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Comparative Life Cycle Assessment of Wall Painting Types in a New City Development: Impacts on Environment and Human Health

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Abstract The paint industry significantly contributes to soil, water, and air pollution. Since it contains a variety of substances, such as heavy metals, solvents, and volatile organic compounds, the environment and human health may be negatively impacted by these pollutants.
To compare different wall painting types utilized in the Ibny Baitak Project, a new city development in Egypt, using the life cycle assessment (LCA) approach. The environmental impact of 12 different painting types is determined by the raw materials utilized, production, and transportation. In particular, the article will assess the effects of alkyd paint, ceramic-based paint, gypsum plasterboard, and acrylic plaster.
By the single score results, the alkyd paint type recorded the highest impact by (1.57 pt), the ceramic-based paint came in the second rank by (1.19 pt), then the acrylic paint by (0.27 pt), finally the Gypsum Plasterboard by (0.25 pt). However, by the weighting result, the Alkyd paint type has recorded the highest of the three environmental impacts by 4.75 $kg\ co_2\ eq$, 65.61 $Mj\ primary$, and 3.30E-06 $DALY$, respectively. In contrast, the Gypsum Plasterboard recorded the lowest numbers by 0.45 $kg\ co_2\ eq$, 5.19 $Mj\ primary$, and 1.13E-06 $DALY$, respectively. The article's findings show solvent-based paints have the most significant environmental impact, whereas water-based and low-VOC paints (such as acrylic paint) have the lowest.
The results of this article can be used to guide decision-making in the building sector and encourage the adoption of more environmentally friendly painting techniques in new urban development initiatives.

Keywords: Life Cycle Assessment; Life Cycle Inventory, Life Cycle Impact Assessment; Wall Paintings; New Assiut City.

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1. Introduction

Because building materials are produced and used, the construction industry has a major detrimental environmental impact [1]. As reported by Ritchie et al. [2] in 2020, 73.2% of global greenhouse gas emissions are attributed to the energy sector, while 24.2% are attributed to the energy utilized in industry, as highlighted in **Fig. 1**. Also since residential buildings make up 10.9% of all buildings, it is crucial to research how they affect the environment. Walls in buildings must be painted, but different paints have varied effects on the environment [3]. Evaluating the impact of different types of wall painting is essential to promote green construction practices.
The paint industry can significantly harm the environment during all stages of production and disposal. To manufacture paint, raw materials such as pigments, solvents, and resins must be extracted and processed, which can lead to pollution and the loss of natural resources. VOCs, or volatile organic compounds, are released during paint-making and harm human health and air quality. As mentioned by the Swedish Paint & Printing Ink Makers' Association (Sveff) [4], VOCs that negatively impact air quality and human health are emitted by using solvents in manufacturing paint. However, because leftover or unwanted paint may include hazardous materials that could contaminate land and water, it can be challenging to dispose of properly [5]. For this reason, scientific studies should examine and assess the impact of waste paint on the environment.
To reduce the effects of the paint industry on the environment, actions can be taken to reduce the use of hazardous chemicals in the manufacture of paint, support low-VOC and water-based paints, and encourage the correct disposal and recycling of paint products [6]. By utilizing sustainable raw material procurement practices and renewable energy sources, the paint industry's overall environmental impact can also be reduced [7].
Many studies have explored the importance use of life cycle analysis (LCA) in informing decision-making for sustainable building design, such as [8]–[15]. The results of these studies have shown that LCA can be a useful tool in influencing decisions about sustainable building design.

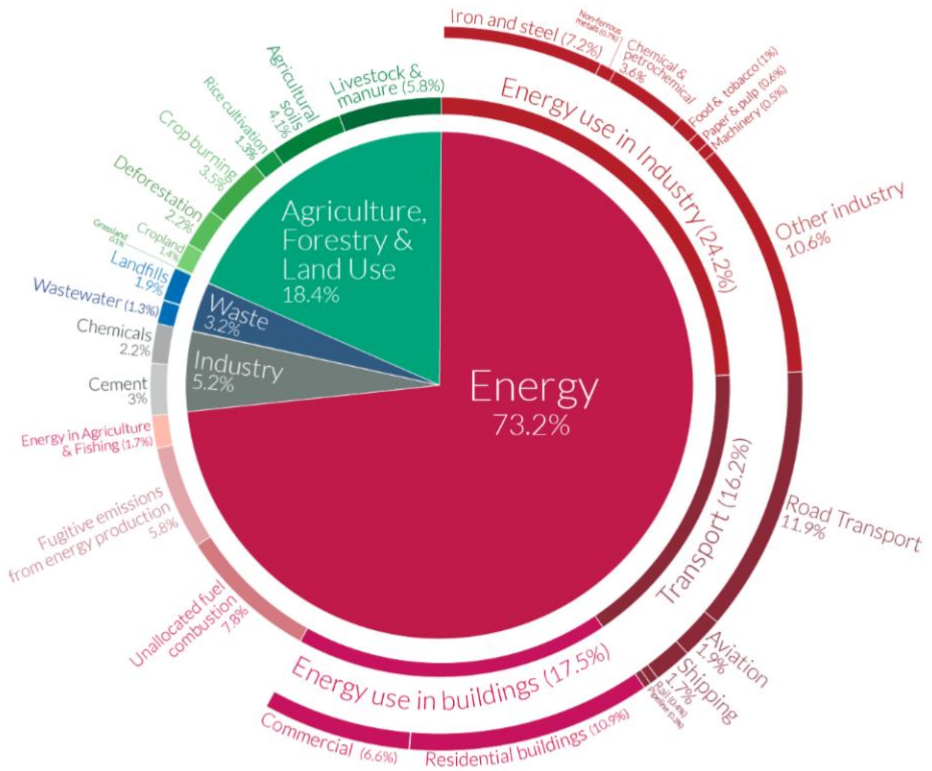


Fig. 1 Greenhouse gas emissions by sector in 2020 [2]

LCA allows for the assessment of environmental implications and the identification of potential improvement areas. Thus, each painting type's environmental impact—including that of the raw materials, manufacture, and transportation—will be assessed using LCA, known as the "cradle-to-gate procedure."

The research problem can be addressed by conducting a comparative LCA of different wall paintings to assess the environmental impacts of midpoint and endpoint methods. In Egypt, there is an apparent shortage of the life cycle inventory database and the LCA application in the industries, as reported by Yacout et al. [16].

Overall, every wall painting has unique advantages and disadvantages depending on its composition, use, and effect on the surroundings. Consider factors like durability, environmental impact, and intended use to choose the ideal paint kind. This article's main objective is to help researchers determine the best paint type. The results of this article will aid in understanding the environmental effects of different types of wall painting and assist the building industry in making decisions that will promote the use of more ecologically friendly painting methods in new city development projects.

2. Literature Review

In this section, the author has divided the literature review into three parts: (1) the LCA application on the wall paint types, (2) the new pain technology such as the nanomaterials, and (3) the possibility of recycling the paint waste and its effect on the environment [17].

An LCA of alternative envelope construction for a new home in South-Western Europe has been reported by Monteiro et al. [9]. The environmental effects of various envelope building materials, including wood, rammed earth, and insulated concrete formwork, have been assessed during the study. According to the paper's findings, rammed earth has a greater environmental impact than wood and insulated concrete formwork because of their lower embodied carbon and lower operating energy consumption [10][20][21].

An LCA of two types of wood façades—coated and thermally modified—has been provided by Búryová et al. [11]. According to the authors, thermally modified wood façades require less care and have a longer lifespan than coated wood façades, so they have a lesser environmental impact. An LCA of external walls in buildings has been reported by D. C. Gámez-García et al. [18]. The results showed that wall material selection significantly influences a building's environmental performance, with insulated panel systems having the least negative effects. B. Han et al. [19] have provided an LCA of ceramic façade materials as alternative painting material and have contrasted it with three other typical façade materials: stone, curtain walls, and aluminum composite panels. The results show ceramic façade materials are more environmentally friendly than stone but less environmentally friendly than curtain walls and aluminum composite panels. [24] According to X. Wang et al. [20], the transparent composite façade system performs better in terms of thermal insulation and has a lower environmental impact than the glass curtain wall system. The study by D. A. Yacout and M. A. Elzahhar [16] assessed the environmental impact of paint production in Egypt by employing the LCA approach to evaluate the impact of multiple environmental indicators, such as energy consumption, water consumption, and greenhouse gas emissions. The findings show that the paint manufacturing process has a major negative influence on the environment, especially regarding energy use and greenhouse gas emissions. According to the Sveff Association [4], paint consumption and manufacture significantly negatively influence Sweden's environment, especially regarding greenhouse gas emissions. Nevertheless, the study also found several ways to enhance paint production's environmental performance. Additionally, S. Papasavva et al. [21] have demonstrated that the painting process has a major negative influence on the environment, mostly because of the energy use and emissions related to the paint curing process [3][19].

Regarding the recycling of gypsum to be used as plasterboards, many articles have studied their impacts on the environment in the paint industry.

J. García-Navarro and A. Jiménez-Rivero [22] have assessed how the various phases of managing end-of-life gypsum affect the environment and have suggested metrics to gauge the procedure's sustainability. The primary conclusions of the N. Papailiopoulou et al. study [23] were that recycling gypsum can dramatically lower energy usage and greenhouse gas emissions throughout the plasterboard manufacturing process while lowering expenses. N. Papailiopoulou et al. [24] also assessed the techno-economic effects of recycled gypsum in plasterboard production. According to the paper's summary, employing recycled gypsum in plasterboard production can drastically cut expenses and negative environmental effects while preserving the product's quality [29][30].

A. Erbs et al. [25] have examined the characteristics of recycled gypsum derived from commercial gypsum and gypsum plasterboards during several recycling cycles. According to the study, recycled gypsum is a good substitute for virgin gypsum in construction applications since it may hold onto its qualities across multiple recycling cycles.

Furthermore, M. C. Chen et al. [26] have highlighted the potential benefits of nanomaterials in paints and coatings, including improved durability and antimicrobial properties. The article also evaluated the potential health and environmental risks associated with nanomaterials in paints and coatings, providing insights into the challenges and opportunities of developing sustainable, functional paints and coatings.

A. D. P. Citra et al. [5] have assessed the quality and environmental impact of employing paint waste as a raw material for paving blocks to repurposing paint wastes. The study evaluates the effects of multiple environmental indicators, such as greenhouse gas emissions, energy consumption, and water usage, using an LCA methodology. The findings demonstrated that paving blocks made from paint waste can positively influence the environment during manufacture, especially regarding water use and greenhouse gas emissions. The study also demonstrated that paint waste-derived paving block quality is on par with typical raw material quality.

The literature analysis revealed an expanding body of knowledge regarding the effects of building supplies and construction techniques on the environment. The papers also highlight the need for LCA in building envelope design and material selection to support environmentally friendly building techniques. According to previous studies, using environmentally friendly building materials and construction techniques can significantly lower the environmental effect of buildings. As a result, this article aims to investigate the paint industry's environmental impacts using the LCA methodology in the Ibny Baitak project in a brand-new Egyptian metropolis.

3. Methodology and Data Collection

A research project's methodology and data collection are crucial elements. The methodology refers to the general approach and processes employed in the research. This article's methodology is divided into LCA and building information modeling. The Ecoinvent database [27] and Revit will be used in this article to collect, acquire and analyze data.

3.1. Life Cycle Assessment Approach

The LCA methodology of wall painting types involves evaluating each stage's environmental impact in the product's life cycle. The International Standards Organization (ISO) is a globally respected standards agency that provides several components, as illustrated in **Fig. 2**. (1) ISO 14040: Principles and framework [28], (2) ISO 14041: Goal definition and inventory analysis [29], ISO 14042: Life-cycle impact assessment [30] and ISO 14043: Life-cycle interpretation [31].

Ali et al. [33] and Al-Ghamdi [34] have revealed their findings following a thorough comparison. It was determined that PRe SimaPro is the LCA tool that is most frequently utilized. As a result, all open-license Ecoinvent databases were used under the academic PRe SimaPro V9.5 license.

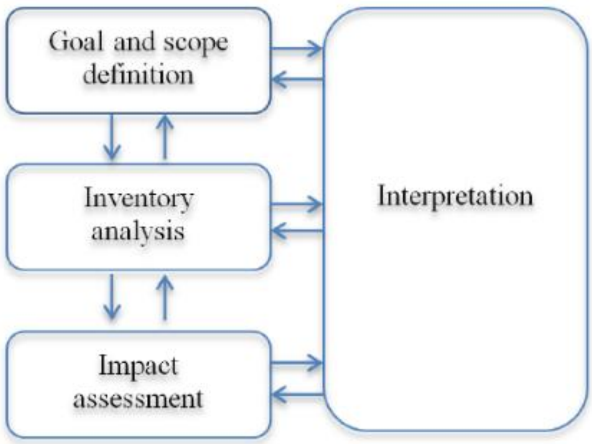


Fig. 2 Life-cycle assessment framework [32].

3.1.1. Goal and scope definition

In this stage, the goals and scope of the LCA study are defined in **Fig. 3**. The article aims to evaluate the environmental impact of different wall painting types. In contrast, the scope defines the functional unit, system boundaries, and data requirements. The study has shown that while conducting an LCA of different wall painting types, functional units should be carefully chosen to guarantee that the evaluation appropriately reflects the product's environmental impact. The functional unit of this investigation is, therefore ($1\ kg$) for the painting types.

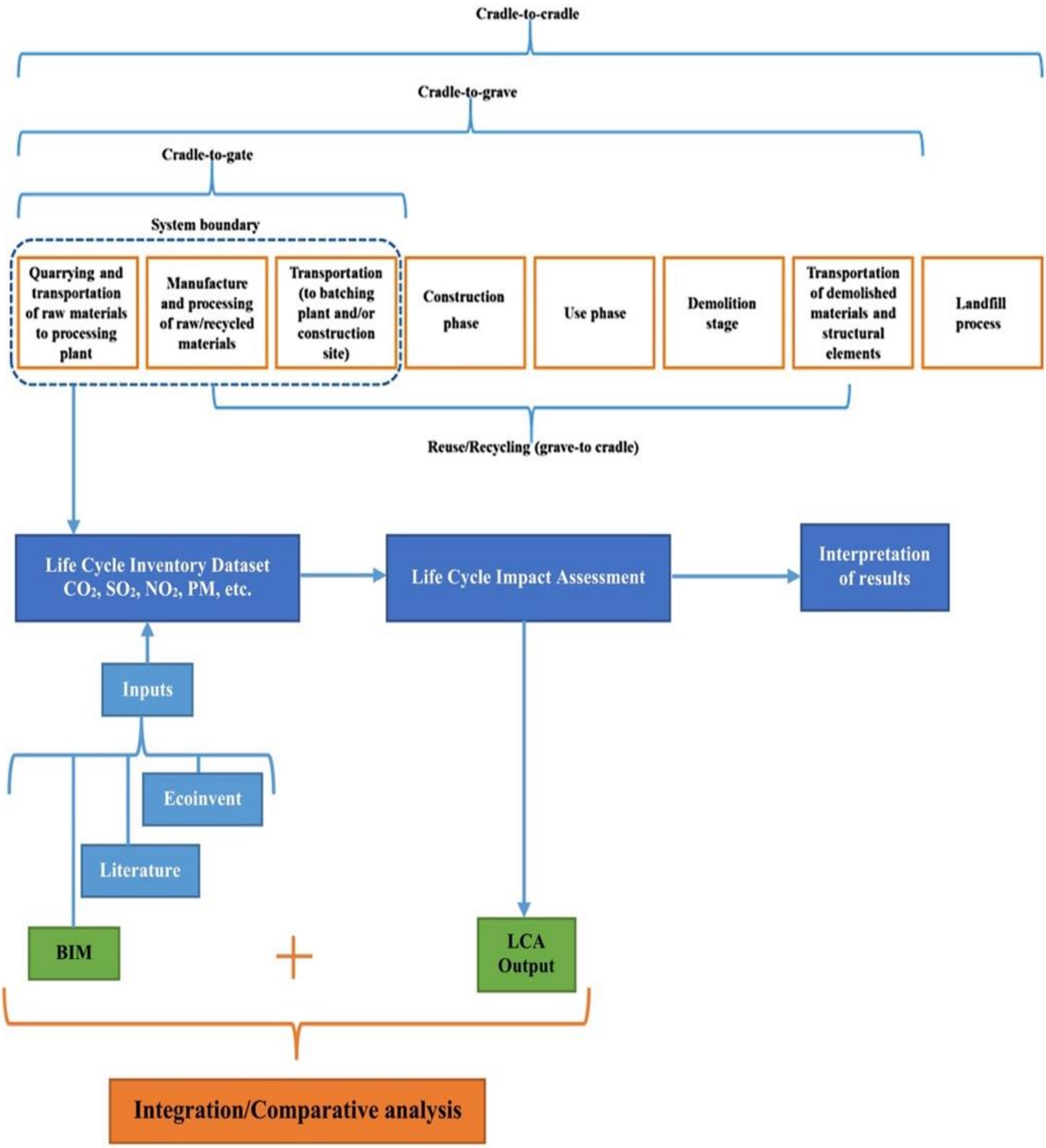


Fig. 3 System boundary of LCA application in this article

Fig. 4, in more detail, this figure highlights the specific system boundary of the pain industry. This research will focus on the (cradle to gate) boundary, which contains only this process: mixing the raw materials, milling, then mixing again, and finally, the filtration process.

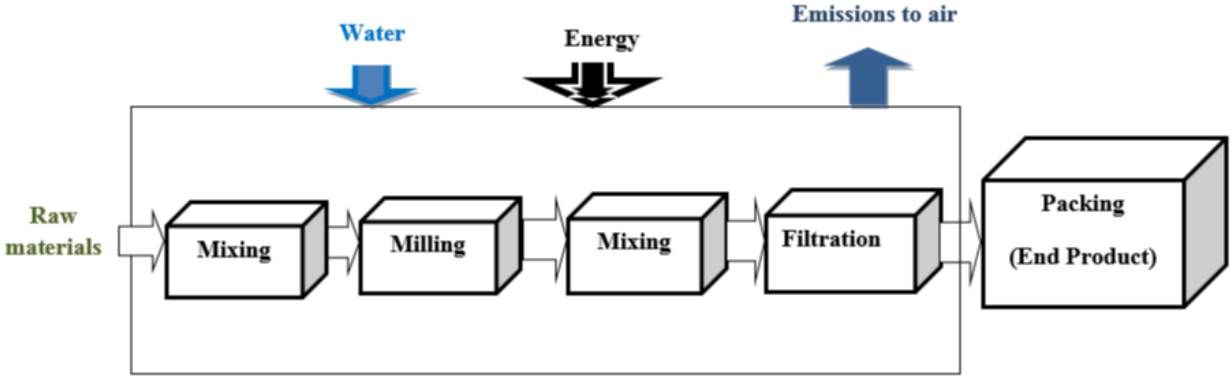


Fig. 4 System boundary of the paint production [16]

The environmental impacts of the 12 wall paint types will be evaluated in this article. As shown in **Fig. 5**, all paint kinds have been built in SimaPro. Then, as shown in **Fig. 6**, the network flows (as examples) of the production processes for alkyd paint, ceramic-based paint, gypsum plasterboard, and acrylic plaster have been established in SimaPro.

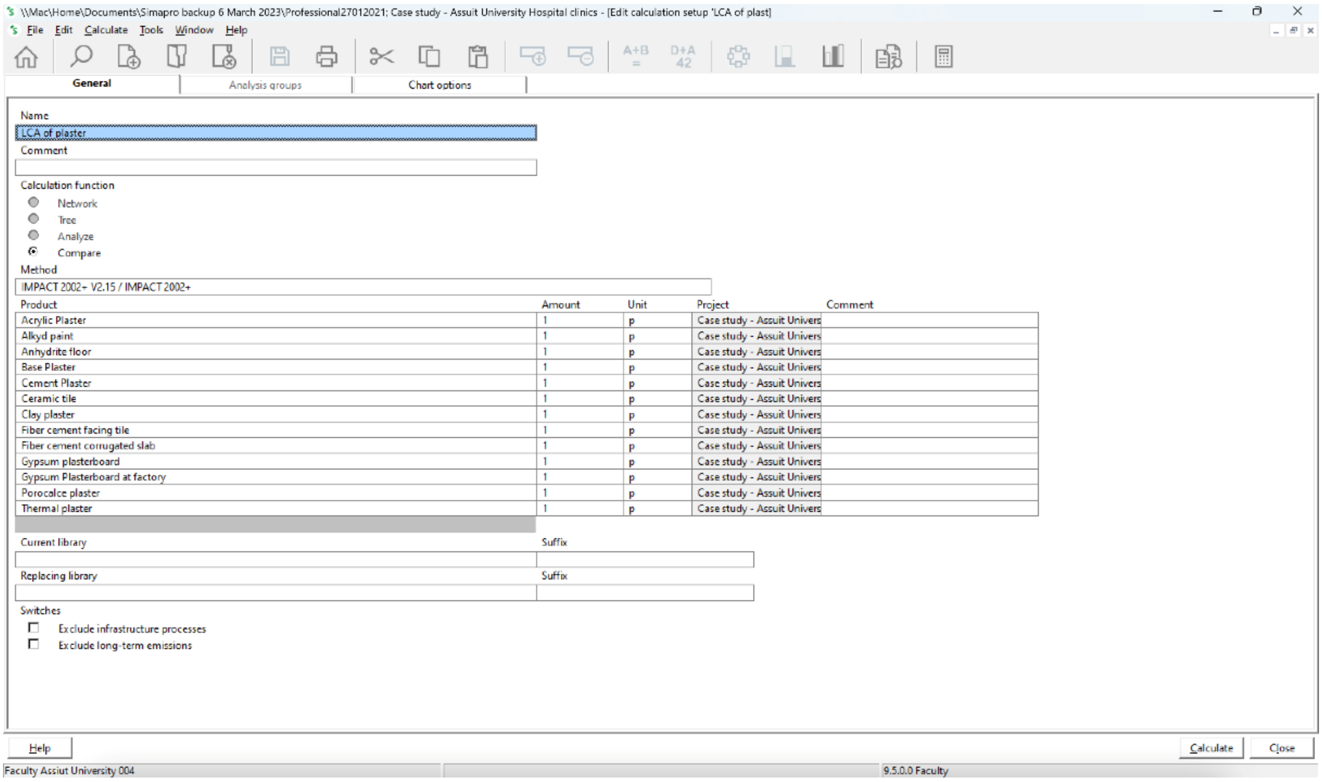


Fig. 5 Calculation setup of the LCA paint scenarios

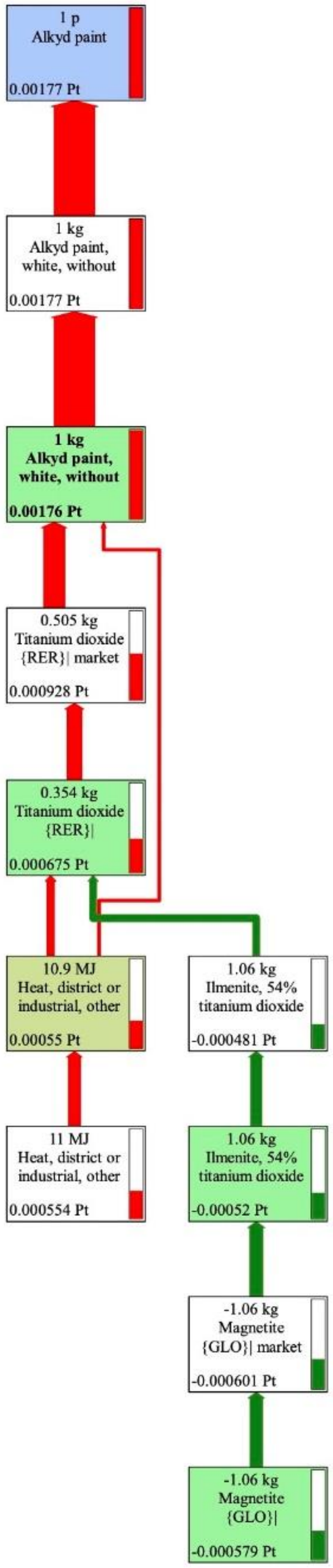


Fig.6 (a) Network flow of Alkyd Paint

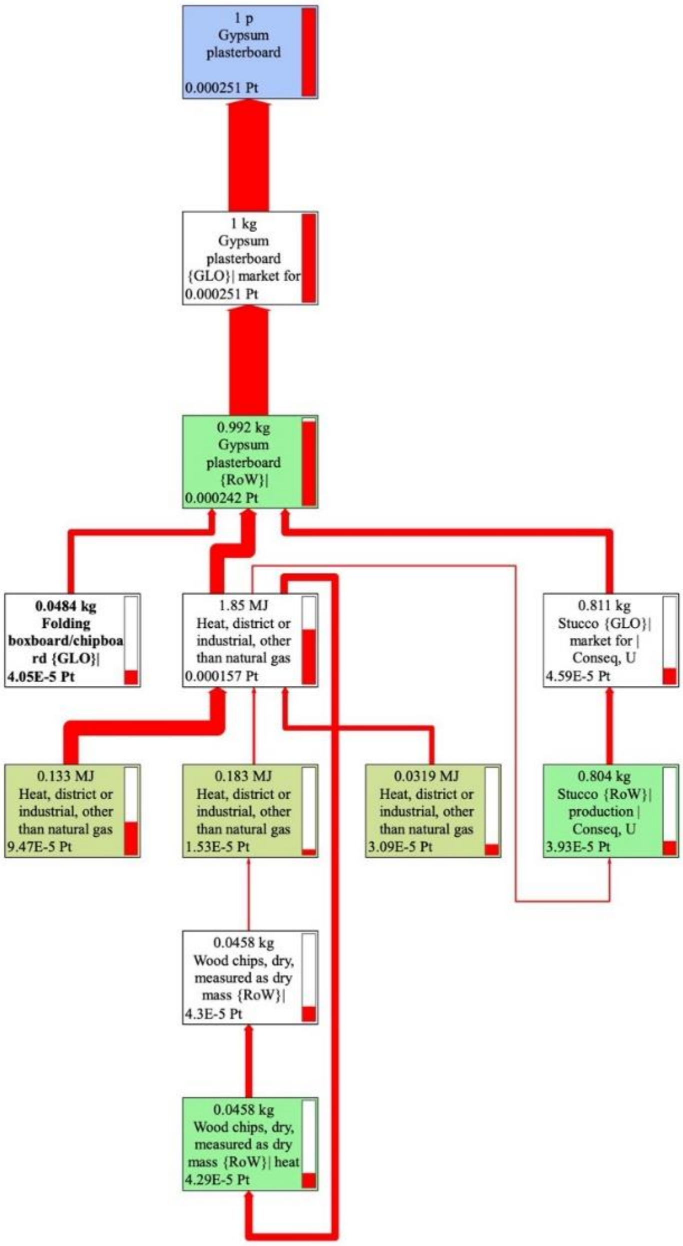


Fig.6 (b) Network flow of Gypsum Plasterboard

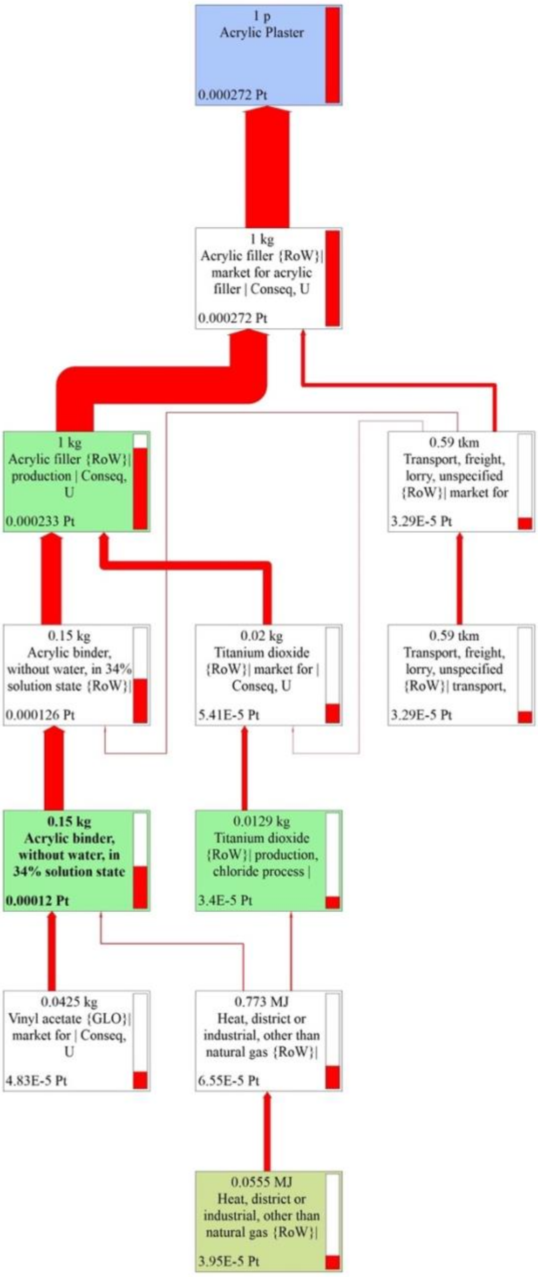


Fig.6 (c) Network flow of Acrylic Plaster

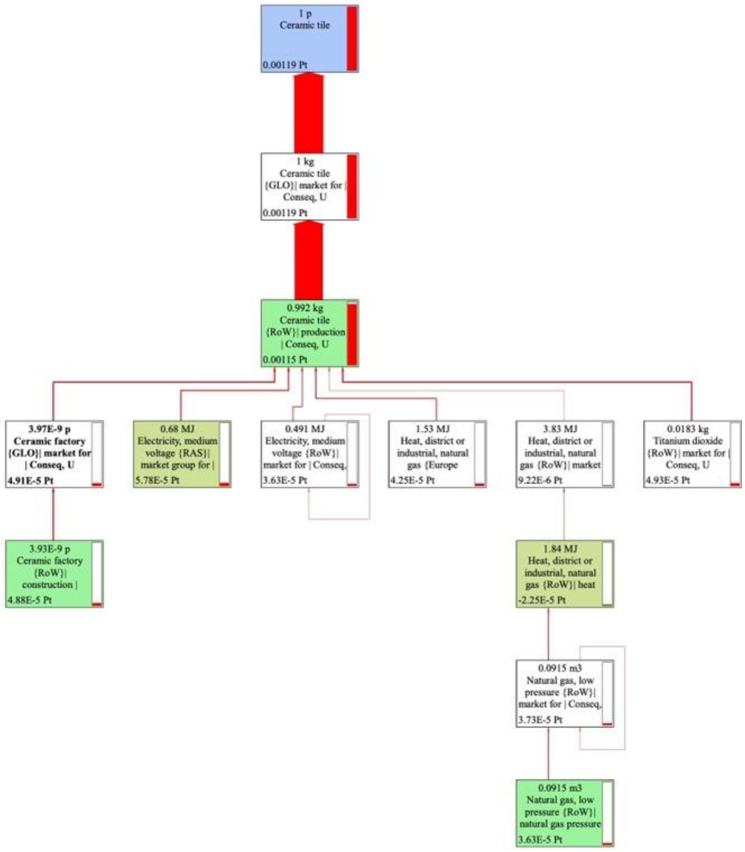


Fig.6 (d) Network flow of Ceramic Tile

Fig. 6 Network flows of four paint examples in SimaPro

3.1.2. Life cycle inventory

All inputs and outputs associated with the wall painting types are identified and quantified in this stage. It includes raw materials, energy consumption, emissions, and waste generated during each stage of the product life cycle, including production and transportation. This article has relied on a few hypotheses from the literature review to fill in the data shortage for the input materials because there are few LCA applications and LCI in Egypt. Rocamora et al. [35] compared many LCA applications of construction materials. The database version used for this investigation is Ecoinvent V3 [27] **Fig. 7**. The Ecoinvent (SimaPro-based) database's global market and concrete-related sectors were specifically picked to be more compatible with Egyptian production methods.

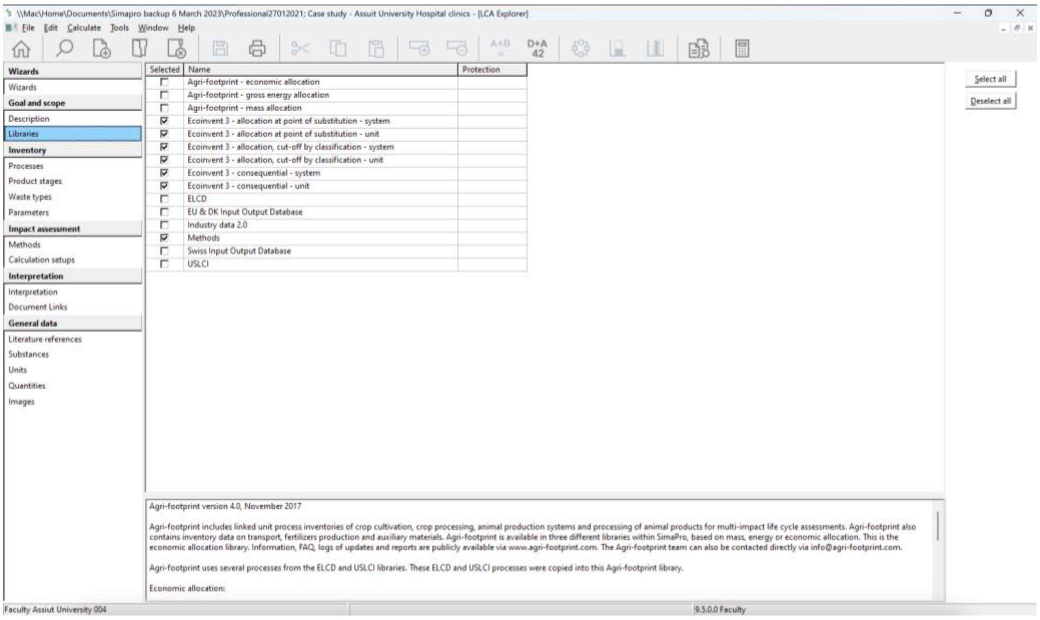


Fig. 7 Ecoinvent database embedded in SimaPro V9.5

3.1.3. Life cycle impact assessment

In this stage, the environmental impact of the wall painting types is evaluated based on their inputs and outputs identified in the inventory analysis. It includes assessing the impact of various environmental indicators, such as global warming potential, acidification potential, and eutrophication potential. So, based on the ISO standard, it differentiates the environmental impacts between the wall paint types. The midpoint and endpoint approaches will be used to calculate the environmental effects in this article. Based on the literature analysis, this article will employ the IMPACT 2002+ approach, which is mentioned in **Table 1**, to explore the environmental consequences based on the literature review [33], [34], [36], [37].

Table 1 IMPACT 2002+ characterization version Q2.2 [38]

[Source]	Midpoint category	Midpoint reference substance	Damage category (end-Point)	Damage unit	Normalized damage unit
[a]	Human toxicity (carcinogens + non-carcinogens)	kg Chloroethylene into air-eq	Human health	DALY	Point
[b]	Respiratory (inorganics)	kg PM2.5 into air-eq	Human health		
[b]	Ionizing radiations	Bq Carbon-14 into air-eq	Human health		
[b]	Ozone layer depletion	kg CFC-11 into air-eq	Human health		
[b]	Photochemical oxidation (= Respiratory (organics) for human health)	kg Ethylene into air-eq	Human health		
			Ecosystem quality	n/a	n/a
[a]	Aquatic ecotoxicity	kg Triethylene glycol into water-eq	Ecosystem quality	PDF·m^2·y	Point
[a]	Terrestrial ecotoxicity	kg Triethylene glycol into soil-eq	Ecosystem quality		
[b]	Terrestrial acidification/ nutrification	kg SO_2 into air-eq	Ecosystem quality		
[c]	Aquatic acidification	kg SO_2 into air-eq	Ecosystem quality		
[c]	Aquatic eutrophication	kg $PO^4{}_3$- into water -eq	Ecosystem quality		
[b]	Land occupation	m2 Organic arable land-eq · y	Ecosystem quality		
	Water turbines	Inventory in m^3	Ecosystem quality		
[IPCC]	Global warming	kg CO_2 into air-eq	Climate change (life support system)	kg CO_2 into air-eq	Point
[d]	Non-renewable energy	MJ or kg Crude oil-Eq (860 kg/m^3)	Resources	MJ	Point
[b]	Mineral extraction	MJ or kg Iron-eq (in ore)	Resources		
	Water withdrawal	Inventory in m^3	n/a		
	Water consumption	Inventory in m^3	Human health		
			Ecosystem quality		
			Resources		

[a] IMPACT 2002, [b] Eco-indicator 99, [c] CML 2002, [d] Ecoinvent, [IPCC] (IPCC AR5 Report), and [USEPA] (EPA)

daly disability-adjusted life years, *PDF* potentially disappeared fraction of species, *-eq* equivalents, *y* year

3.2. Building Information Modeling

The Building Information Modeling (BIM) methodology of wall painting types involves using digital models to manage the information and processes related to building projects' design, construction, and maintenance. BIM is a collaborative process that involves multiple stakeholders, including architects, engineers, contractors, and owners, who work together to create a digital model of the building project. According to earlier studies by Senem Seyis and Shu Su et al. [39], [40], which have been summarized, LCA and BIM together can considerably evaluate the environmental costs of material manufacturing. This article will use this all-encompassing strategy, where LCA will examine the environmental effects of various scenarios, and BIM will offer data on the building components for LCA input. The most popular BIM program is Autodesk Revit, a 2020 student-licensed version.

3.3. Study Area

Because it is a new city and needs help to give its residents the best structures and services, this article will use the New Assiut City (NAC) in Assiut, Egypt, as a case study. Therefore, this section's focus is on how the NAC is presented. On the (Cairo - Sohag) desert highway, close to its intersection with the (Hurghada - Assiut) road, the NAC is roughly 15 kilometers from Assiut. According to the NAC master plan, the urban block of the city is made up of a third district (the future extension area), an industrial zone, and a regional area in addition to two residential neighborhoods divided by a primary service axis (city center), as shown in **Fig. 8**.

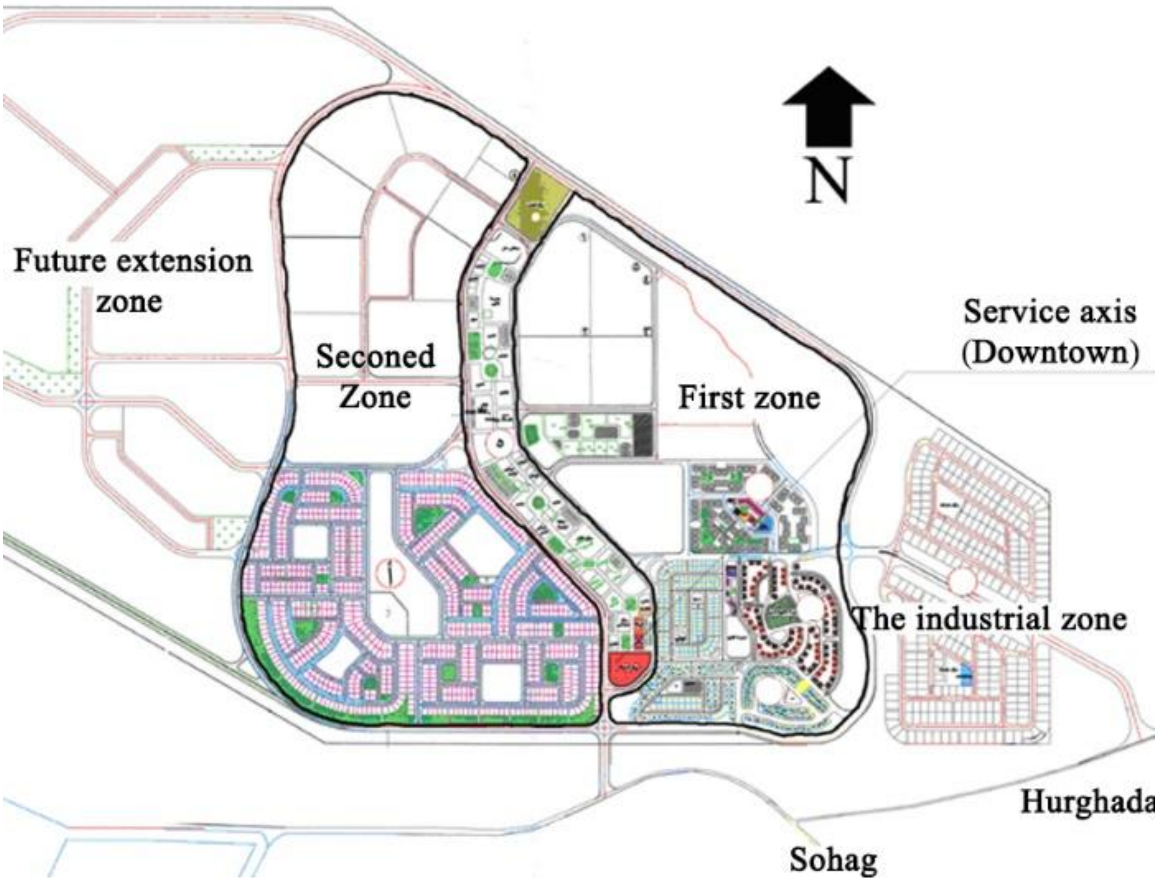
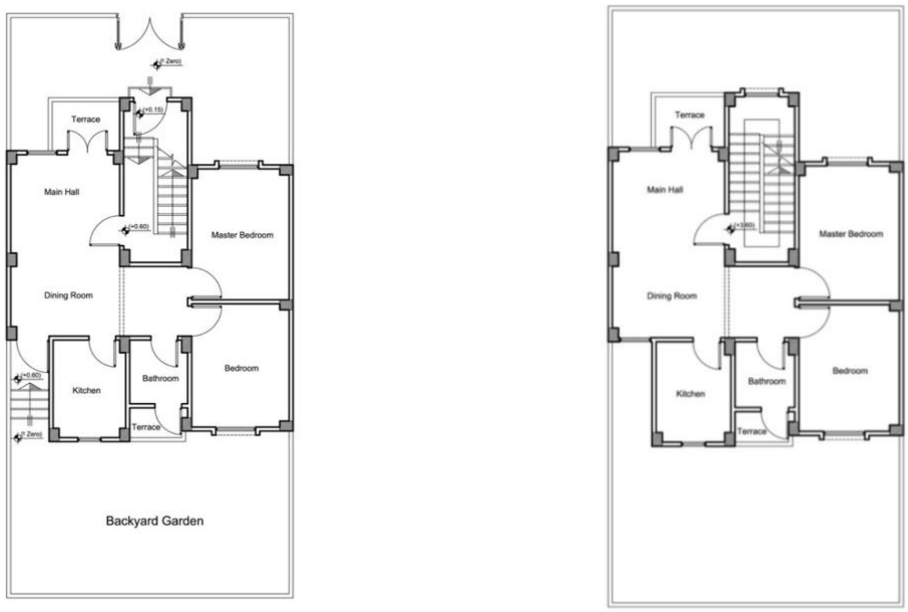


Fig. 8 NAC master plan [48]

The beneficiary citizen builds a housing (residential) unit on them with a construction rate of 50% of the block so that the area of the housing unit is (63 m^2) and is made up of two bedrooms, a hall, a kitchen, and a bathroom, with a stair with an area of (12 m^2) to make a flat floor (75 m^2). There are three models, (X), (Y), and (Z), with different designs. This paper will take a model (Z) as a case study, as illustrated in **Fig. 9**.



Ground floor First floor

Fig. 9 Ibny Baitak project model (Z)

4. Results and discussion

In this stage, the results of the LCA study are interpreted and communicated to the stakeholders. The interpretation includes identifying the study's key environmental impacts and limitations and identifying areas for improvement.

4.1 EIA Mid-point results

In this section, the results of all scenarios will be presented by the midpoint method for single score and weighting results.

4.1.1 Single score results

Fig. 10 highlights the results of 12 wall painting types by the single score with different environmental impact categories. The analysis will focus on the four painting types as defined before. The Alkyd paint type has recorded the highest adverse environmental impact by (1.57 pt), the ceramic-based paint came in the second rank by (1.19 pt), then the acrylic paint by (0.27 pt), and finally the Gypsum Plasterboard by (0.25 pt). That is why Alkyd paint has a high environmental impact due to its oil-based composition and VOC emissions during application, by Pellisthe et al. [41]. Acrylic came in the third rank because it is considered a low-VOC option and has a relatively low environmental impact Bolhari et al. [14]. Gypsum plasterboard has a relatively low environmental impact, as it is made from natural gypsum and can be recycled or disposed of safely; it can be supported by [24], [42], [43].

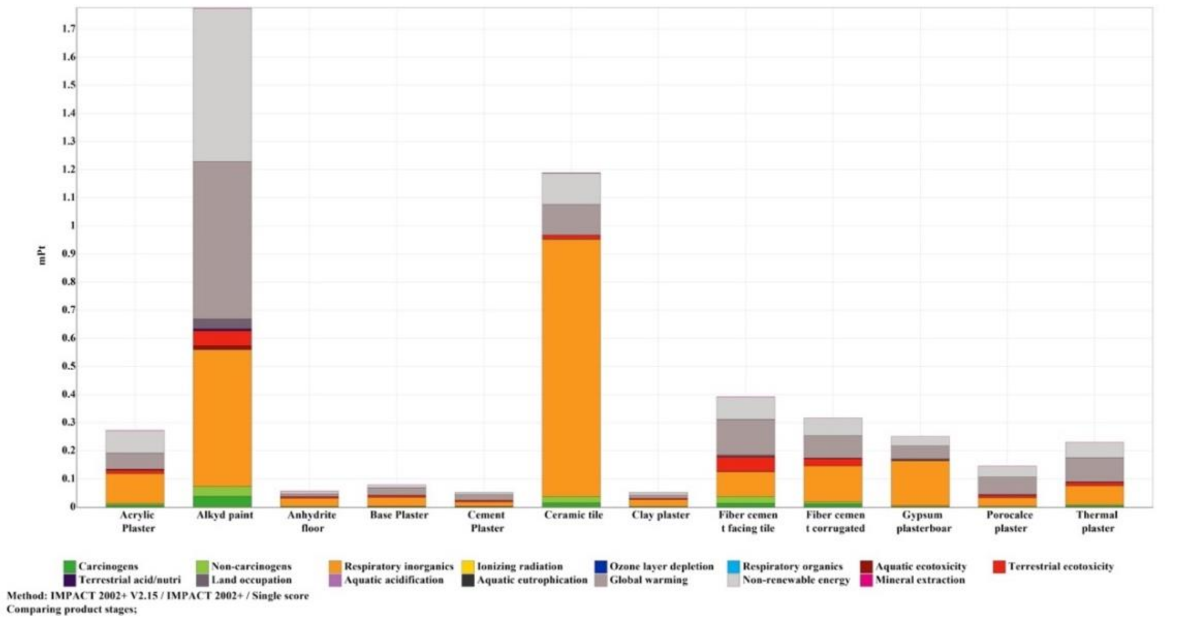


Fig. 10 Single score results by midpoint method

4.1.2 Weighting results

Considering the environmental impacts, **Fig. 11** depicts the environmental midpoint method. The paint industry has three significant environmental impacts: global warming potential, non-renewable energy, and respiratory inorganic, in consent with Han et al. [44]. By numbers, the Alkyd paint type has recorded the highest of the three environmental impacts by 4.75 $kg\ co_2\ eq$, 65.61 $Mj\ primary$, and 3.30E-06 $DALY$, respectively. Some LCIA techniques have embraced Disability Adjusted Life Years ($DALY$) as a measure of human health environmental impact to incorporate varied points linked to damages to human health, as mentioned by Dastjerdi et al., Li et al., Shi et al. and Hu et al. [45]–[48]. In contrast, the Gypsum Plasterboard recorded the lowest numbers by 0.45 $kg\ co_2\ eq$, 5.19 $Mj\ primary$, and 1.13E-06 $DALY$, respectively, consistent with Jimenez Rivero et al. [49].

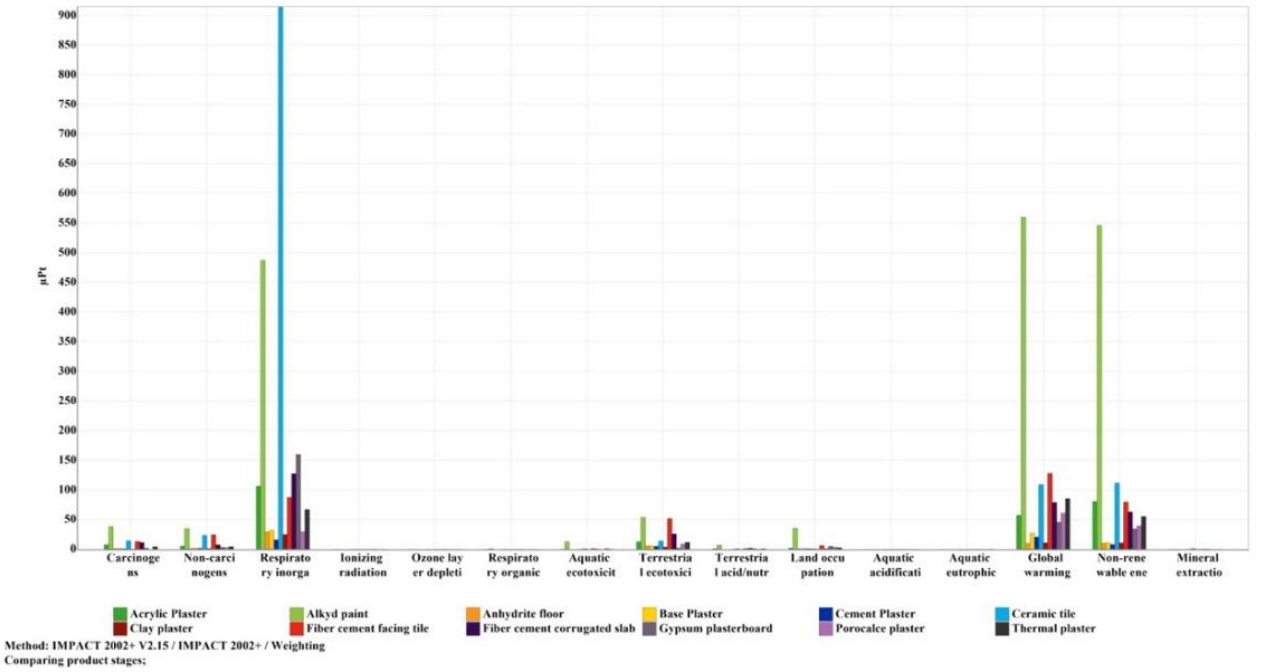


Fig. 11 Weighting results by midpoint method

4.2 EIA Endpoint results

In this section, the results of all scenarios will be presented by the endpoint method for single score and weighting results.

4.2.1. Single score results

Regarding the endpoint results, **Fig. 12** shows that the human health effect has recorded the highest values among all painting types. The alkyd paint, ceramic-based paint, acrylic plaster, and gypsum plasterboard impact will be presented. Which have recorded 0.54 mpt, 0.95 mpt, 0.12 mpt, and 0.07 mpt, respectively, in confirm with Suárez et al. [50].

The impacts of climate change and resource depletion came in the second and third ranks, respectively. The two previous impacts have recorded the highest value in the Alkyd paint types, which were 0.45 mpt and 0.43 mpt. It is worth mentioning that the human health impact hits the highest numbers in the ceramic-based paint, 0.95 mpt compared to the Alkyd paint, 0.54 mpt, by a 43.15% decrease; this result is in line with Han et al. and Bovea et al. [44], [51]. The gypsum plasterboard still has the lowest numbers among the four painting types studied.

4.2.2. Weighting results

As discussed, the $DALLY$ definition mentioned before is that the ceramic-based pain has the most significant number (6.75E-06 $DALLY$ and the Alkyd paint has (3.81E-06 $DALLY$ as -06 $DALLY$) and the Alkyd paint has (3.81E-06 $DALLY$) as it is highlighted in **Fig. 13**, in agreement with NPIA [52]. Conforming to the Sveff association report [4], the ecosystem quality has a negligible impact on the paint industry.

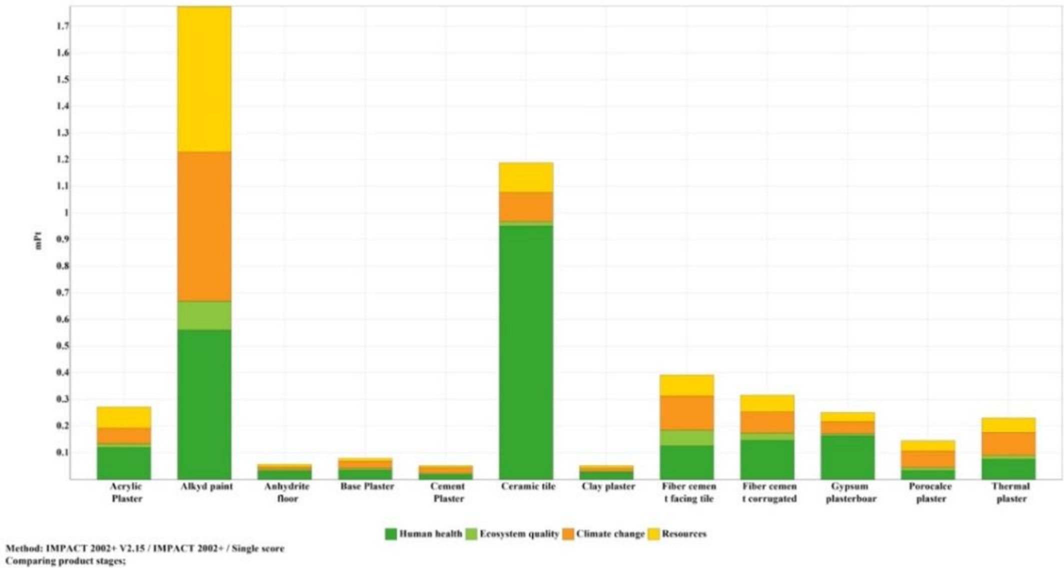


Fig. 12 Single score results by endpoint method

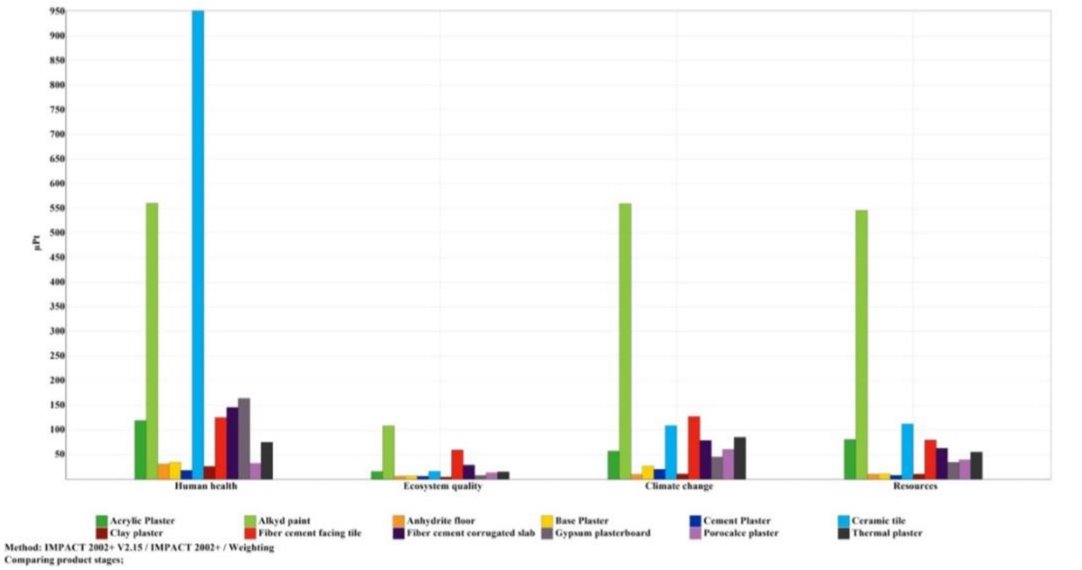


Fig. 13 Weighting results by endpoint method.

5. Conclusion

In conclusion, the comparative LCA of several wall painting kinds utilized in the Ibny Baitak Project offers a thorough evaluation of the environmental impact of each type of paint. Based on their composition, use, and environmental effects, the article examined 12 different types of wall painting.

Based on its environmental effect, the article's findings show that each form of painting has benefits and drawbacks. Alkyd paint had the most significant environmental impact because of its oil-based makeup and VOC emissions during the application, which Pellis et al. support [41]. Due to its durability and extended lifespan, ceramic paint had a lower environmental impact than some other types of paint, which by NPIA, Han et al., and Boveal et al. [19], [51], [52]. The gypsum plasterboard paint has a comparatively minimal environmental impact since it is derived from natural gypsum and can be recycled or disposed of properly, as agreed upon by [22], [24], [25], [42], [43], [49], [50], [53], [54], it. The finding has significant ramifications for green building techniques. The sort of wall painting chosen can significantly affect the construction project's total environmental impact.

Several obstacles could be encountered when conducting a comparative LCA of different wall painting types, such as alkyd, ceramic, acrylic, and gypsum plasterboard, for the Ibny Baitak Project as a case study in a new city. Some of the obstacles are [17]:

1. *Data accessibility:* One of the main obstacles to performing an LCA is the lack of information on the environmental effects of each stage of the product's life cycle.
2. *Process variability:* Every wall painting has a different production procedure depending on the producer and region. Information from numerous manufacturers and sources may need to be obtained.

3. *Interactions with other building materials:* The environmental effects of wall painting may be affected by other building materials employed.
4. *Cost factors:* The cost of each type of wall paint may make conducting an LCA more difficult.

6. Limitations and future work

There are several restrictions and areas for further research that should be considered [17]:

1. The article had a designated scope because it only examined the four varieties of wall paint used in the Ibny Baitak Project—crylic, gypsum plasterboard, ceramic, and alkyd. The analysis did not include other types of wall painting, including anhydrite, paint with a ceramic base, corrugated fiber cement, percale plaster, and thermal plaster.
2. LCA makes assumptions and evaluates the environmental effect of each stage of the product's life cycle using the Ecoinvent database. On the other hand, these assumptions could raise doubts and compromise the study's accuracy.
3. While LCA concentrates on a product's environmental implications, sustainable construction methods also consider social and economic impacts.

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