability; building materials

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1. Introduction

1.1. Gypsum Plasterboard

Gypsum plasterboard is widely used as a surface covering material in commercial and residential buildings [1,2]. Available in fire-resistant and general-purpose types, plasterboard serves as an easily applied and durable cladding for walls, floors, and ceilings [3–5]. Comprised primarily of gypsum (97%) and additives (3%), plasterboard offers easy installation, low cost, and beneficial properties such as sound attenuation and thermal insulation [6–8].

Due to these characteristics, gypsum plasterboards are gaining global popularity, with world gypsum production accounting for around 150 million metric tons in 2021 [9]. Plasterboard production in 2022 reached 28 billion square feet in the US and around 3 billion square feet in the UK [10,11]. Plasterboard production and applications are associated with challenges both from its inherent mechanical properties and from an environmental point of view [12,13]. On the other hand, the Plasterboard Sustainability Action Plan [11] and Net Zero Waste targets in the UK [14] emphasize identifying hotspots and improvement areas in the plasterboard life cycle [15]. The Plasterboard Sustainability Action Plan aims to reduce the environmental impacts of plasterboard throughout its life cycle stages. In addition, the shift towards a circular economy aims to alleviate strain on natural resources while fostering sustainable growth, job creation, and economic resilience. One of the main objectives of the mentioned action plans is to enhance material resource efficiency and enable circularity within the various industrial sectors.

The construction sector is one of the main intensive raw material consumers and contributes to the generation of a huge amount of waste worldwide. Hence, it is evident that shifting the current linear consumption pattern to a circular economy and reducing generated waste is a hotspot in the construction industry [16]. Furthermore, the increasing demand for energy-efficient, environmentally friendly materials and circular economy concepts necessitates new developments within current business as usual production and consumption practices. One of the powerful tools for evaluating these aspects within the construction sector is life cycle assessment (LCA).

1.2. Life Cycle Assessment

LCA serves as a valuable method for evaluating potential environmental impacts across the entire life span of a product or service. This encompasses stages from natural resource acquisition through to production, use, and waste management. These unique features of LCA facilitate avoiding burden shifting from one life cycle stage to another or from one environmental impact to another [17]. There are different variations of the LCA method, which are beyond the scope of this study and can be found in other studies [17–19]. The first step to fulfil the sustainability requirements of the plasterboard life cycle is to conduct a thorough LCA based on current plasterboard production and usage practices. This will identify hotspots for possible improvements and suggest possible scenarios to reduce the overall environmental burden of the plasterboard product throughout its entire life cycle [20]. Despite the extensive use of plasterboard in the construction sector, a thorough plasterboard LCA is lacking in the literature [21].

1.3. Plasterboard LCA Literature Review

The analysis of existing literature highlights two primary categories within plasterboard LCA studies. The first group primarily involves comparing the LCA of conventional plasterboard, representative of the status quo, with alternative options made either wholly or partially from materials other than raw gypsum. The second group evaluates the LCA solely within the plasterboard recycling phase. In addition, existing works in both groups evaluate a limited number of impact categories. The comprehensive scope of LCA helps analysts identify and avoid burden-shifting from one environmental impact to another. As such, an apparent energy reduction in one portion of the value-chain may result in an unintended consequence elsewhere.

The study by Bushi (2011) on the LCA of two types of gypsum plasterboard in the USA, focusing on nine different impact categories with particular emphasis on energy consumption and CO_2 emissions, revealed that energy usage at the plasterboard manufacturing stage was the most significant contributor to five impact categories and primary energy consumption [12]. This study also highlighted that energy consumption accounted for over 70% of the total environmental impacts. Additionally, the study reported a high environmental impact contribution from lining paper during the plasterboard manufacturing stage. Similarly, Rodrigo-Bravo (2022) conducted an LCA study assessing two varieties of gypsum ceiling tiles: one made of from recycled polyurethane foam waste and the other being a conventional gypsum tile. Their investigation revealed that the polyurethane foam tile demonstrated better environmental performance. It exhibited a reduction of 14% in energy consumption, 14% in CO_2 emissions, and a 25% decrease in water consumption compared to conventional gypsum ceiling tiles. Moreover, their research pinpointed the production stage as the primary contributor to the environmental impact of both types of tiles throughout their life cycle [22]. Quintana (2018) conducted an LCA comparing conventional plasterboard with composite boards made of various natural fibres and bio-based epoxy resin. The study found a 50% reduction in CO_2 emissions for the composite made of flax, while an identical emission level was found for the coir board compared to traditional plasterboard. The results of the study indicated that using natural fibre epoxy-based composites with resin reduced the environmental impact across all categories. Carbon emissions are reduced by 40% for shredded cotton boards and by up to 60% for flax boards compared to natural gypsum plasterboards. Additionally, the study showed that selection of the impact assessment method can affect the results, varying from 31% to 50% depending on the method chosen [23]. In another study, the environmental impacts of conventional plasterboard and gypsum board containing flue gas desulfurization (FGD) were compared through an LCA focusing on only five impact categories. The results indicated that the FGD board had a 6% lower overall environmental impact compared to natural gypsum plasterboard. From the results, the FGD board outperformed the natural gypsum board, showing a 72% reduction in the human health damage impact category and 76% in non-renewable resource consumption category [24]. Another study evaluated the benefits of recycling plasterboard in terms of resource use efficiency and its contribution to the circular economy. They found that, while there is no significant variation in life cycle energy use, Green House Gas emissions (GHG) decreased with increasing recycled content due to the degradation of plasterboard lining paper in landfills [13]. Weimann (2021) evaluated the environmental impacts of recycling post-consumer plasterboard waste on an industrial scale. The results showed that the utilization of recycled gypsum can be environmentally advantageous compared to the use of natural or FGD gypsum, especially in the impact categories of land transformation and eutrophication. However, transportation distances showed a strong influence on the environmental impact [25].

1.4. Aims of This Research

This research aims to assess the potential environmental impacts of plasterboard throughout its life cycle stages. A distinctive feature of this study is its comprehensive LCA dedicated to the plasterboard life cycle in the UK, utilizing primary data from a plasterboard manufacturer and a waste recycler. It encompasses 18 impact categories to ensure a thorough assessment, which is lacking in the current literature. This research aims to quantify the relative significance of diverse impact categories and identify primary contributing processes, thereby offering valuable insights for decision-makers, scientists, stakeholders, and the public. It will highlight critical processes that require potential improvements throughout the entire plasterboard life cycle. Specifically, the study focuses on scrutinizing each impact category in relation to the most influential processes involved.

2. Materials and Methods

The International Standard Organization (ISO) 14040 has laid out a framework for conducting LCA, encompassing four sequential steps [20]. These steps commence with goal and scope definition, proceed to Life Cycle Inventory (LCI) analysis, Life Cycle Impact Assessment (LCIA), and culminate in interpretation of the results [19]. The goal and scope definition stands as a pivotal initial phase, establishing the purpose, boundaries, and specifics of the LCA. This phase entails defining objectives, delineating the intended applications of assessment results, and setting boundaries for inclusion and exclusion within the analysis, all within the framework of the functional unit. The functional unit serves as a critical reference point, allowing for comparison and analysis of alternative goods or services based on the specific function they provide.

The LCI phase entails gathering and quantifying all pertinent inputs (such as resources, energy, and materials) and outputs (including emissions and waste) linked to the product, process, or activity across its complete life cycle. LCI generates an inventory of the environmental burdens or impacts related to each stage of the product's life, spanning from raw material extraction through manufacturing, distribution, utilization, and disposal.

During the LCIA step, an examination of the plasterboard's environmental effects throughout its entire life cycle takes place. This process entails employing indicators to gauge and comprehend the contributions of resource extraction, waste, and emissions to various potential impacts. LCIA assesses the plasterboard's life cycle concerning different impact categories like climate change, toxicity, noise, and land use. It offers an evaluation of these impacts based on a specific functional unit, occasionally amalgamating multiple impacts to assess metrics such as years of human life lost due to climate change or carcinogenic effects.

Interpretation in LCA denotes a pivotal phase wherein collected data and assessment results undergo analysis and communication to comprehend the environmental implications of a product or process. For instance, consider a study comparing the environmental impacts of two types of packaging materials—plastic and paper—used for packaging a specific product. Following the LCA, the interpretation phase might reveal that, while it exhibits lower impacts in terms of production emissions, plastic's long-term environmental consequences due to poor biodegradability significantly outweigh those of paper. Consequently, the study's interpretation could suggest that, despite certain immediate advantages, the long-term environmental impacts of using plastic packaging might be more detrimental than those of using paper. This insight could influence decisions regarding packaging material selection, favouring the adoption of more environmentally friendly options like paper. Therefore, stakeholders may seek further information to determine which difference holds greater significance. Addressing such issues is often an optional step, yet one that unequivocally merits attention, drawing not only from the natural sciences but also extensively from social science and economics [26].

2.1. LCA Goal and Scope Definition

The goal of the LCA in this paper is to conduct a comprehensive assessment of plasterboard production in the UK, following the principles outlined in ISO 14040. The study aims to assess the environmental impacts associated with all stages of the plasterboard's life cycle, from raw material extraction to end-of-life disposal (cradle to grave), and identify the hotspots throughout the plasterboard life cycle.

2.1.1. Functional Unit

The assumed functional unit in this study is 1 m^2 (8.44 kg) of plasterboard with a thickness of 12.55 mm. The product system specifications, presented in Table 1, are derived from the Environmental Product Declaration (EPD) for 1 kg of plasterboard production. As the functional unit is 8.44 kg, the values in Table 1 have been adjusted accordingly in the analysis. This conversion was validated by the plasterboard manufacturer [6].

Table 1. Specifications of standard plasterboard sourced from UK plasterboard manufacturer's Environmental Product Declaration.

Technical Data/Physical Characteristics	Values
EN Classification	B1/20/6
Fire Classification	A1
Gross Density	1250 kg/m^3
Parameter	Part
Gypsum and Minerals	98.7%
Additives	1.3%
Total	100%
Packaging: Wooden Pallet	0.024 kg per kg
Packaging: Bags	Bags made of paper (1.7 g of paper/kg) and polyethylene (0.4 g of PE/kg)

2.1.2. System Boundary

The system boundary separates the unit of the plasterboard and related services from the Technosphere, which is the part of the atmosphere where all human activities take place [26]. The plasterboard LCA stages include raw material extraction (A1), transportation from the natural gypsum mining site to the plasterboard manufacturing site (A2), manufacturing (A3), transportation from the manufacturing site to the construction site (A4), installation (A5), end-of-life (C2 and C4), and plasterboard recycling (C3) stages.

The system boundary in this study includes raw materials supply (extraction/production), manufacturing, installation, and end of life. In Figure 1, transportations for all mentioned stages are shown in arrows with the letter 'T'. Heat and electricity consumption are related to all stages and are calculated as the sum of the values from each of the studied stages. Additionally, the generated waste in all stages (during the raw materials extraction, manufacturing, and installation) are included in the analysis. However, plasterboard waste processing (C2–C4) are considered separately and investigated based on the primary dataset provided by a plasterboard recycler.

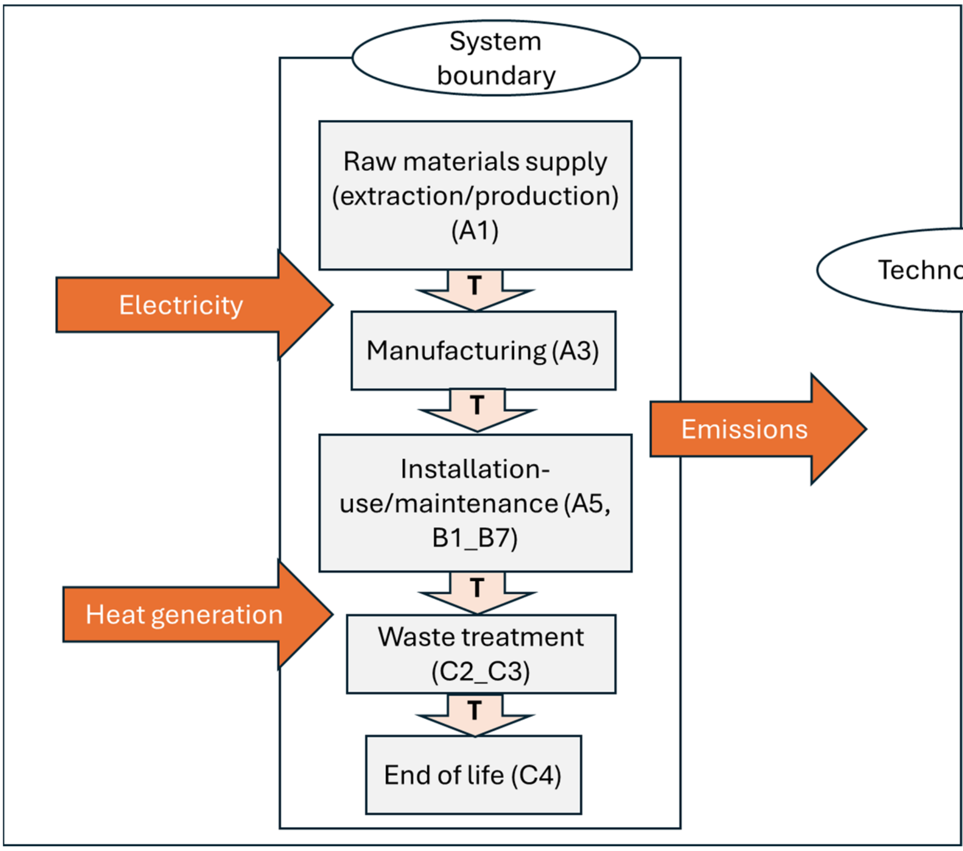

Figure 1. System boundary for plasterboard life cycle assessment.

Vehicle maintenance processes were excluded in the LCA for transportation machinery. Transportation vehicles are assumed to operate at full capacity between collection sites and destination sites, covering an average distance of 30 km between plasterboard waste collection and processing sites. The maintenance and use phase of the plasterboard (B1–B7) were not considered in the analysis because it was assumed to have minimal environmental effects. A similar assumption was made by Pedreño-Rojas et al. (2020) [7] and Bushi and Mell (2011) [12] regarding the EPDfor gypsum plasterboard in the UK [6]. Primary data for the maintenance and use phase were not available.

2.1.3. Data Inventory Collection

Two types of inventory data were implemented in this study. First, primary data were collected from a plasterboard manufacturer, a plasterboard recycler, a construction company, and a demolition contractor for the manufacturing, recycling, installation, and end-of-life stages. Second, data regarding energy and fuel production and raw material production (such as glue, adhesives, paper, and lime) were collected from multiple resources, including data from a plasterboard manufacturer's Environmental Product Declaration (EPD) for standard plasterboard, Ecoinvent (V3.9) dataset, and SimaPro (V9.5) database. It should be pointed out that, in terms of the secondary datasets, the default location is considered to be the UK (inventory data in Simapro include different countries; however, this paper utilized the UK dataset only).

- Raw material extraction (A1): all raw material extraction inventory was collected from the Ecoinvent database.
- Transportation from raw material mining sites to the plasterboard manufacturing site (A2): inventory data were sourced from the manufacturer, including the distances and specifications of the vehicle used.
- Manufacturing: inventory data for manufacturing sourced from a plasterboard manufacturer.
- Transportation from manufacturing site to construction site: inventory data for the used vehicles were sourced from the manufacturer, and an average distance of 30 km was assumed for the distances.
- Installation and use stage (A5, B1–B7): primary data were collected from a plasterboard installer for this stage.
- End of life (C2, C3, C4): Recycling inventory data were sourced from a plasterboard recycler, including the specifications of transportation vehicles and the recycling process. An average distance of 30 km was assumed for the distances between the recycling site and waste collection sites.
- Energy flow: the energy flow and usage include all the stages.

2.2. Inventory Data Quality

The LCA model for the plasterboard life cycle includes two datasets comprising primary and secondary datasets. Primary datasets were collected from a plasterboard manufacturer, a recycler, and an installer, while secondary datasets were gathered from Ecoinvent 3.9, as appropriate. The plasterboard life cycle had three stages including manufacturing, recycling and waste processing, and installation. Table 2 summarizes the primary data collection level for the LCA model.

Table 2. Summary of primary data collection.

Stage	LCA	Data Quality Level
Manufacturing	Used machinery and equipment energy consumption, fuel type, working hours of equipment, transportation distances, and the quantity of used materials	Data collection spreadsheets for plasterboard
Recycling	Used machinery and equipment energy consumption, fuel type, working hours of equipment, transportation distances, and the quantity of used materials	Data collection spreadsheets for plasterboard
Installation	Used machinery and equipment energy consumption, fuel type, working hours, transportation distances, and the quantity of used materials	Data collection spreadsheets for plasterboard

2.3. Environmental Impact Assessment Method

The LCA employs two primary methods to assess environmental impacts: the midpoint and the endpoint methods. The midpoint method quantifies intermediate environmental indicators, such as greenhouse gas emissions, acidification, and human toxicity, offering a detailed analysis of specific stressors caused by activities within a product's life cycle [27]. On the other hand, the endpoint method evaluates broader impact categories, directly linking environmental stressors to their ultimate effects on human health, ecosystem quality, and resource availability [28]. Endpoint indicators, such as potential years of life lost due to health impacts, loss of biodiversity, and alterations in resource availability, offer a comprehensive view of a product or system's influence on both human welfare and the environment. These indicators directly connect environmental stressors to their ultimate effects, allowing for a deeper understanding of the broader impacts. In contrast, midpoint methods, while more straightforward for public reporting and interpretation, focus on specific environmental factors and provide a detailed analysis of distinct stressors caused by various activities within a product's life cycle.

Following the collection of inventory data, the analysis utilized the ReCiPe 2016 Midpoint (E) method [29] within SimaPro software to calculate the results. The ReCiPe 2016 Midpoint LCIA method was selected due to its wide range of impact categories (18 impact category) compared to other methods. ReCiPe 2016 has several features that make this method suitable for this study: (1) it contains the broadest set of midpoint impact categories; (2) it enables impact categories to implement characterization factors at an international scale; and (3) it does not include potential impacts from future extractions in the impact assessment and assumes that they have been included in the inventory analysis. These features differentiate it from other approaches, such as Eco-indicator 99 [30] and Impact 2002+ [29]. The process commences with a characterization phase, which is subsequently complemented by a normalization analysis aimed at facilitating the interpretation of the obtained results. In addition, the ReCiPe method, compared to other methods, can be applied to global scale for some impact categories; for instance, species extinction is extended to the global scale [28]. Additionally, a comparison of various methods for building materials suggests that the ReCiPe midpoint method shows more realistic results [31].

2.4. Allocation Method

Allocation within the LCA deals with the multifunctionality or secondary processes shared among multiple product systems. Standards like ISO 14040, ISO 14044, EN 15804, and EN 15978 propose several strategies to tackle this complexity. ISO 14044 advocates for a hierarchical approach, discouraging allocation whenever feasible. Instead, it suggests strategies such as breaking down processes into sub-processes or employing system expansion, where secondary functions are incorporated within the system boundary. The system expansion approach needs to be adopted to avoid the multifunctionality of processes in the product systems. However, it was deemed appropriate to apply system expansion in this study as it only concerns the cradle-to-gate production of the plasterboard from manufacturers' perspective.

3. Results

3.1. Characterization Analysis

Characterization analysis in LCA involves the conversion of all collected inventory data, such as resource consumption and emissions from various life cycle stages, into specific environmental impact categories, namely the global warming potential impact category, using mathematical models and characterization factors. This step assigns values or scores to different inputs and outputs, enabling the translation of raw data into indicators representing potential environmental impacts such as climate change, acidification, eutrophication, human toxicity, and others. This process facilitates the quantification and assessment of the product's overall environmental footprint across different impact categories [32]. Table 3 shows the characterization analysis of the plasterboard, with each impact category expressed in an equivalent (eq) unit. Additional information on the units used in the ReCiPe midpoint method was explored in a study by Huijbregts et al. (2017) [28].

Table 3. Characterization analysis based on ReCiPe midpoint method for 1 m^2 of plasterboard.

Impact Category	Unit	Total
Global warming	kg CO_2 eq	2.172
Stratospheric ozone depletion	kg CFC-11 eq	1.4×10^{-6}
Ionizing radiation	kBq Co-60 eq	0.16495
Ozone formation, Human health	kg NO_x eq	0.00744
Fine particulate matter formation	kg $PM_{2.5}$ eq	0.003435
Ozone formation, Terrestrial ecosystems	kg NO_x eq	0.00764
Terrestrial acidification	kg SO_2 eq	0.0076
Freshwater eutrophication	kg P eq	0.0004
Marine eutrophication	kg N eq	0.000114
Terrestrial ecotoxicity	kg 1,4-DCB	9.48236
Freshwater ecotoxicity	kg 1,4-DCB	0.0417
Marine ecotoxicity	kg 1,4-DCB	0.05902
Human carcinogenic toxicity	kg 1,4-DCB	0.07856
Human non-carcinogenic toxicity	kg 1,4-DCB	0.90908
Land use	m^2a crop eq	0.10333
Mineral resource scarcity	kg Cu eq	0.02765
Fossil resource scarcity	kg oil eq	0.76485
Water consumption	m^3	0.01557

Based on Table 3, the life cycle of 1 m^2 (8.44 kg) of plasterboard results in the production of 2.14 kg of CO_2 eq. Similarly, other impact categories in Table 3 exhibit values specific to their respective impacts. It is important to note that comparing impact categories is not feasible due to variations in the units utilized in the characterization analysis. Within the characterization analysis, each impact category is represented in distinct units that are not directly comparable to one another. Terrestrial ecotoxicity, for example, has a value of 9.48 kg of 1,4-DCB equivalent, while the impact category of stratospheric ozone depletion is represented by 1.4×10^{-6} kg of CFC-11 equivalent. Table 4 provides a characterization analysis for the raw material supply stage only, including total values that enable comparison with the impacts of the remaining stages.

Table 4 reveals the significant role of the material supply stage (A1) in nine impact categories (the raw material supply overall impact is more than 50% of the total impact within the respective category). Within mineral resource scarcity, raw material supply stands out with a substantial contribution of 92.43% to the overall environmental burden. Similarly, the material supply stage has a dominant influence on the marine eutrophication category, accounting for 91.59% of the overall impact. Water consumption is another category where the material supply stage exhibits the highest contribution, representing 81.62% of the overall impact. The freshwater ecotoxicity category is also significantly affected by the material supply stage, contributing to 62.36% of the total impact. However, the material supply stage has a lower overall share in the ionizing radiation category, representing only 15.40% of the total effect. Similarly, the fossil resource scarcity category is less affected by the material supply stage, accounting for 25.23% of the total impact. Table 5 shows the characterization analysis for transportation (all transportation during the plasterboard life cycle).

Table 5 provides a characterization analysis of transportation. A more detailed breakdown of analysed processes can be found below, including all impact categories alongside a comprehensive list of processes, each accompanied by their respective percentages contributing to these impact categories. It is important to note that results in Table 5 include background processes as well, such as coal mining for heat generation during plasterboard manufacturing, electricity generation, waste treatment from coal mining, etc. These should not be confused with the foreground processes. Since energy use encompasses all the studied stages, if necessary, the identified hotspot energy-intensive stage is clarified; otherwise, the energy use applies to the whole life span of the plasterboard.

Table 4. Characterization analysis based on ReCiPe midpoint method for plasterboard raw material supply stage.

Impact Category	Unit	Total	Raw Material Supply	% of Raw Material Supply
Global warming	kg CO_2 eq	2.17237	0.59474	27.38
Stratospheric ozone depletion	kg CFC-11 eq	1.37×10^{-6}	5.90836×10^{-7}	43.13
Ionizing radiation	kBq Co-60 eq	0.16495	0.02541	15.40
Ozone formation, Human health	kg NO_x eq	0.00744	0.00194	26.05
Fine particulate matter formation	kg $PM_{2.5}$ eq	0.00344	0.00160	46.51
Ozone formation, Terrestrial ecosystems	kg NO_x eq	0.00764	0.00202	26.48
Terrestrial acidification	kg SO_2 eq	0.00759	0.00236	31.10
Freshwater eutrophication	kg P eq	0.00040	0.00025	61.93
Marine eutrophication	kg N eq	0.00011	0.00010	91.59
Terrestrial ecotoxicity	kg 1,4-DCB	9.48236	3.15325	33.25
Freshwater ecotoxicity	kg 1,4-DCB	0.04170	0.02600	62.36
Marine ecotoxicity	kg 1,4-DCB	0.05902	0.03457	58.58
Human carcinogenic toxicity	kg 1,4-DCB	0.07856	0.04745	60.40
Human non-carcinogenic toxicity	kg 1,4-DCB	0.90908	0.53950	59.35
Land use	m^2a crop eq	0.10333	0.05492	53.15
Mineral resource scarcity	kg Cu eq	0.02765	0.02556	92.43
Fossil resource scarcity	kg oil eq	0.76485	0.19300	25.23
Water consumption	m^3	0.01557	0.01271	81.62

Table 5. Characterization analysis based on ReCiPe midpoint method for plasterboard life cycle processes.

Impact Category	Unit	Total	Transportation	% of Transportation
Global warming	kg CO_2 eq	2.17237	0.444804	20.48
Stratospheric ozone depletion	kg CFC-11 eq	1.4×10^{-6}	0.0000003	21.43
Ionizing radiation	kBq Co-60 eq	0.16495	0.012323	7.47
Ozone formation, Human health	kg NO_x eq	0.00744	0.004128	55.48
Fine particulate matter formation	kg $PM_{2.5}$ eq	0.00344	0.001371	39.85
Ozone formation, Terrestrial ecosystems	kg NO_x eq	0.00764	0.004194	54.90
Terrestrial acidification	kg SO_2 eq	0.00759	0.003814	50.25
Freshwater eutrophication	kg P eq	0.00040	0.000098	24.50
Marine eutrophication	kg N eq	0.00011	0.000003	2.73
Terrestrial ecotoxicity	kg 1,4-DCB	9.48236	5.861724	61.82
Freshwater ecotoxicity	kg 1,4-DCB	0.04170	0.007203	17.27
Marine ecotoxicity	kg 1,4-DCB	0.05902	0.012508	21.19
Human carcinogenic toxicity	kg 1,4-DCB	0.07856	0.017341	22.07
Human non-carcinogenic toxicity	kg 1,4-DCB	0.90908	0.215788	23.74
Land use	m^2a crop eq	0.10333	0.024864	24.06
Mineral resource scarcity	kg Cu eq	0.02765	0.001139	4.12
Fossil resource scarcity	kg oil eq	0.76485	0.146671	19.18
Water consumption	m^3	0.01557	0.000953	6.12

According to Figure 2, the material supply stage emerges as the primary contributor across 11 impact categories. A more detailed breakdown of the impact categories is given in the below sections, which include all impact categories alongside a comprehensive list of processes, each accompanied by the respective percentages contributing to these impact categories. It is important to note that all background processes are included in all impact category analyses below, such as coal mining for heat generation during plasterboard manufacturing, electricity generation, waste treatment from coal mining, etc. These should not be confused with the foreground processes.

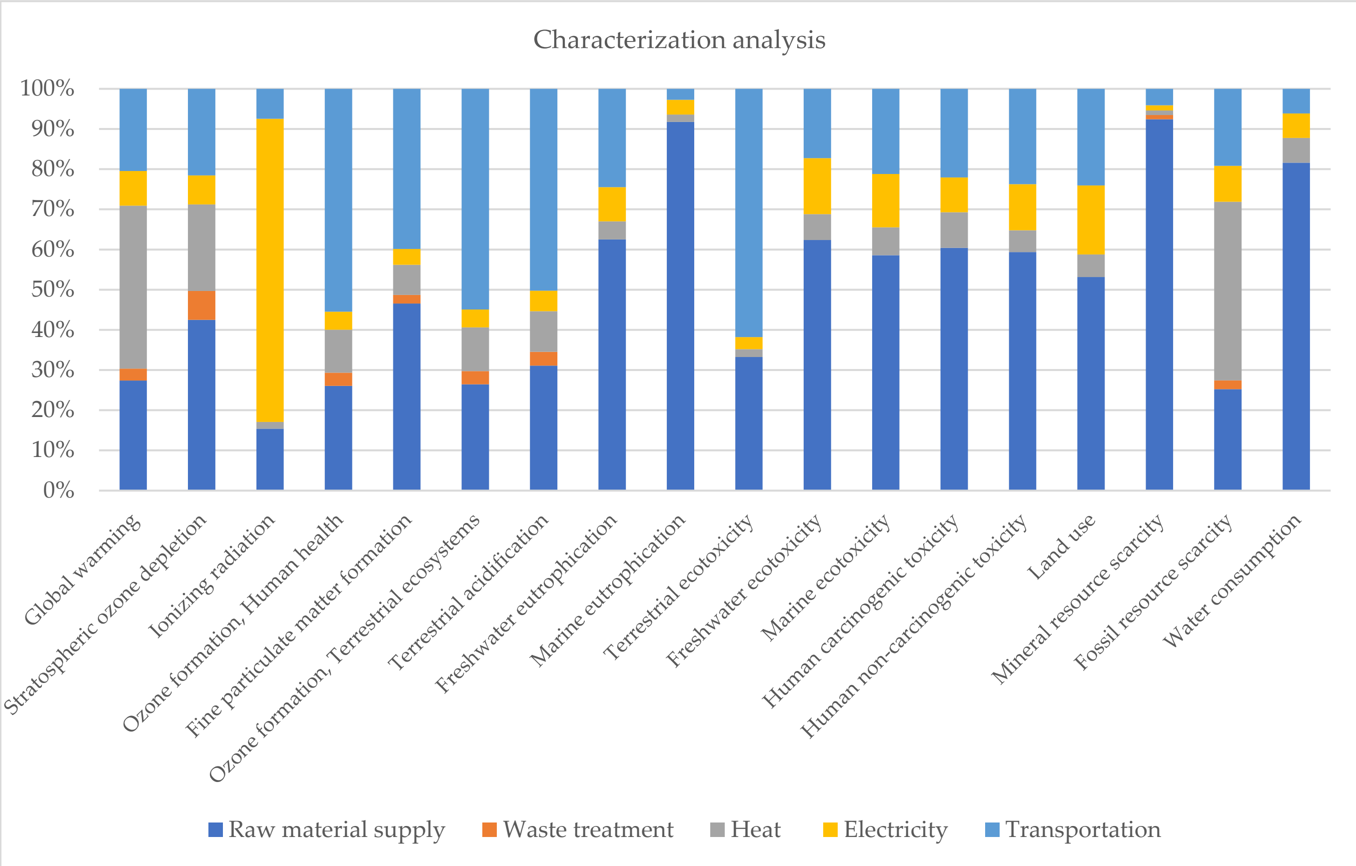

Figure 2. Characterization analysis based on the share of studied processes.

3.1.1. Global Warming Potential

The global warming potential impact category is affected mostly by heat generation, accounting for 41%; raw material supply [27%] (raw gypsum 8.65%, plasticizer production 5.10%); transportation [20%] (road 9.69%, sea 6.8%); electricity generation [9%]; and, finally, waste treatment processes, which contribute to 3% of the total CO_2 emissions.

3.1.2. Stratospheric Ozone Depletion

Within this category, the raw materials supply stage account for 43% (glue production 9.90%, ethoxylated alcohol production 9.79%), the transportation process has 22% (road transportation 10.98%, sea transportation 7.53%), heat generation has 22%, electricity generation has 8%, and waste treatment contributes to 5% of the total CFC-11 equivalent emissions.

3.1.3. Ionizing Radiation

The ionizing radiation category is mostly affected by electricity generation [75%], followed by raw material supply [15%] (plasticizer production 3.75%), the transportation process [8%] (train transportation 4.70%, road transportation 1.62%), and heat generation [1.67%] of the kBq Co-60 equivalent emissions.

3.1.4. Ozone Formation (Human Health)

Within the ozone formation (Human health) category, the transportation process [56%] (sea transportation 41.50%), raw material supply [26%] (gypsum production 13.34%), heat generation [11%], electricity generation [4%], and, finally, waste treatment [4%] contribute to the overall ozone formation (Human health) equivalent emissions.

3.1.5. Fine Particulate Matter Formation

This category is affected by raw material supply [47%] (gypsum production 27.46%), the transportation process [40%] (sea transportation 28.63%), heat generation [7%], electricity generation [4%], and, finally, waste treatment contributes 2% of the overall fine particulate matter formation equivalent emissions.

3.1.6. Ozone Formation (Terrestrial Ecosystems)

Within this category, the transportation process accounts for 55% (sea transportation 40.70%), raw material supply has 27% (gypsum production 13.22%), heat generation has 11%, electricity generation has 4%, and waste treatment contributes 3% of the overall ozone formation (Terrestrial ecosystems) equivalent emissions.

3.1.7. Terrestrial Acidification

The terrestrial acidification category is affected by the transportation process, which accounts for 50% (sea transportation plays a significant 40.29%); raw material supply has 31% (gypsum production 10.26%, ethoxylated alcohol production 4.69%); heat generation has 10%, electricity generation has 5%; and, lastly, waste treatment contributes 4% of the overall terrestrial acidification equivalent emissions.

3.1.8. Freshwater Eutrophication

Within this category raw material supply accounts for 62% (gypsum production 15.48%, lime production 13.18%), the transportation process has 25% (road transportation 12.26%), electricity generation has 9%, and heat generation contributes 4.59% to the overall freshwater eutrophication category.

3.1.9. Marine Eutrophication

Raw material supply accounts for 92% (ethoxylated alcohol production 45.93%, starch production 18.90%, glue production 9.38%), electricity generation has 3.88%, transportation process has 2.99% (road transportation 1.17%), and, finally, heat generation occupies the fourth position, contributing 1.53% of the N equivalent emissions within this category.

3.1.10. Terrestrial Ecotoxicity

The transportation process accounts for 62% (road transportation 55.47%), the raw material supply stage has 33% (gypsum production 12.81%, plasticizer production 9%), electricity generation has 2.98%, and heat generation contributes 1.93% to the terrestrial ecotoxicity category.

3.1.11. Freshwater Ecotoxicity

Within the freshwater ecotoxicity category, raw materials supply accounts for 62% (plasticizer production 19.96%, gypsum production 14.26%), followed by transportation [17%] (road transportation 10%), electricity generation [14%], and heat generation contributes to 6.45% of the overall freshwater ecotoxicity equivalent emissions.

3.1.12. Marine Ecotoxicity

Raw material supply accounts for 59% (plasticizer production 18.54%, gypsum production 14.20%), the transportation process has 21% (road transportation 13.8%), electricity generation has 13%, and heat generation contributes to 6.93% of marine ecotoxicity impact category.

3.1.13. Human Carcinogenic Toxicity

The human carcinogenic impact category is affected by the raw material supply, which accounts for 60% (steel screw production 17.83%, gypsum production 16.49%); transportation process has 22% (train transportation 10.8%, sea transportation 8.37%); heat generation has 9%; and electricity generation contributes 9%.

3.1.14. Human Non-Carcinogenic Toxicity

Within this category, raw materials supply accounts for 59% (plasticizer production 18.85%, gypsum production 15.79%), the transportation process has 24% (road transportation 16.65%), electricity generation has 12%, and heat generation contributes 5.43% to the overall human non-carcinogenic toxicity category.

3.1.15. Land Use

Raw material supply accounts for 53% (ethoxylated alcohol production 21.82%, starch production 11.59%), the transportation process has 24% (road transportation 18.65%), electricity generation has 17%, and heat generation contributes 5.60% to the land use impact category.

3.1.16. Mineral Resource Scarcity

The mineral resource scarcity impact category is affected by the raw materials supply stage by 93% (gypsum production 84.36%, screw production 3.36%), the transportation process by 4.1%, electricity generation by 1.26%, heat generation by 1.15%, and waste treatment by 1.02%.

3.1.17. Fossil Resource Scarcity

This impact category is affected by heat generation with 44.46%, raw material supply with 25% (plasticizer production 7.30%, gypsum production 5.45%), the transportation process with 19% (road transportation 10.18%, sea transportation with 5.7%), electricity generation with 9%, and, lastly, waste treatment with 2.19% of the overall kg of oil equivalent emissions.

3.1.18. Water Consumption

The water consumption category is affected by the raw material supply stage with 82%, heat generation with 6%, transportation process with 6% (road transportation 2.7%, train transportation 2.5%), and, lastly, electricity generation with 6% of contributions.

Although the impact categories are listed without a specific order, processes within each impact category are listed based on the magnitude of the process. The transportation and raw material supply stages have been explained in more detail, including road, sea, and train for the transportation process, and background processes for the raw materials supply chain. However, from the characterization analysis, different categories cannot be compared to each other due to differences in the exclusive units used for each category. Hence, normalization analysis enables comparison between all categories.

3.2. Normalization Analysis

In the LCA methodology, normalization is an optional step defined by the ISO 14040 standard [20]. While not mandatory, normalization offers several advantages in evaluating and comparing the impacts of different environmental categories. This involves adjusting environmental impacts to a common basis, often a functional or reference unit, to eliminate scale biases. Initially, the functional unit, representing the quantifiable performance of the system, is defined. Environmental indicators, like greenhouse gas emissions, are then expressed per unit of this functional unit. SimaPro, in contrast to some methods, employs the approach of multiplying the impact category by the inverse of the reference value. Normalization aids in identifying critical categories or processes, enabling targeted sustainability strategies. The reference system chosen in this study was Europe per person in SimaPro, facilitating a comparison between the ecological footprint of the average European consumer unit and that of an average individual from the rest of the world. Table 6 provides a normalization analysis for the plasterboard life cycle. Although this analysis does not have a specific unit, it allows for a comparison across all impact categories considered in the LCA.

Table 6. Normalization analysis ($\times 10^5$).

Impact Category	Total
Human carcinogenic toxicity	762.85
Freshwater ecotoxicity	165.56
Marine ecotoxicity	135.74
Fossil resource scarcity	78.01
Terrestrial ecotoxicity	62.39
Freshwater eutrophication	60.91
Ozone formation, Terrestrial ecosystems	43.00
Ozone formation, Human health	36.14
Ionizing radiation	34.31
Global warming	27.15
Terrestrial acidification	18.53
Fine particulate matter formation	13.43
Water consumption	5.84
Human non-carcinogenic toxicity	2.91
Marine eutrophication	2.47
Stratospheric ozone depletion	2.29
Land use	1.67
Mineral resource scarcity	0.02

Table 6 illustrates the results of the normalization analysis conducted for the life cycle of plasterboard. The impact category of human carcinogenic toxicity emerges as the most significant, with several processes standing out as major contributors. Within the human carcinogenic toxicity category, the most important processes are related to the production of steel screws (for attaching the plasterboards to the wall). During the plasterboard installation, for 1 m^2 of plasterboard 0.015 kg of steel is used (screw for attachment of plasterboard to the wall). Background processes contributing to the human carcinogenic toxicity category are electric arc furnace slag (treatment and residual material landfilling), steel production (unalloyed), basic oxygen furnace slag (treatment and residual material landfilling), ethoxylated alcohol production, polyurethane adhesive production, spoil from hard coal mining, spoil from lignite mining, and sludge from steel rolling. These processes play a crucial role in shaping the overall human carcinogenic toxicity impact of plasterboard's life cycle. Given that the production of steel screws is a major contributor to human carcinogenic toxicity, exploring alternative methods for attaching plasterboard to walls could be beneficial. This could include adhesive-based systems or innovative fastening solutions that use fewer or no steel components. Additionally, investigation of alternative materials for fastening or attaching plasterboard that have lower environmental impacts, for instance, using screws made from recycled materials or materials with lower toxicity, could help mitigate the impacts in this category.

Within the freshwater ecotoxicity category, background processes such as ethoxylated alcohol production, the treatment of sulfidic tailings from copper mine operations, the treatment of scrap copper, polyurethane adhesive production, steel production, spoil from hard coal mining, spoil from lignite mining, raw gypsum production, and basic oxygen furnace slag (treatment and residual material landfill) exhibit the highest contributions to the freshwater ecotoxicity impact category. Copper mining and sulfuric acid production are background processes required to produce the plasticiser, which finally lead to increasing the freshwater ecotoxicity category. Increasing the use of recycled materials in plasterboard production can reduce the demand for primary resources, predominantly virgin gypsum. This helps mitigate the environmental impacts associated with gypsum mining and processing activities. Additionally, implementation of measures to improve resource efficiency in the plasterboard manufacturing processes, such as reducing water usage, energy consumption, and waste generation can help to minimize the environmental burden associated with resource extraction and processing, which can finally reduce the overall impacts within the freshwater ecotoxicity category.

Marine ecotoxicity represents the third most significant impact category. Within this category, background processes such as the production of ethoxylated alcohol, the treatment of sulfidic tailings from copper mine operations, scrap copper treatment, polyurethane adhesive production, emissions from brake wear in lorries, and offshore oil/gas production all play pivotal roles in driving the marine ecotoxicity category into the third highest place. To address the significant environmental impacts associated with marine ecotoxicity across the plasterboard life cycle stages, it is crucial to focus on mitigating the contributions of key background processes. First and foremost, exploring alternatives to ethoxylated alcohol and polyurethane adhesives, which are major contributors, could significantly reduce marine ecotoxicity. Additionally, efforts should be dedicated to minimize the environmental impacts of copper mining operations and the treatment of sulfidic tailings is essential, as these processes contribute to marine ecotoxicity through the release of pollutants. Moreover, implementing measures to reduce emissions from brake wear in lorries and promoting sustainable practices in offshore oil/gas production can further mitigate marine ecotoxicity. By addressing these key contributors through material substitution, waste reduction, and improved production processes, it is possible to minimize the environmental impacts of plasterboard production on marine ecosystems.

Fossil resource scarcity ranks fourth in overall impact, primarily driven by processes like onshore and offshore natural gas and petroleum production, as well as ethoxylated alcohol production. Terrestrial ecotoxicity closely follows, with key contributors including brake wear emissions from lorries, ethoxylated alcohol production, sea transport, and tire wear emissions from lorries. To address the environmental impacts of plasterboard's life cycle, particularly regarding fossil resource scarcity and terrestrial ecotoxicity, several measures can be implemented. Firstly, prioritizing the adoption of renewable energy sources and improving energy efficiency in plasterboard production can help reduce reliance on fossil fuels and mitigate fossil resource scarcity. Additionally, promoting sustainable transportation practices, such as using electric or hybrid vehicles with reduced brake and tire wear emissions, can minimize terrestrial ecotoxicity. Moreover, exploring alternative materials and processes for ethoxylated alcohol production, which emerges as a significant contributor to both impact categories, can further reduce environmental burdens. By integrating these strategies into the plasterboard life cycle, it is possible to lessen the environmental footprint and promote sustainability across the entire life cycle of plasterboards.

3.3. Life Cycle Costing

Due to confidentiality concerns of the plasterboard manufacturer, a detailed breakdown of the plasterboard life cycle cost could not be presented; however, a generalized cost analysis is given in Table 7.

Life cycle cost analysis encompasses various stages, including raw material supply, transportation (across all stages), manufacturing, recycling (where 10% of the total mass constitutes recycled plasterboard), installation (limited to 8.44 m^2 of plasterboard and not the complete wall), and the maintenance stage. Machinery maintenance and other associated costs during the manufacturing stage are considered part of Capital Expenditure (CAPEX).

CAPEX, which refers to the allocation of funds by an organization for the acquisition, enhancement, or maintenance of long-term assets, aims at fostering operational efficiency, expansion, or technological advancement. Distinguished from operational expenditures (OPEX), which address day-to-day operational costs, CAPEX is characterized by its strategic and forward-looking nature. It significantly contributes to enhancing a company's capabilities and competitive positioning. The unit is represented in EUR for the year 2023 based on the data from the plasterboard manufacturer, recycler, and installer, based on the currency rate of EUR 1.1492 (average exchange rate). From the cost analysis, the most significant contributor the overall cost of plasterboard can be seen as the raw material supply stage and workforce costs throughout the plasterboard life cycle stages.

Table 7. Life cycle cost of breakdown of wall plasterboard from raw material supply to the end-of-life stage.

Costs		Unit per 8.44 kg	Plasterboard
Capex	Maintenance	EUR	EUR 0.38
	Machinery	EUR	EUR 0.7
OPEX	Transportation	EUR	EUR 3.7
	Materials	EUR	EUR 5.52
	Energy	EUR	EUR 2.2
	Process	EUR	EUR 3.5
	Workforce	EUR	EUR 5.43
	Remaining costs	EUR	EUR 5.57
Total cost		EUR	EUR 27

3.4. Sensitivity Analysis

Two sensitivity analysis were carried out for this study; the first scenario includes replacing fossil fuels with renewable energies and the second scenario includes transportation distances. The results of normalization analysis are shown in Table 8 for the energy consumption scenario.

Table 8. Sensitivity analysis for using hydroelectricity rather than natural gas electricity generation ($\times 10^5$).

Impact Category	Total	Sensitivity Analysis	Change
Human carcinogenic toxicity	762.85	663.79	−12.99
Freshwater ecotoxicity	165.56	143.31	−13.44
Marine ecotoxicity	135.74	119.55	−11.93
Fossil resource scarcity	78.01	74.86	−4.04
Terrestrial ecotoxicity	62.39	66.17	+6.05
Freshwater eutrophication	60.91	57.59	−5.45
Ozone formation, Terrestrial ecosystems	43.00	43.66	+1.53
Ozone formation, Human health	36.14	36.72	+1.61
Ionizing radiation	34.31	8.27	−75.89
Global warming	27.15	25.67	−5.44
Terrestrial acidification	18.53	18.37	−0.89
Fine particulate matter formation	13.43	13.43	+0.02
Water consumption	5.84	5.52	−5.40
Human non-carcinogenic toxicity	2.91	2.72	−6.44
Marine eutrophication	2.47	2.25	−8.88
Stratospheric ozone depletion	2.29	2.02	−11.98
Land use	1.67	1.38	−17.56
Mineral resource scarcity	0.02	0.02	+14.14

Based on the normalization analysis, the use of renewable energy positively affected the overall environmental impacts of the plasterboard life cycle, as demonstrated in Table 8. Thirteen impact categories exhibit a decrease in values, while five categories show a slight increase, notably the mineral resource scarcity category with a 14.14% increase, followed by the terrestrial ecotoxicity category with a 6.05% increase. Sensitivity analysis for the transportation distance is given in Table 9.

Based on transportation sensitivity analysis, by increasing transportation distances, the terrestrial ecotoxicity impact category shows an increase of around 37% and the ozone formation (human health) impact category increases by 34.22%. Ozone formation (terrestrial ecosystems) and terrestrial acidification show increases of around 32%. The least-affected impact categories, however, are marine eutrophication with 2.8% and water consumption with 5.6% increases. On the other hand, a shorter distance (0.5×) shows a decrease in all categories. Terrestrial ecotoxicity has the highest decrease ratio around 30% followed by the ozone formation (human health) category with a 26% reduction.

Table 9. Sensitivity analysis for the transportation distance normalization, ($\times10^5$).

Impact Category	Total	0.5 × Distance	2 × Distance
Global warming	27.2	24.6	32.3
Stratospheric ozone depletion	2.3	2.1	2.7
Ionizing radiation	34.3	33.1	36.8
Ozone formation, Human health	36.1	26.7	54.9
Fine particulate matter formation	13.4	10.9	18.6
Ozone formation, Terrestrial ecosystems	43.0	31.9	65.1
Terrestrial acidification	18.5	14.0	27.5
Freshwater eutrophication	60.9	53.7	75.2
Marine eutrophication	2.5	2.4	2.5
Terrestrial ecotoxicity	62.4	43.2	100.6
Freshwater ecotoxicity	165.6	151.6	193.5
Marine ecotoxicity	135.7	121.6	163.9
Human carcinogenic toxicity	762.8	680.8	926.8
Human non-carcinogenic toxicity	2.9	2.6	3.6
Land use	1.7	1.5	2.1
Mineral resource scarcity	0.02	0.02	0.02
Fossil resource scarcity	78.0	71.1	91.8
Water consumption	5.8	5.7	6.2

4. Discussion

Plasterboard LCA research can be grouped into two categories: conventional plasterboard and recycled plasterboard. However, these studies often focus on a limited number of impact categories, while the current paper tries to cover most of the known impact categories to avoid burden shifting issues. From the results the importance of all impact categories, especially the human carcinogenic toxicity, freshwater ecotoxicity, marine ecotoxicity, fossil resource scarcity, terrestrial ecotoxicity, freshwater eutrophication, and ozone formation (Terrestrial ecosystems) categories, is highlighted, which is missing in other studies due to their focus on energy consumption and CO_2 emissions, such as in [12,22,23].

Based on the results, raw material supply and transportation emerge as key drivers of environmental impacts across multiple categories. The substantial influence of these upstream activities highlights the importance of considering the entire supply chain in sustainability assessments. Specifically, the dominance of raw material supply in categories such as mineral resource scarcity and freshwater eutrophication emphasizes the need for sustainable sourcing practices and resource management strategies. Similarly, transportation plays a crucial role in categories like marine eutrophication and terrestrial acidification, highlighting the significance of efficient logistics and transport planning.

The human carcinogenic impact category has emerged as the most significant environmental burden. Despite the prevailing focus on carbon dioxide (CO_2) emissions in society's sustainability and net-zero strategies, it is crucial to acknowledge the significant importance of other impact categories. This emphasizes the need to investigate all available impact categories in LCA studies to avoid underestimating realistic environmental impacts. The global warming potential impact category does not rank among the top-three most affected categories in the plasterboard life cycle, as revealed by the results. Within the human carcinogenic impact category, the raw material supply stage (raw gypsum, steel, and plasticizer production) is the dominant contributors, tallying at 762.85 units (see Table 6).

In terms of the global warming potential impact category, the findings align with Bushi (2011) [12], who reported that energy consumption during plasterboard manufacturing was the main contributor to this impact category. In this study, heat generation during manufacturing was found to account for 40% of the overall global warming potential impact category. In terms of the terrestrial acidification, transportation is the major contributor however, Bushi (2011) [12], reported that the major contributor to the acidification is the on-site energy consumption mostly due to the diesel consumption. Transportation is also the major contributor to the ozone formation (human health, terrestrial) and terrestrial ecotoxicity impact categories. Regarding the remaining impact categories, raw material supply is the major contributor. Furthermore, this study did not find evidence of a significant impact from paper production, which had previously been reported to account for 8 to 30% of the overall environmental impact in the plasterboard life cycle, according to Bushi (2011) [12]. By comparing CO_2 emissions in this study with other studies, the findings in this study are in line with other studies with a slight difference. A total of 2.17237 kg of CO_2 was obtained in this study, which is slightly higher than the 2.138 kg of CO_2 reported by Quintana (2018) [23] and lower compared Peng (2014) [24] who reported 2.43 kg of CO_2 emissions.

While this study demonstrated that the raw material supply stage is the major contributor to nine impact categories, Rodrigo-Bravo (2022) [22] reported the production stage as the primary contributor to the overall environmental impact without further elaboration on the contributing processes.

According to this study:

- The top three affected impact categories are human carcinogenic, freshwater ecotoxicity, and marine ecotoxicity, with the material supply chain stage being the highest contributor in each.
- Compared to human carcinogenic toxicity, the remaining 15 impact categories have at least 10 times lower environmental impact.
- This study highlighted the pivotal role of energy sources on environmental impacts during the production stage, emphasizing the urgency of transitioning to sustainable and renewable energy sources. This transition is essential to mitigate the environmental impacts associated with plasterboard production to reduce the global warming potential impact category.
- Moreover, findings of this research showcased that recycling plasterboard waste significantly reduces impacts linked to freshwater and marine ecotoxicity. This pinpoints the need for effective waste management practices and promotion of recycling initiatives to alleviate the environmental repercussions tied to plasterboard disposal.
- Logistic optimization will also affect most studied impact categories, as it is one of the high-contributor processes in all of them. From the logistical point of view, such improvements are already well documented in the literature [32].
- The LCC analysis reveals the significant contributions of raw material supply and workforce costs to the overall cost of plasterboard, emphasizing the importance of cost-efficient resource management and labour utilization.

The implications of these findings extend across various stakeholders within the plasterboard industry.

Policy Recommendations:

The findings of this study offer actionable measures for policymakers to promote sustainability in construction and waste management, including regulations, standards, and incentives for renewable energy adoption, recycling, and sustainable resource use in plasterboard production. Specific recommendations include establishing renewable energy targets, producer responsibility schemes, and integrating sustainability into procurement processes. These findings also drive changes in industry practices, enabling plasterboard manufacturers and construction companies to optimize processes, improve efficiency, and implement waste management strategies like energy-efficient technologies and closed-loop recycling to reduce environmental impacts and enhance sustainability performance.

Promotion of Best Practice: By highlighting the environmental hotspots and critical stages within the plasterboard life cycle, this study emphasises the importance of promoting best practice among stakeholders. Industry associations, trade organizations, and professional bodies can disseminate the study's findings to their members and facilitate knowledge-sharing platforms to exchange best practice, lessons learned, and innovative solutions. Collaborative initiatives, such as industry-wide sustainability certifications, supply chain transparency programs, and cross-sector partnerships can foster a culture of continuous sustainable consumption and production improvement and drive collective action towards sustainability goals. Additionally, using new manufacturing optimization methods, such as machine learning (ML), could be a possible environmental impact reduction strategy that has already been documented to have acceptable manufacturing optimization improvement potential [33].

Capacity Building and Training: To facilitate the adoption of sustainable practices within the construction and waste management sectors, capacity building and training programs can be developed based on the study's findings. Additionally, educational institutions, vocational training centres, and industry associations can design curricula, workshops, and certification courses focused on resource efficient and circular practices, life cycle assessment methodologies, and green building standards. By investing in workforce development and skills enhancement, stakeholders can ensure the widespread adoption of sustainable practices and foster a culture of environmental stewardship within the industry.

The LCA results from this study can be applied in the following areas:

Reducing Carbon Footprint: Comparing data from this study to broader environmental concerns related to climate change can help identify plasterboard production's contribution to greenhouse gas emissions.

Resource Depletion: LCA results examined mineral resource scarcity, water consumption, and fossil resource scarcity, offering insights into sustainable resource management practices amidst concerns about finite resource availability.

Waste Generation: Quantifying waste treatment impacts and emissions associated with plasterboard production, including waste gypsum, air pollutants, and wastewater, LCA results can guide strategies to reduce waste generation, improve recycling, and minimize environmental pollution.

Circular Economy Opportunities: LCA results can inform opportunities for enhancing plasterboard production sustainability through circular economy principles. Optimizing material efficiency, increasing recycled material use, and designing products for easy disassembly and recycling can reduce environmental impacts and promote resource efficiency and circularity.

While the study has provided valuable insights into the plasterboard life cycle, certain limitations should be acknowledged. Notably, the scope of the study did not include aspects such as service life and maintenance processes due to time constraints and a lack of available data. Furthermore, data collection from raw material suppliers, including raw gypsum, screw metals, and glue, presented challenges, leading to the utilization of secondary data from the Ecoinvent 3.9 database. Future research endeavours could address these dimensions, seeking to deepen our understanding of their impact on reducing the overall environmental footprint associated with plasterboard.

Moving forward, it is crucial to address unit discrepancies and data availability issues to improve comparative assessments. Transparency and collaboration are key to addressing concerns about cost data confidentiality.

Considering the study's limitations, future research should explore:

Innovative Recycling Techniques: research into advanced sorting, chemical processes, and circular economy integration can enhance plasterboard recycling efficiency and minimize waste generation.

Alternative Materials: investigating bio-based composites, recycled aggregates, and gypsum substitutes can diversify raw material sources and reduce reliance on finite resources in plasterboard production.

Impact of Policy Changes: analysing policy influences on plasterboard manufacturing practices and sustainability can guide future research and inform decision-making processes.

Cutting-edge Recycling Technologies: exploring AI, robotics, and advanced material recovery systems can improve plasterboard recycling efficiency and accelerate the transition to a circular economy model.

Environmental Impact Assessment of Emerging Materials: Conducting LCAs to compare traditional and emerging materials' environmental footprints can inform sustainable material selection in plasterboard manufacturing. Additionally, investigating the scalability, scalability, and scalability of emerging materials in plasterboard manufacturing can help identify opportunities for mainstream adoption and market penetration.

5. Conclusions

The comprehensive LCA conducted on wall plasterboard aimed to examine its environmental impacts, identify hotspots, and pinpoint areas for potential mitigation strategies. Based on the results:

1. Within the whole plasterboard LCA, the highest environmental impact occurs within the human carcinogenic toxicity category, equivalent to 0.07856 1,4-DCB. This impact predominantly resulted from raw material supply stages. Steel screw production, gypsum production, and transportation processes involving train and sea transportation contributed to this impact category the most. Additionally, heat and electricity generation significantly contributed to this impact category.
2. Freshwater ecotoxicity and marine ecotoxicity emerged as the second and third highest impact categories, respectively, mirroring contributions from raw material supply, transportation processes, and the energy generation process (energy generation during various stages of the plasterboard life span).
3. The raw materials supply stage showed the highest overall impact in the wall plasterboard life cycle and using secondary materials instead of raw materials could reduce the overall environmental impacts of plasterboard.
4. A concise life cycle costing analysis revealed that the material supply stage and labour costs emerge as the predominant contributors to the overall expenses associated with the plasterboard life cycle.
5. A sensitivity analysis was performed by substituting hydroelectricity with natural gas electricity generation. The results of this analysis indicated that utilizing renewable energy sources generally reduces the overall environmental impact across most impact categories. However, it is noteworthy that in five impact categories a slight increase in environmental impact was observed.

The study's insights emphasize the critical need for transitioning to sustainable energy sources, implementing efficient waste management practices, and optimizing logistics to curtail the adverse environmental impacts associated with plasterboard production. Additionally, considering the time and cost restrictions in this study, future studies can investigate the recycling technologies, maintenance and use phase environmental impacts, optimization of manufacturing and recycling processes, utilization of secondary materials in plasterboard industry, and re-evaluation of the plasterboard life cycle using only primary datasets. These recommendations underline the pathway toward enhancing plasterboard's sustainability and minimizing its ecological footprint in the UK construction sector.

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Conflicts of Interest: British Gypsum, which is part of the Saint-Gobain Group, is a leading manufacturer of plasterboard and plaster-based drylining systems and products. ENVA is a leading provider of recycling and resource recovery solutions for re-use in manufacturing. Wernick is a manufacturer and hirer of portable and modular accommodation and buildings and an installer of plasterboard. British Gypsum and ENVA are part of the ICEBERG project and received funding from the European commission and do not have any conflicts of interests in the results reported in the paper. Author Alexis Massey was employed by the Wernick company and declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

References

1. Gaião, C.; de Brito, J.; Silvestre, J. Inspection and Diagnosis of Gypsum Plasterboard Walls. *J. Perform. Constr. Facil.* **2011**, *25*, 172–180. [CrossRef]
2. Telue, Y.; Mahendran, M. Behaviour and design of cold-formed steel wall frames lined with plasterboard on both sides. *Eng. Struct.* **2004**, *26*, 567–579. [CrossRef]
3. Ariyanayagam, A.D.; Kesawan, S.; Mahendran, M. Detrimental effects of plasterboard joints on the fire resistance of light gauge steel frame walls. *Thin-Walled Struct.* **2016**, *107*, 597–611. [CrossRef]
4. Kolaitis, D.I.; Founti, M.A. Development of a solid reaction kinetics gypsum dehydration model appropriate for CFD simulation of gypsum plasterboard wall assemblies exposed to fire. *Fire Saf. J.* **2013**, *58*, 151–159. [CrossRef]
5. Pedreño-Rojas, M.; De Brito, J.; Flores-Colen, I.; Pereira, M.F.C.; Rubio-De-Hita, P. Influence of gypsum wastes on the workability of plasters: Heating process and microstructural analysis. *J. Build. Eng.* **2020**, *29*, 101143. [CrossRef]
6. Gyproc WallBoard 12.5 mm. Envrieonmental Product Decleration, British Gypsum, S-P-03948, Vol. 03948, No. October, United Kingdom, 2021. Available online: https://www.environdec.com/library/epd506 (accessed on 19 April 2024).
7. Pedreño-Rojas, M.; Fořt, J.; Černý, R.; Rubio-De-Hita, P. Life cycle assessment of natural and recycled gypsum production in the Spanish context. *J. Clean. Prod.* **2020**, *253*, 120056. [CrossRef]
8. Sam, K. Chapter 6—Choosing Materials and Products. In *Green Construction Project Management and Cost Oversight*; Architectural Press: Princeton, NJ, USA, 2010; pp. 221–266. ISBN 9781856176767. [CrossRef]
9. Statista. Available online: https://www.statista.com/statistics/264936/global-gypsum-production-by-major-countries/ (accessed on 29 March 2023).
10. Statista. Available online: https://www.statista.com/statistics/219348/us-sales-of-wallboard-products/ (accessed on 29 March 2023).
11. DEFRA, Plasterboard Sustainability Action Plan Framework. London, UK. 2010. Available online: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/69303/pb13439-plasterboard-101019.pdf (accessed on 19 April 2024).
12. Bushi, L.; Meil, M.J. A Cradle-to-Gate Life Cycle Assessment of ½″ Regular and 5/8″ Type X Gypsum Wallboard. *Athena Sustain. Mater. Inst.* **2011**, 152. Available online: https://gypsum.org/wp-content/uploads/2019/05/15_Gypsum_Wallboard-1_2-in-Regular-5_8-in-Type-X.pdf (accessed on 19 April 2024).
13. Rivero, A.J.; Sathre, R.; Navarro, J.G. Life cycle energy and material flow implications of gypsum plasterboard recycling in the European Union. *Resour. Conserv. Recycl.* **2016**, *108*, 171–181. [CrossRef]
14. DEFRA. Waste Management Plan for England. London, UK. 2021. Available online: https://assets.publishing.service.gov.uk/media/60103f71d3bf7f05bc42d294/waste-management-plan-for-england-2021.pdf (accessed on 19 April 2024).
15. Gálvez-Martos, J.-L.; Chaliulina, R.; Medina-Martos, E.; Elhoweris, A.; Hakki, A.; Mwanda, J.; Al-Horr, Y. Eco-efficiency of a novel construction material produced by carbon capture and utilization. *J. CO2 Util.* **2021**, *49*, 101545. [CrossRef]
16. Regulation (EU) No. 305/2011 of the European Parliament and of the Council. Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32011R0305 (accessed on 20 August 2021).
17. Finnveden, G.; Potting, J. Life Cycle Assessment. In *Encyclopedia of Toxicology*, 3rd ed.; Wexler, E., Ed.; Academic Press: Oxford, UK, 2014; pp. 74–77. [CrossRef]
18. Ekvall, T. Attributional and Consequential Life Cycle Assessment. In *Sustainability Assessment at the 21st Century*; IntechOpen: London, UK, 2019; Chapter 4. [CrossRef]
19. Hauschild, M.Z.; Rosenbaum, R.K.; Olsen, S.I. *Life Cycle Assessment: Theory and Practice*; Springer International Publishing: Berlin/Heidelberg, Germany, 2018; pp. 3–8. [CrossRef]
20. *ISO 14040*; Environmental Management–Life Cycle Assessment–Principles and Framework. ISO: Geneva, Switzerland, 2006. Available online: https://www.iso.org/standard/37456.html (accessed on 30 March 2023).

21. Silvestre, J.D.; Gaião, C.; De Brito, J. Gypsum plasterboard walls: Inspection, pathological characterization and statistical survey using an expert system. *Mater. Construcción* **2012**, *62*, 285–297. [CrossRef]
22. Rodrigo-Bravo, A.; Cuenca-Romero, L.A.; Calderón, V.; Rodríguez, A.; Gutiérrez-González, S. Comparative Life Cycle Assessment (LCA) between standard gypsum ceiling tile and polyurethane gypsum ceiling tile. *Energy Build.* **2022**, *259*, 111867. [CrossRef]
23. Quintana, A.; Alba, J.; del Rey, R.; Guillén-Guillamón, I. Comparative Life Cycle Assessment of gypsum plasterboard and a new kind of bio-based epoxy composite containing different natural fibers. *J. Clean. Prod.* **2018**, *185*, 408–420. [CrossRef]
24. Peng, Z.G.; Ma, L.L.; Gong, X.Z. Comparison of Life Cycle Environmental Impacts between Natural Gypsum Board and FGD Gypsum Board. *Key Eng. Mater.* **2014**, *599*, 15–18. [CrossRef]
25. Weimann, K.; Adam, C.; Buchert, M.; Sutter, J. Environmental Evaluation of Gypsum Plasterboard Recycling. *Minerals* **2021**, *11*, 101. [CrossRef]
26. Rebitzer, G.; Ekvall, T.; Frischknecht, R.; Hunkeler, D.; Norris, G.; Rydberg, T.; Schmidt, W.-P.; Suh, S.; Weidema, B.P.; Pennington, D.W. Life cycle assessment: Part 1: Framework, goal and scope definition, inventory analysis, and applications. *Environ. Int.* **2004**, *30*, 701–720. [CrossRef] [PubMed]
27. Andersen, S.C.; Birgisdottir, H.; Birkved, M. Life Cycle Assessments of Circular Economy in the Built Environment—A Scoping Review. *Sustainability* **2022**, *14*, 6887. [CrossRef]
28. Huijbregts, M.A.J.; Steinmann, Z.J.N.; Elshout, P.M.F.; Stam, G.; Verones, F.; Vieira, M.; Zijp, M.; Hollander, A.; van Zelm, R. ReCiPe2016: A harmonised life cycle impact assessment method at midpoint and endpoint level. *Int. J. Life Cycle Assess.* **2017**, *22*, 138–147. [CrossRef]
29. Feng, H.; Zhao, J.; Hollberg, A.; Habert, G. Where to focus? Developing a LCA impact category selection tool for manufacturers of building materials. *J. Clean. Prod.* **2023**, *405*, 136936. [CrossRef]
30. Morsali, S. Cement production effects on human health with respect to cement lifecycle assessment. In Proceedings of the First International Congress on Specialized Research in Science, Engineering and Academic-Industrial Technologies, Shiraz, Iran, 15 June 2017.
31. Hauschild, M.Z.; Goedkoop, M.; Guinée, J.; Heijungs, R.; Huijbregts, M.; Jolliet, O.; Margni, M.; De Schryver, A.; Humbert, S.; Laurent, A.; et al. Identifying best existing practice for characterization modeling in life cycle impact assessment. *Int. J. Life Cycle Assess.* **2013**, *18*, 683–697. [CrossRef]
32. Ghasemi, M.; Rajabi, M.S.; Aghakhani, S. Towards sustainability: The effect of industries on CO_2 emissions. *J. Futur. Sustain.* **2023**, *3*, 107–118. [CrossRef]
33. Nasab, A.R.; Elzarka, H. Optimizing Machine Learning Algorithms for Improving Prediction of Bridge Deck Deterioration: A Case Study of Ohio Bridges. *Buildings* **2023**, *13*, 1517. [CrossRef]

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