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Life Cycle Assessment of Sustainable Manufacturing Processes: A Comparative Analysis of Materials Used for Lighting Poles

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ABSTRACT

To ensure sustainable selection of materials in light of rapid global changes, a fundamental alteration of the approach to the material selection process is required in order to mitigate harms to the environment. A case study was conducted in terms of life cycle assessment (LCA), which compares the environmental impacts of the prevalent materials in the industry of lighting pole manufacturing, namely, steel, galvanized steel, stainless steel, and aluminum. The study employed the ReCiPe 2016 method with the use of OpenLCA software that covered a wide range of midpoint and endpoint impact categories, the main ones being energy consumption, global warming potential, ecotoxicity, and human health impacts. The results showed that aluminum has the smallest environmental footprint in most categories of the impacts; thus, it is the most environmentally friendly material. In contrast, stainless steel exhibits the most environmental concerns in several categories, particularly, the toxic impacts. While steel has higher energy requirements and global warming potential, galvanized steel has a greater impact on ecotoxicity.

Keywords: Life Cycle Assessment, Sustainable Manufacturing, Lighting Poles, Material Selection, Environmental Impact.

تقييم دورة حياة عمليات التصنيع المستدامة: تحليل مقارن للمواد المستخدمة في أعمدة الإنارة

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ملخـــــــص البحـــــــث

لضمان اختيار مستدام للمواد في ضوء التغييرات العالمية السريعة، يلزم إجراء تغيير أساسي لنهج عملية اختيار المواد من أجل التخفيف من الأضرار في البيئة. أجريت دراسة حالة من حيث تقييم دورة الحياة (LCA)، والتي تقارن الآثار البيئية للمواد السائدة في تصنيع أعمدة الانارة، وهي الصلب والصلب المجلفن والفولاذ المقاوم للصدأ والألومنيوم. استخدمت الدراسة طريقة ReCiPe 2016 مع استخدام برنامج OpenLCA الذي غطى مجموعة واسعة من فئات تأثير نقطة الوسط ونقطة

النهاية، والتي تضم استهلاك الطاقة، وإمكانية الاحترار العالمي، والسمية البيئية، وآثار صحة الإنسان. أظهرت النتائج أن الألومنيوم لديه أقل بصمة بيئية في معظم فئات التأثيرات، وبالتالي فهي أكثر المواد صديقة للبيئة. على النقيض من ذلك، فإن الفولاذ المقاوم للصدأ يظهر أكثر التأثيرات البيئية في العديد من الفئات، وخاصة التأثيرات السامة. في حين أن الصلب لديه متطلبات طاقة أعلى وإمكانات الاحترار العالمي، كذلك كان للفولاذ المجلفن تأثير أكبر على السمية البيئية.

الكلمات الدالة: تقييم دورة الحياة، التصنيع المستدام، أعمدة الإنارة، اختيار المواد، التأثير البيئي.

1. Introduction

The rapid urbanization and global transportation system enlargement are putting great importance on the infrastructural system in which lighting systems play a crucial role for both road safety and functionality [1]. Lighting poles, which are the backbone of these systems, are usually manufactured from materials that require a large amount of resources and, consequently, impact the environment and make the infrastructure development more detrimental to it. Within the current scenario of increasing environmental issues and scarcity of natural resources, manufacturing that is sustainable and using only the needed materials in the projects is becoming critical [2]. The evaluation of life cycle assessment (LCA) comes out as a comprehensive methodology for the quantification and comparison of the environmental impacts that are associated with the products and systems across their full life cycle, from raw material extraction to the end-of-life management (cradle-to-grave) [3, 4]. The LCA methodology offers an all-encompassing viewpoint, facilitating the identification of environmental hotspots and enabling informed decision-making based on reliable information for sustainable solutions [5].

The concept of sustainable manufacturing, or environmentally friendly manufacturing, has emerged as an effective approach to reduce environmental damage, improve economic viability, and promote social responsibility in industrial activities [6]. This includes various methods to reduce carbon emissions, material recycling, and environmentally friendly processes to maintain the sustainability of future generations and the environment [7]. Bringing together the economic, environmental, and social dimensions of sustainability will allow the manufacturing sectors to offer a growth path where they maintain a responsible utilization of resources and deliver long-term viability [8].

Life cycle assessment (LCA) stands as a robust technique for evaluating the environmental outcomes of products, techniques, or services in the course of their entire lifespan, encompassing the extraction of raw materials to the end of life. A vital segment inside LCA is the life cycle impact assessment (LCIA), which interprets stock statistics into quantifiable environmental effect ratings. Within LCIA, midpoint and endpoint methodological processes are employed. These techniques, while sharing the aim of environmental effect evaluation, diverge in their attention, methodological frameworks, and realistic packages, each providing precise insights into the complexities of environmental burdens [9].

In LCIA, however, the endpoint approach focuses mainly on the ultimate impacts on the environment, looking at damage to areas of protection, such as human health, ecosystem quality, and resource availability. This approach puts environmental impacts into broader damage categories, which provide a more synthesized output that is easy to interpret by decision-makers and stakeholders [12, 13]. Research conducted by Li et al [14], and Huijbregts et al [9], shows how the endpoint approach is effective in expressing the overall environmental effects of products and processes; therefore, making it especially appropriate for policies and wide stakeholders.

Midpoint and endpoint approaches have their strengths and limitations. The midpoint approach offers precise and detailed information on specific environmental impacts, which aids in identifying hotspots and optimizing processes. The standardized indicators of this approach help make comparable the performances of different technologies [15]. Nonetheless, due to its complexity, it may be difficult for non-specialists to interpret, and its narrow focus on specific impacts may ignore broader environmental and social implications [12, 13]. On the other hand, the endpoint approach has better interpretability and a wider perspective, encompassing human health, ecosystems, and resources, thus helping in decision-making and communication. Despite this, endpoint methods involve simplifications and heightened ambiguity owing to the amalgamation of intricate mechanisms, which may compromise certain aspects of scientific accuracy and detail [15, 16]. Acknowledging the complementary advantages of both approaches, this study applies both the midpoint and endpoint approaches.

This paper evaluates the environmental performance of various materials widely used in the lighting poles construction through life cycle assessment (LCA). Specifically, a comparative LCA of steel AISI 1040, galvanized steel, stainless steel 304, and aluminum 6063 lighting poles is performed to identify the material with the least environmental impact profile. The research aims to quantify and compare the life cycle environmental impacts of lighting poles manufactured from the selected materials across a comprehensive set of environmental indicators, and to provide data-driven recommendations for material selection in lighting pole manufacturing. Ultimately, the findings of this study are intended to provide manufacturers, policymakers, and infrastructure developers to make environmentally conscious material choices, contributing to the broader transition towards a more sustainable built environment and promoting sustainable infrastructure development.

2. Materials and Methods

This study uses a comprehensive life cycle assessment (LCA) framework based on the methodology developed by Hauschild et al. [17]. In this research three methodological steps have been conducted and are presented in the sub-sections below, starting with the goal and scope definition and ending with the life cycle impact assessment. The lighting pole is designed using SolidWorks software. The lighting pole consists of three components. The first one is a long and thin pole which is responsible for the support. The second one is a short and thick mast arm that extends from the pole and holds the light. The third one is a hexagonal base which fixes the lighting pole to the ground. Figure 1 represents the assembled lighting pole, clearly illustrating its components and the locations where the welding occurs. Each component is labelled for easy identification.

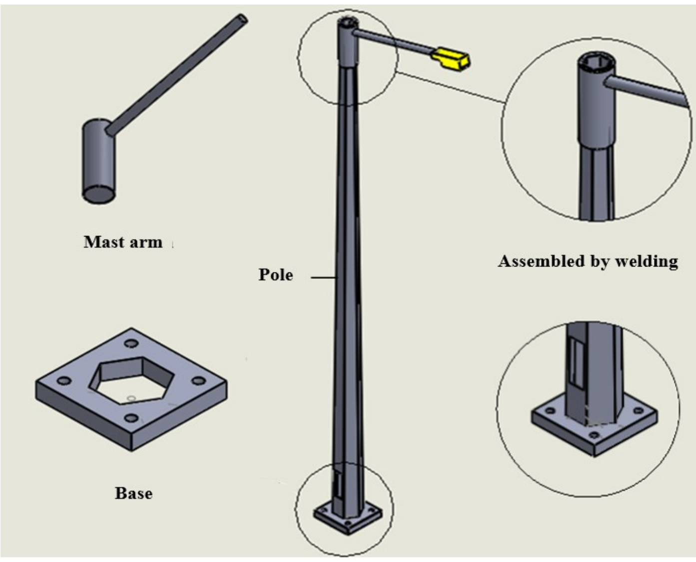

Figure 1. 3D model of a lighting pole

2.1 Goal and Scope Definition

The main objective of the LCA is to measure the environmental impacts of lighting poles produced from steel AISI 1040, galvanized steel, stainless steel 304, and aluminum 6063. All four lighting poles are compared based on the following functional unit: structural support for mounting lighting fixtures at an appropriate height of 9 meters above the ground. The service life for steel is 30 years and for galvanized steel, stainless steel and aluminum is 50 years [18, 19]. The system boundary was identified as "gate-to-gate", which refers to all manufacturing processes until the lighting poles are ready for transport from the manufacturing gate, and the transportation to installation sites. The use and end-of-life phases were not included in the system boundary as the main focus was on manufacturing.

2.2 Life Cycle Inventory Analysis

The life cycle inventory (LCI) phase involved the quantification of material and energy inputs and environmental releases associated with the manufacturing processes of lighting poles for each material type. Primary data were collected from Al-Enmaa manufacturing company, including process-specific data on material used as shown in Table 1. Supplementary data were obtained from international material suppliers and literature sources [20, 21], such as material safety data sheets (MSDS) and chemical composition information, as shown in Table 2.

Table 1. Material properties of the lighting pole

Properties \ Material	Steel	Galvanized steel	Stainless steel	Aluminum
	Original	Alternatives		
Metal density (g/mm³)	0.00775	0.00775	0.008	0.0027
Electrodes material	ER70S-6	ER70S-6	E308/308L	E4043
Electrodes density (g/mm³)	0.00785	0.00785	0.00844	0.0078
Dimensions (m)	9 x 0.17-0.08 (tapered)			

Table 2. Coated electrode's chemical composition according to the AWS

Chemical compound \ Electrodes material	Steel and galvanized steel	Stainless steel	Aluminum
	ER70S-6 (%)	E308/308L-16 (%)	E4043 (%)
Carbon	0.15	-	-
Manganese	1.85	0.04	-
Silicon	1.15	2.5	0.05
Phosphorus	0.025	1	4.5
Iron	-	0.04	-
Sulfur	0.035	-	0.8
Nickel	0.15	0.03	-
Chromium	0.15	11	-
Molybdenum	0.15	21	-
Vanadium	0.03	0.75	-
Copper	0.5	-	-
Titanium	-	0.75	0.3
Magnesium	-	-	0.2
Zinc	-	-	0.05

Secondary data were sourced from established life cycle inventory databases: Agrebalyse, Worldsteel, and ecoinvent, accessed through OpenLCA software. These databases provided generic data for upstream processes, ensuring a comprehensive inventory. Figure 2 shows the lighting pole product system's inflows, outflows, and system boundaries. Inflows include materials from which the lighting pole is made (steel, galvanized steel, stainless steel, and aluminum) and energy (electricity and diesel). and heat required for welding operations, electrodes, and the gas used for the welding process. Outflows include emissions, slag, and waste.

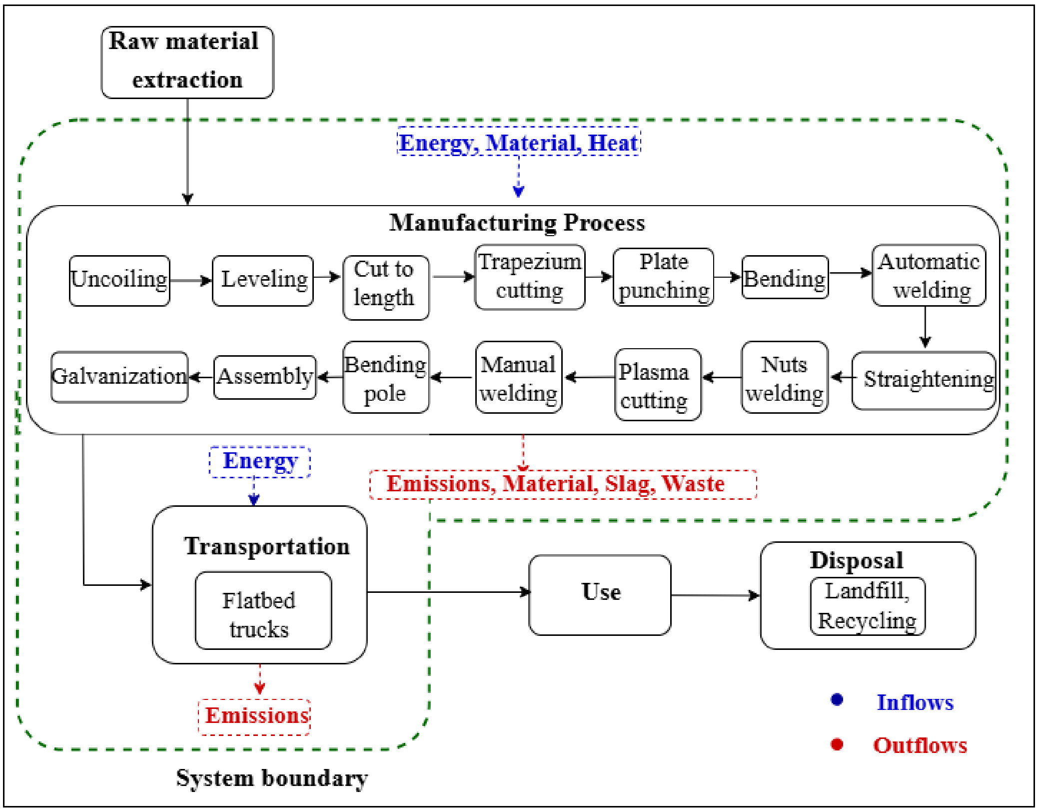

Figure 2. Flow diagram and system boundary for the lighting pole product system

The elementary flows data have been collected from the Al-Enmaa factory, in particular from the specifications of welding machines that are used in the production process, and from the results of the consumption of energy and materials, as well as from databases, as shown in Table 3.

Table 3. Welding process variables

Process variables / Welded part	Welding length (mm)	Cross-section area (mm^2)	Welding current (A)	Welding voltage (V)	Travel speed (mm/min)
Pole welding	9000	4.61	130	28	600
Spot welding	90	10	85	15	45
Base welding	950	10	85	26	95

The following equations are used to calculate the electrode material consumption, welding energy, and slag, according to Favi, et al [22]:

$$C_{\text{elc.mat.}} = \frac{A \times \rho_{\text{elc. mat}} \times L}{DE_{\text{elc. mat.}}} \quad (1)$$

$C_{\text{elc. mat.}}$ represents the electrode material consumption, the total volume of electrode material that is consumed during the welding process. The A denotes the cross-sectional area for the pole, $\rho_{\text{elc. mat}}$ is the electrode material density, L refers to the length of the electrode that has been consumed, $DE_{\text{elc. mat.}}$ is defined as the deposition efficiency for the electrode material, expressed as a percentage (%). Deposition efficiency measures how effectively the electrode material is transferred and deposited onto the workpiece during welding.

$$E_{\text{wel.}} = \frac{\sum_1^n \frac{i_k \times V_k \times 60}{Travel\ speed}}{3{,}600{,}000} \times L \times n \tag{2}$$

$E_{\text{wel.}}$ represents the total energy consumed during welding, i_k the welding current, V_k the welding voltage, n indicates the number of times the welding process is repeated over the same weld joint.

$S_{\text{elc. mat.}}$ is the mass of slag produced from the electrode material, the slag produced is calculated by first determining the deposition efficiency $DE_{\text{elc. mat.}}$ of the electrode material, and then multiplied by the electrode material consumption.

$$S_{\text{elc. mat.}} = C_{\text{elc. mat.}} \times (1 - DE_{\text{elc. mat.}}) \tag{3}$$

The emission of metal pollutants E_{fumes} from welding can be estimated by determining the mass of the electrode consumed and the emission factor EF for the welding process/electrode combination. The formula, as outlined by the U.S. Environmental Protection Agency [23], is as follows:

$$EF = FGR \times FCF \times Ci \tag{4}$$

$$E_{\text{fumes}} = C_{\text{elc. mat.}} \times EF \tag{5}$$

FGR stands for the fume generation rate. It indicates the kilograms of fumes generated per kilogram of welding rod consumed. FCF is the fume correction factor. It relates the amount of metal in kg present in the fumes to the total weight of the fumes in kg. This factor corrects for the difference between the actual metal content in the fumes and the total fume mass, providing a more accurate measurement of metal-specific emissions. Ci represents the concentration of a specific substance listed as part of the welding rod's composition, expressed as a percentage (%). Rod emissions are determined for each welding operation, and these emissions are based on several historical documentation-derived parameters, such as fume generation rate and fume correction factor [23]. The required factors of the deposition rate are shown in Table 4.

Table 4. Welding factors for emissions

Welding process	**(FGR)**	**(FCF)**	**(DE)**
GMAW/GTAW	0.01	0.5464	0.98
SMAW	0.02	0.2865	0.99

One of the important things to consider is heat input. Heat input can be calculated with a standard formula, which helps to evaluate the level of concern necessary [24]. The formula for heat input is:

$$Heat\ input = \frac{60 \times i_k \times V_k}{1000 \times Travel\ speed} \tag{6}$$

The plasma cutting emission factor $EF_{\text{Plasma Cutting}}$ is an important parameter for assessing the environmental impact of plasma cutting machining, and relates the mass of a specific pollutant generated to a unit of plasma cutting. It can be calculated according to the following equation by Broman, et al [25]:

$$EF_{Plasma\ Cutting} = \rho_{mat} \times t \times k \times FGR \tag{7}$$

To compare the environmental performance of different plasma cutting processes, and to calculate the total pollutant emissions from the plasma cutting process, $E_{\text{Plasma Cutting}}$ an equation is used. Where ρ_{mat} denotes the metal density, t represents the metal thickness, k stands for the average kerf, which is the average width of the material removed during the plasma cutting process. Lastly, FG represents fume generation, a measure of the amount of fumes generated during the plasma cutting process.

$$E_{\text{Plasma Cutting}} = CS \times CT \times EF_{\text{Plasma Cutting}} \tag{8}$$

CS represents metal cutting speed, it indicates the rate at which the plasma cutter cuts metal. CT denotes the cutting time, which is the duration for which the plasma cutting process is operational.

All the materials use the dry-cutting technique. The thickness of each type of metal is same. The cutting time required per unit remains consistent regardless of the material type. All parameter values were obtained from Al-Enmaa Factory and are shown in Table 5.

Table 5. Parameters for plasma cutting process

Parameters \ Material	Steel	Galvanized steel	Stainless-steel	Aluminum
	Original	**Alternatives**		
Metal thickness (mm)	3	3	3	3
Kerf (mm)	2	2	2	2
Metal cutting speed (mm/min)	900	900	900	900
Metal density (g/mm^3)	0.00775	0.00775	0.008	0.0027
Cutting time (min/unit)	2	2	2	2

2.3 Life Cycle Impact Assessment (LCIA)

The LCIA phase aimed to translate the LCI results into potential environmental impacts using the ReCiPe 2016 method implemented within OpenLCA 2.0.2 software. ReCiPe 2016 is a widely recognized and comprehensive impact assessment method that covers a broad range of midpoint and endpoint impact categories.

OpenLCA software provides all the values for the conversion factor of the inventory to the midpoint $F_{Ir\rightarrow M}$ after the analysis process, and after obtaining the inventory results Ir, the midpoint characterization factor $CFm_{x,c}$ is calculated according to Huijbregts, et al. [9], as follows:

$$CFm_{x,c} = Ir \times F_{Ir\rightarrow M} \tag{9}$$

Endpoint characterization factors $CFe_{x,c,a}$ are directly derived by multiplying the midpoint characterization factors by the conversion factor of the midpoint to the endpoint $F_{M\rightarrow,E,c,a}$, for each impact category by [9]:

$$CFe_{x,c,a} = CFm_{x,c} \times F_{M\rightarrow,E,c,a} \tag{10}$$

3. Results and Discussion

This section presents the findings of the life cycle assessment (LCA) of the materials used in the lighting poles. Figure 3 provides a visual representation of the product system of a steel lighting pole, built by OpenLCA software, including the interrelated processes involved in its life cycle. This comprehensive system illustrates the production processes sequence of the steel pole, highlighting their associated environmental impacts. The analysis focuses on both midpoint and endpoint impact categories, providing a full understanding of the environmental performance of each material.

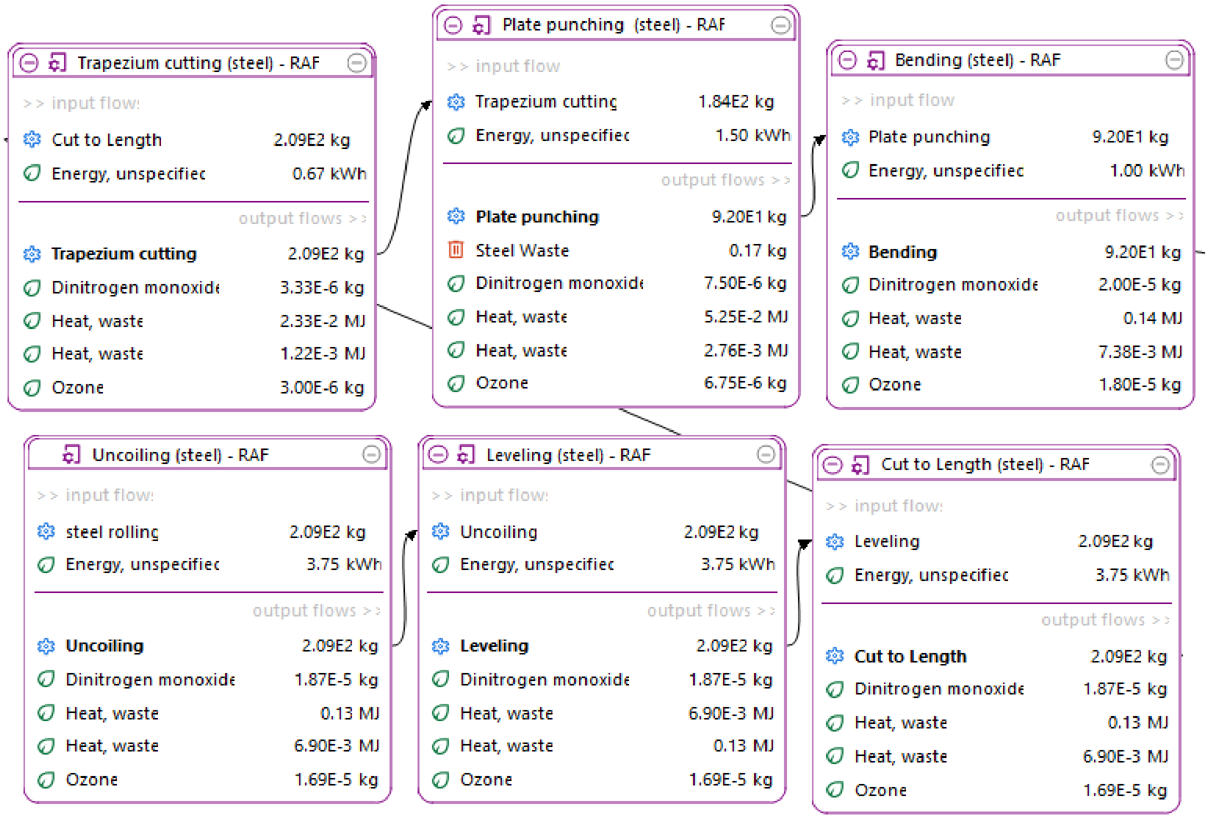

Figure 3. Part of the product system for lighting pole made of steel

Midpoint categories evaluated in this study included: energy consumption (EC), global warming potential (GWP), freshwater aquatic ecotoxicity potential (FAETP), marine aquatic ecotoxicity potential (MAETP), terrestrial ecotoxicity potential (TETP), human toxicity potential - cancer (HTPc), and human toxicity potential - noncancer (HTPnc). Endpoint categories, representing damage to areas of protection (human health and ecosystems), were also assessed to provide a broader perspective on environmental consequences.

3.1 Energy Consumption

The highest energy consumption occurs during uncoiling, leveling, and cut to length processes, where the energy values reach 11.25 kWh, while other processes contribute less to energy consumption. Steel emerges as the most energy-intensive material throughout the process, whereas aluminum requires the least energy, as shown in Figure 4.

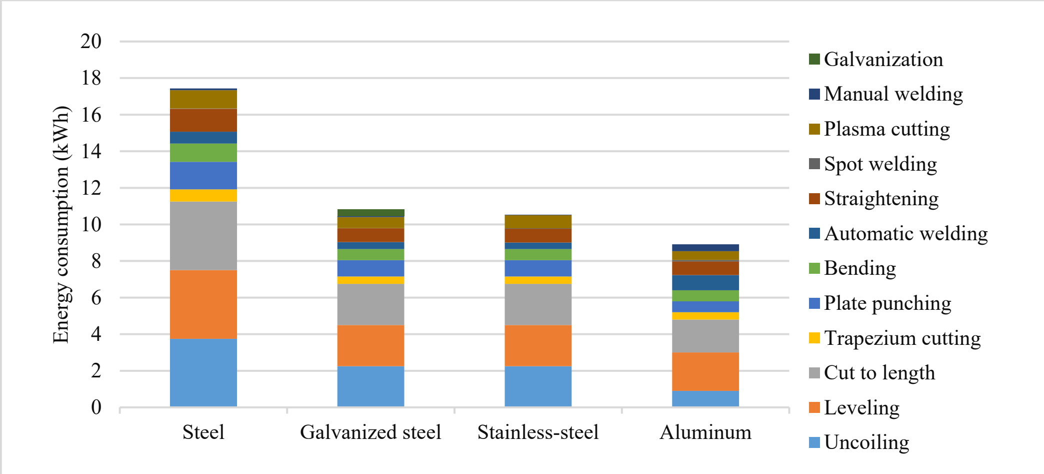

Figure 4. Energy consumption

3.2 Global Warming Potential

Steel material exhibits the highest global warming potential, with a value of 2.78E-02 kg CO2-Eq. Comparing the alternative materials, stainless steel and galvanized steel generally demonstrate lower climate change potential compared to steel. Aluminum exhibits the lowest climate change potential, as indicated in Figure 5.

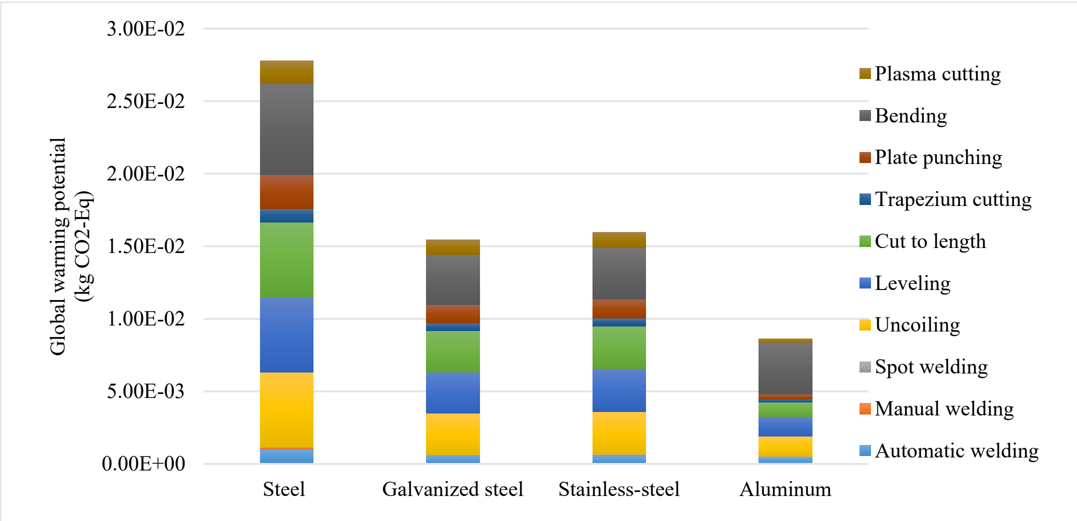

Figure 5. Global warming potential

3.3 Ecotoxicity Potentials

Figures 6,7 and 8 show FAETP, MAETP, and TETP respectively. Aluminum has the lowest ecotoxicity potential among most categories due to the low emission of ecotoxic substances during its production process. Galvanized steel has the highest potential ecotoxicity values, especially for freshwater and marine aquatic environments, due to the emission of chromo VI during galvanization. Stainless steel is also a major contributor to terrestrial ecotoxicity, while steel makes low impact. Automatic welding and galvanization processes are seen as fundamental contributors to the ecotoxicity of materials.

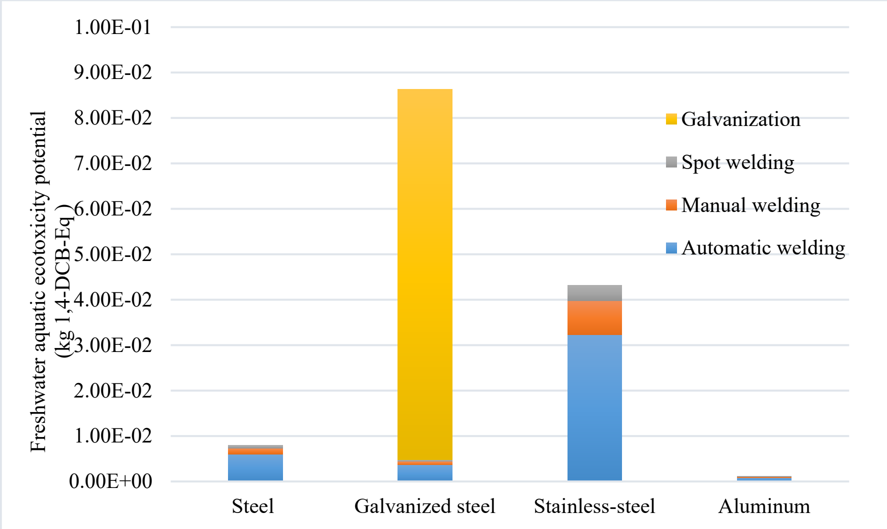

Figure 6. Freshwater aquatic ecotoxicity potential

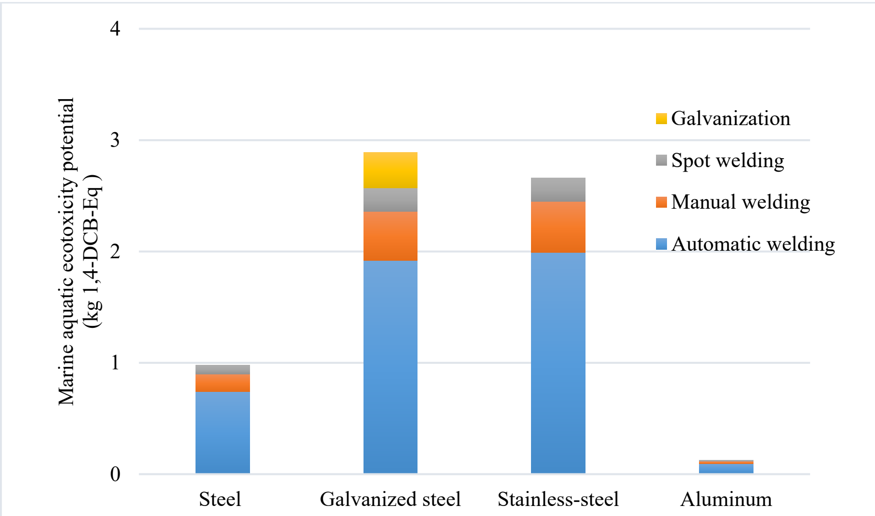

Figure 7. Marine aquatic ecotoxicity potential

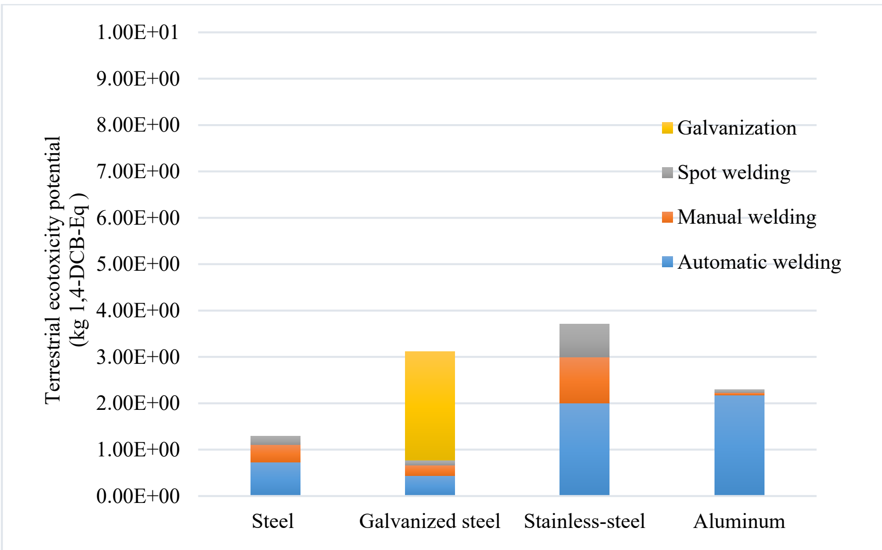

Figure 8. Terrestrial ecotoxicity potential

3.4 Human Toxicity Potentials

The carcinogenic human toxicity potential (HTPc) and non-carcinogenic human toxicity potential (HTPnc) are shown in Figures 9 and 10, respectively. Because of the emissions of nickel and chromium VI during the galvanization process, galvanized steel has the highest potential for human toxicity in both categories. Aluminium has the lowest potential for human toxicity, while steel and stainless steel have intermediate profiles. The methods of automated welding and galvanization are important contributors to the effects on human toxicity.

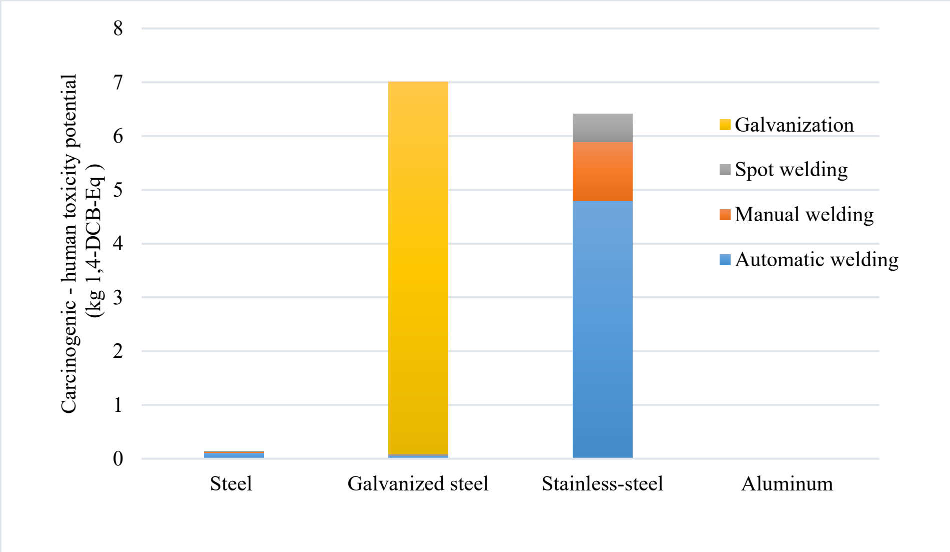

Figure 9. Carcinogenic human toxicity potential

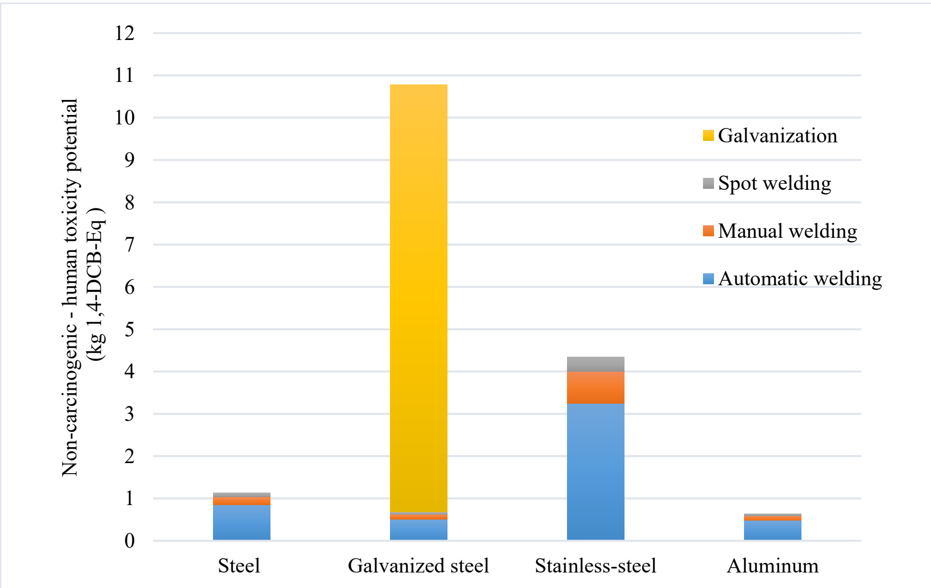

Figure 10. Non-carcinogenic human toxicity potential

3.5 Endpoint Characterization

Endpoint characterization results, shown in Figures 11 and 12, reveal similar trends to the midpoint assessment. Aluminum consistently demonstrates the lowest impacts on both ecosystem quality and human health, while stainless steel often exhibits the highest impacts. Galvanized steel shows relatively high impacts on ecosystem quality.

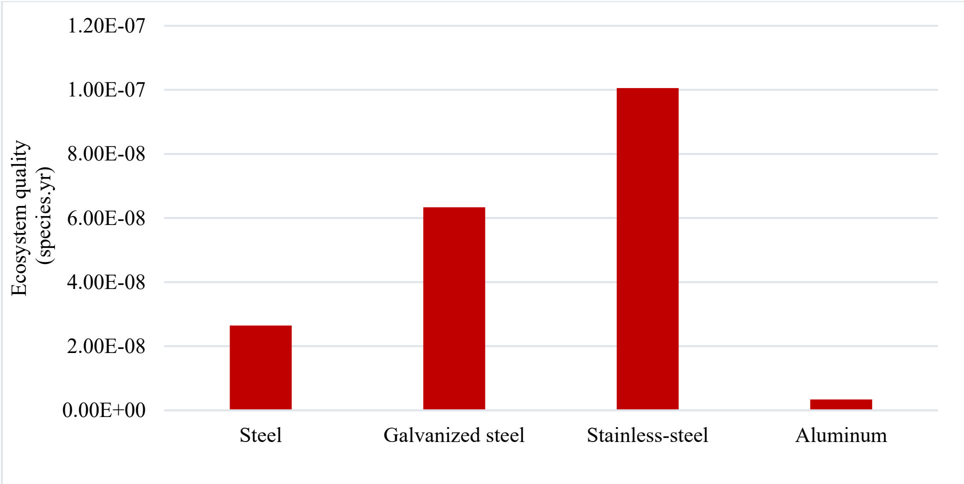

Figure 11. Ecosystem quality indicator

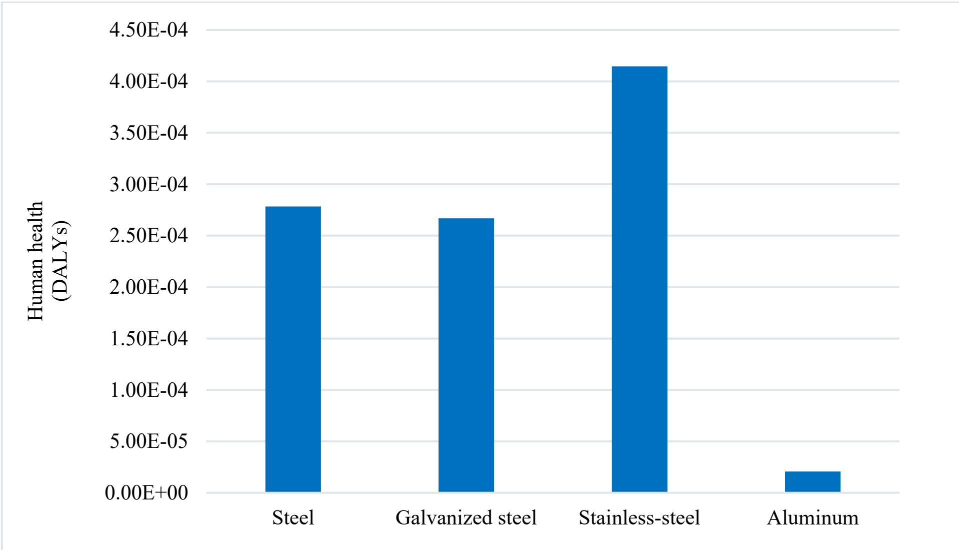

Figure 12. Human health indicator

4. Conclusion

This study performs a comparative life cycle assessment (LCA) of steel, galvanized steel, stainless steel, and aluminum light poles to evaluate their respective environmental impacts and sustainability. In many impact categories, aluminum has been found to have the least environmental impact and as such, can be regarded as the environmentally preferable material for lighting poles. Galvanized steel and stainless steel are durable but can cause a lot of damage to the environment. They can increase ecotoxicity and human toxicity. Steel demonstrates intermediate environmental performance.

However, it is imperative to acknowledge the potential constraints imposed by the study's design. The utilization and end-of-life phases were outside the limits of the system boundary. Furthermore, the study utilized secondary data from databases, which may represent average conditions and may not fully reflect site-specific manufacturing practices. It is recommended that the system boundary be expanded to encompass the entire life cycle, including installation, operational energy consumption, maintenance, and end-of-life management options such as recycling or disposal. Future research could benefit from more detailed primary data collection from a wider range of manufacturing facilities and geographical regions to enhance the robustness and generalizability of the findings.

Nomenclature and Abbreviations

AWS	American Welding Society
CO_2-Eq	Carbon Dioxide Equivalent
DCB-Eq	Dichlorobenzene Equivalent
DE	Deposition Efficiency
EC	Energy Consumption
E4043	Electrode material for aluminum welding
E308/308L	Electrode material for stainless steel welding
ER70S-6	Electrode material for steel and galvanized steel welding
FAETP	Freshwater Aquatic Ecotoxicity Potential
FCF	Fume Correction Factor
FGR	Fume Generation Rate
GWP	Global Warming Potential
HTPc	Human Toxicity Potential - Cancer
HTPnc	Human Toxicity Potential - Non-Cancer
kWh	Kilowatt-hour
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
MAETP	Marine Aquatic Ecotoxicity Potential
MSDS	Material Safety Data Sheets
Species.yr	Endpoint indicator for ecosystem quality and human health
TETP	Terrestrial Ecotoxicity Potential

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