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Sustainability and environmental life cycle analysis of welding processes

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Abstract

Purpose – Welding is a widely used manufacturing process in many industries. The process consumes a lot of energy and resources, pollutes the environment, and emits gases and fumes into the atmosphere that are dangerous to human health. There are various welding processes, and the suitable welding process is usually chosen based on cost, material, and conditions. Subjectivity is the most significant impediment to selecting an optimal process. As a result, it is critical to develop the appropriate set of criteria, use the best tool and methodology, and collect sufficient data. This study examines the sustainability of welding processes and their environmental impact.

Design/methodology/approach – The welding process's sustainability was examined and discussed in general, considering the technological specifics of each welding process, physical performance, and environmental, economic, and social effects. The study investigates the environmental impact of MMAW, GMAW, and GTAW/GMAW processes through experimental work and LCA methodology.

Findings – MMAW is the most environmentally harmful technology, whereas GMAW has the least impact. The GTAW/GMAW process outperformed the other processes in terms of yield stress, but the analyses revealed that it had a greater environmental impact than GMAW.

Originality/value – The study provides an environmental impact summary and demonstrates the effects of welding parameters and processes. This gives users an understanding of choosing the best welding technique or making the process more environmentally friendly. These recommendations help policymakers identify hot spots and implement the right plans to achieve more sustainable manufacturing.

Keywords Environment, LCA, Sustainability, Welding, Process parameters

Paper type Research paper

List of abbreviations

AP –	Acidification potential
BM –	Base metal
EP –	Eutrophication potential
GMAW –	Gas metal arc welding
GTAW –	Gas tungsten arc welding
GWP –	Global warming potential
HAZ –	Heat-affected zone
MMAW –	Manual metal arc welding
NIST –	National institute of standards and technology
LCA –	Life cycle assessment
SCLA –	Social cycle assessment
SOD –	Stratospheric ozone depletion
WM –	Weld metal

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Introduction

Given the serious threat that global warming poses to humankind, reducing air pollution, greenhouse gas emissions, hazardous materials, and waste is of utmost importance. According to the most recent study (Rivas *et al.*, 2020), the industry has a big influence. It takes a lot of energy, generates a lot of solid waste, and has a major impact on greenhouse gas emissions worldwide (Ferreira and Mainier, 2015). Thus, to reduce the damaging effects of manufacturing processes on the environment, modern industrial production must now embrace sustainability and sustainable development (Rivas *et al.*, 2020; Hoyos *et al.*, 2023). Although the term "sustainability" originally referred to environmental qualities, or the capacity to preserve the environment, it is now used in literature to describe a concept that has the potential to provide a clear understanding of all the significant variables that affect the environment, the economy, and society (Sangwan *et al.*, 2016). This is known as the "tree bottom line theory", and it's a useful tool that can help industry choose and develop technology that will be both affordable and environmentally and socially acceptable. Sustainability and sustainable development are often used as synonyms, but even though they are based on similar principles they are defined differently in literature (Sproesser *et al.*, 2017). Sustainable development aims to improve the quality of life without depleting the environment's resources by incorporating social, economic, environmental, and physical elements (Baker, 2021). The pursuit of technological, organizational, and human advancement in the manufacturing sector while preserving energy and resources would be considered sustainable development in manufacturing. According to Jamal *et al.* (2020), five key concepts must be followed to achieve sustainable manufacturing: improving production efficiency, using sustainable raw materials, reducing waste, and improving chain management. The three main determinants of process preference in the manufacturing sector are quality, speed, and cost (Hoyos *et al.*, 2023). Selecting sustainability indicators can be challenging for manufacturers due to subjective selection procedures and the fact that most indicators are industry-specific or have inconsistent definitions (Jamal *et al.*, 2020). To provide a clear and defined framework for users to choose sustainability indicators, the National Institute of Standards and Technology (NIST) categorized a wide range of indicators into five primary categories: economic growth, social well-being, environmental stewardship, performance measurement, and technological advancement (Jamal *et al.*, 2020). The scheme for classifying the indicators used for the implementation of sustainability is depicted in Figure 1.

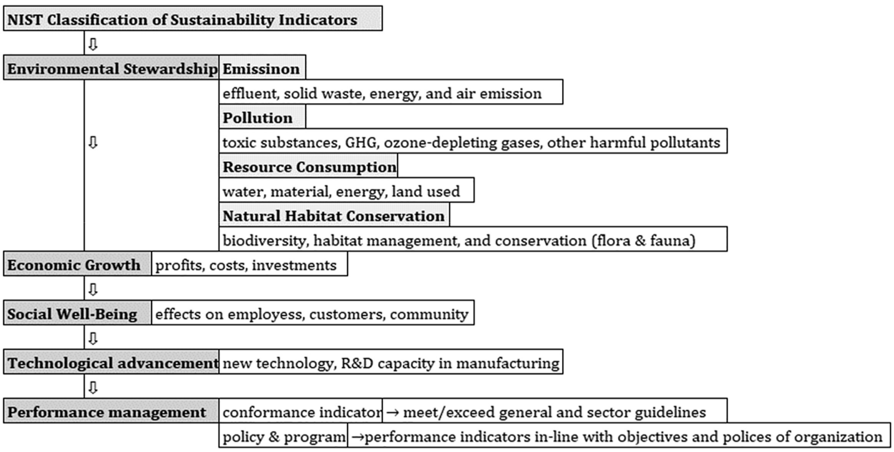

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Figure 1. Sustainability indicator characterization

Many assessment methods and guidelines are available, but the industry sector still struggles with implementing sustainability. As a result, when developing sustainable manufacturing processes, it's important to have a support system that helps with transparent and accurate decision-making. This system should evaluate the effects on the environment, the economy, and society while also helping select the best process parameters and setup (Rivas *et al.*, 2020). The ISO-standardized methodologies of life cycle assessment (LCA) and social life cycle assessment (SCLA) (ISO14044 and ISO 14040, 2006) are used extensively in research and production to evaluate whether processes and products follow the concepts of sustainability. The LCA method is applied to examine the impact on the environment, while the SCLA method analyses the social aspects by evaluating the possible positive and negative social and socio-economic effects that products, processes, or services may have (Sangwan *et al.*, 2016). To achieve the goals of sustainable manufacturing, life cycle assessments are carried out on a range of products and procedures. LCA is primarily used to compare technologies and asses environmental performance by identifying and collecting environmental impact indicators and data related to the process under consideration, such as materials, energy, and transportation (Sangwan *et al.*, 2016; Shaukat *et al.*, 2022).

In recent years, there has been a lot of attention given to studies examining the sustainability of some of the most widely used welding processes. Welding is a key joining process used in today's manufacturing, particularly in the metal sector. The procedures used require a substantial amount of resources and energy, both of which are essential to the environment. Welding machines and other production processes are thought to account for 70% of the energy used in manufacturing, so since they are so common, technological advancements should be accompanied by studies on environmental preservation and safety (Rahmati *et al.*, 2022). Socially, welding is a dangerous process that harms the environment and the health of people. As such, sustainability needs to be characterized within a complete framework that accounts for social, environmental, and economic aspects. Several research papers examine different welding processes to enhance process effectiveness, optimize costs, and social factors, and examine environmental impacts (Alkahla and Pervaiz, 2017). For instance, four distinct welding techniques are investigated by Ya – Ju Chang *et al.* (2015) to weld high-strength steel plates that are 20 mm thick. It discusses the specifics of the employed welding technologies and considers the health and environmental impacts. The study concludes that because of its low productivity and increased health risks for welders, the MMAW process is the most environmentally harmful. Further indicators regarding the impact of the overall sustainability score, such as the preparation of specimens, various welding positions, mobility, and so forth, must still be included. Although most of the researchers examined the essential sustainability strategies to reduce the environmental impact of welding processes, such as energy reduction, waste management improvements, optimization of process parameters, and enhancing the training of welders, there is still a need for further investigation (Sproesser *et al.*, 2017). A strong framework of indicators and the creation of a larger system boundary of the analysis can help produce more reliable findings.

This paper begins with a summary of the topics related to welding sustainability and model development characteristics. In the subsequent chapters, three of the most employed welding techniques—manual metal arc welding (MMAW), gas metal arc welding (GMAW), and a combination of GMAW and gas metal tungsten welding (GTAW)—are used for experimental work. Structural steel plates, 10 mm thick are welded with varying parameters, and tension and hardness test samples are extracted to investigate their physical performance. The data obtained are used to analyze the optimization of parameters and their influence on the environment for each process separately. The environmental impact is analyzed with the LCA assessment methodology. Lastly, suggestions are made for the future course of research on MMAW, GMAW, and GTAW processes for greater sustainability.

Sustainability of welding processes

Welding technology

Welding is a necessary industrial manufacturing process that involves applying various heat sources to melt and coalesce metal. It is widely used for joining and integrating elements in a variety of industries and sectors, including the nuclear, electronic, chemical, oil and gas, construction, automotive, and shipbuilding industries, as well as the energy-power generation, household appliances, and machinery fabrication (Rahmati *et al.*, 2022; Sproesser *et al.*, 2017). In the construction industry, welding is largely in charge of expenses and, consequently, value creation given that it's used to make metal structures (Ya – Ju Chang *et al.*, 2015). The reason for its widespread use and appeal is that it can be an easy, quick, and affordable method of producing joints with excellent quality and performance. Apart from their widespread popularity in the industry, they are also believed to be the reason for the high energy and resource consumption of the sector, as well as the harmful effects they have on the health of workers and the pollution in the surrounding area. A process-related life cycle assessment is therefore frequently required to identify the environmental burdens and identify strategies for reducing these effects along with technological advances (Pittner and Rethmeier, 2022).

MMAW, GMAW, and GTAW are the three most employed welding technologies. The process's specificity and their respective capacities are not the same. MMAW process uses inexpensive equipment and coated electrodes, it's very flexible and does not require shielding gas (Rahmati *et al.*, 2022; Sproesser *et al.*, 2017). The process involves melting the base metal and the coated electrode with an electrical arc initiated between them. The coating of the electrode is a mixture of metal and chemical elements called flux that evaporates during welding and forms a gas cloud that shields the molten metal from ambient air and prevents the contamination of the weld by forming a slag. This process requires pre-processing preparation like edge preparation, clamping, and post-preparations on welded passes like cleaning and treatments that can impact the production process. The metal's thickness determines the groove preparation, which varies, and this is related to resource consumption control. It can be filled with molten metal by using a single pass or multipass weld. The process is frequently regarded as hazardous due to its associated spatter, radiation, fumes, and other dangerous side effects (Ya – Ju Chang *et al.*, 2015). Because MMAW is a manual process, it takes longer to change electrodes and clean after each pass, which reduces process productivity. It depends on the worker's abilities and carries a serious risk to their health (Amza *et al.*, 2010). Monitoring and adequately adjusting several process-dependent variables, like current, voltage, speed, polarity, route gap, position of welding, electrode angle, and bevel, is essential to producing a high-quality MMAW weld. This welding process can be used for a wide range of alloys and metals, such as nickel, stainless steel, aluminum, and others (Rahmati *et al.*, 2022).

The GMAW process is also a flexible and easy-to-use welding process, but in comparison to MMAW, it does not produce slag waste. The electrical arc is initiated between the basic metal and a metal wire that feeds to the molten pool continuously semi-automated. The melted metal is protected with shielding gas (inert or active) that comes out of the nozzle and spreads over the welding pool. It can be manually controlled, or automated and achieve high deposition rates and speeds during welding. All commercial metals and alloys can be welded using it in various working positions with the appropriate parameter adjustments (Chucheep *et al.*, 2018). The primary benefits include the capacity to modify process parameters within the process and compensate for geometry deviations (Ya – Ju Chang *et al.*, 2015). Spray arc and pulsed arc transfer are common modes of operation to attain high deposition rates. The most recent technological development in GMAW is the highly concentrated spray arc that allows for higher penetration depths and reduction of flange angles (Sproesser *et al.*, 2016a, b, 2017). The use of the modern spray arc technique lowers material consumption and therefore improves the environmental impact of the process (Sproesser *et al.*, 2017). The GTAW process is slightly different from the previously discussed arc welding processes. The arc is created by the contact of a non-consumable tungsten electrode and the base material, while the flow of shielding inert gas from the welding torch covers and protects the molten metal. Helium, argon, or a combination can be inert gas (Hoyos *et al.*, 2023). The energy produced by the arc is utilized to melt and fuse the consumable filler material (Jamal, 2017). The welder's abilities are crucial since the filler material is manually added from the side. The process can be more difficult than other arc welding procedures because of the potential for hot cracking and softening of the weld fusion zone and heat-affected zone (HAZ), which may compromise the mechanical properties (Hoyos *et al.*, 2023). A crucial component in gas arc welding processes is the shielding gas (argon–Ar and carbon dioxide – CO_2). These gas mixtures serve the dual purposes of protecting the weld area from air oxidation and increasing welding productivity by reducing weld imperfections and post-weld treatment requirements (Nakhla *et al.*, 2012).

Physical performance

Most research papers on sustainable welding processes include the physical performance category of indicators (Jamal, 2017). Many quality-related indicators belong to this category, such as visual appearance, defects, roughness, and mechanical properties of the welded products (Jamal *et al.*, 2020). The weld is formed with the crystallization of molten metal and needs to be uniform and defect-free, to ensure maximal physical performance. However, welded joints are susceptible to a variety of defects, and this can seriously compromise the joint's integrity (Aranđelović *et al.*, 2023). This is because they can have a significant impact on the stress concentrations and distributions (Aranđelović *et al.*, 2023). For investigation of the mechanical properties, standardized tests are used to obtain necessary data on yield stress, maximal tension strength, Young's modulus, shear modulus, toughness, and hardness. Since a structure's yield stress is where failure begins, it is important to have this data to ensure structural integrity. This value is usually less than the one obtained by testing the mechanical properties solely on the base metal. All the above data are crucial for assuring the quality of the welded products.

Environmental impact

Gas emissions, waste, and non-renewable resources are major environmental concerns when analyzing the environmental impact of welding processes (Jamal, 2017). Air pollution includes fumes and gases as well as the carbon dioxide footprint left by the energy used in welding operations. According to the accepted definition of air pollution, an air pollutant is any biological molecule or particle that harms the Earth's natural atmosphere (Alkahla and Pervaiz, 2017). During welding operations, the temperature in the arc can reach 20,000 centigrade, breaking down compounds from the base and filler metal into atoms, and ionizing the shielding gas (Rahmati *et al.*, 2022). This results in the emission of toxic gases and vapors, known as fumes, which are harmful to both human health and the environment. Carbon dioxide, nitrogen dioxide, and ozone are among the dangerous gases produced during welding processes (Fard and Fard, 2016; Amza *et al.*, 2009). Electric arc welding is thought to produce these pollutants in substation quantities. However, this does not apply to all welding techniques and processes. Pressure welding, which includes friction stir welding and magnetic pulse welding, is considered a green welding process because it emits fewer fumes (Kaliudis, 2015). For sustainability analysis of welding processes, it is also necessary to compute the use of auxiliary materials, such as slag and vaporized shielding gas since they are not recovered (Jamal, 2017). Reducing the energy used in the process is a good way to improve MMAW's environmental performance, according to a research paper by Alkahla and Pervaiz (2017). This has advantages for the environment and the economy. The LCA analysis carried out by Ya – Ju Chang *et al.* (2015) on the MMAW, GMAW, and LAHW processes, showed that MMAW had the largest environmental impact. Other researchers' findings (Sangwan *et al.*, 2016; Alkahla and Pervaiz, 2017) indicate that MMAW has the greatest impact on eutrophication, acidification, global warming, and photochemical ozone depletion. In Sangwan *et al.* (2016) study the environmental effect of modified GMAW lies between that of MMAW and LAHW, with LAHW having the least impact.

Economic impact

Gaining profit has always been a priority for most companies, therefore this is an important category of several indicators. This measures the investment costs for the corresponding physical performance and environmental and social impact (Jamal *et al.*, 2020). According to Jamal (2017), one must consider and calculate the consumables costs, equipment costs, operating costs, and energy consumption. The sum of these costs is divided by the cost of the base material for rendering a dimensionless outcome (Jamal, 2017). According to Sproesser *et al.* (2017), a cost evaluation function is used to calculate the total costs of welding, considering the initial equipment costs as well as the operating costs. In the given evaluation function, for economic cost criterion c, there is an index n_{cp} that represents fixed costs such as equipment purchase, installation, and implementation, while the slope m_{cp} represents variables such as labor cost, filler material cost, electricity, and shielding gas. The calculations are based on welding time per weld seam length and consumption rates. The study found that investment and equipment manufacturing have a significant impact on environmental criteria such as eutrophication. According to the conclusion of the article written by Alkahla and Pervaiz (2017), labor and other overheads account for 80–85% of the overall cost of welding operations. To maximize profits, various optimization methodologies can be used to reduce consumption and costs.

Social impact

When considering the social aspects of welding processes, it is essential to look at the health risks and dangers involved during this operation (Alkahla and Pervaiz, 2017). During arc welding, fumes, and gases are produced that are very toxic and harmful to human health, such as carbon dioxide, nitrogen dioxide, and ozone (Fard and Fard, 2016). The fumes consist of particles of 0.1–1 μm and heavy metals like chromium (Cr), manganese (Mn), nickel (Ni), and iron (Fe) (Alkahla and Pervaiz, 2017). Their impact on health is determined by several factors, including the quantity of fumes produced, the type of metal used, the composition of filler material and coatings, and the welder's exposure time. This is only one employee-related indicator, health, and safety, which is thought to be more important and is used in many research papers. Other indicators would be the development and satisfaction of the employees and the analysis of the influence of these processes on the community and customers (Jamal, 2017). The study in the article by Sangwan *et al.* (2016) focuses on two critical social conditions: fair wages and health and safety for the stakeholder group workers in Germany. The sufficiency of salary can be recognized by comparing the wage status of welders to the non-poverty wage calculated using non-poverty wages. When analyzing the health and safety of a welding process, the effects of the fumes on welders are the most important factors. The most dangerous hazard for welders is fume inhalation, which can be reduced with proper welding process planning and design (Alkahla and Pervaiz, 2017). There is a separate methodology for analyzing the social impact that can be used for welding processes. This is the social life cycle analysis (SLCA) methodology (UNEP, 2009). The framework of SLCA covers goal and scope definition, life cycle inventory analysis, life cycle impact analysis, and interpretation. In the guidelines, there are identified five stakeholder groups: workers, consumers, local communities, society, value chain actors, and other subcategories (Sangwan *et al.*, 2016).

Methodology and materials

Model development for environmental assessment

The flowchart in Figure 2 illustrates how the model's framework of the analysis in this study addresses relevant sustainability performance categories for welding: physical performance and environmental impact. There is no consideration of the aspects of economic, social, and technological advancement. Various indicators may be included in the categories, tailored to the analysis of each case. Since these indicators have an impact on the assessment, they must be carefully considered, and measured, and must be relevant to the study. One can assess the relative importance of each of the measurements and calculations by looking at the results separately. However, there should be a suitable scaling and weighting of each indicator for an overall measurement of the impact of a particular category. An overall score on the sustainability assessment can be obtained by adding the results from each category (Jamal, 2017). This study investigates the life cycle analysis and the environmental impact of MMAW, GMAW, and the combined use of GTAW and GMAW welding processes. The system boundaries in an LCA define what is considered and what is excluded in the analysis (Bekker *et al.*, 2016). Figures 3–5 depict the system boundaries for each welding

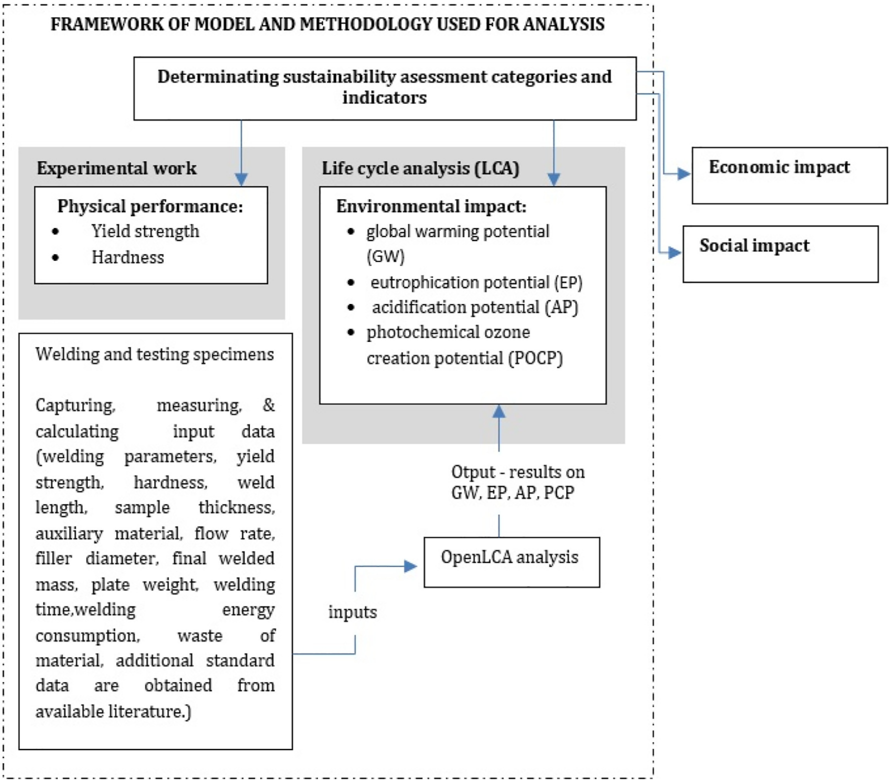

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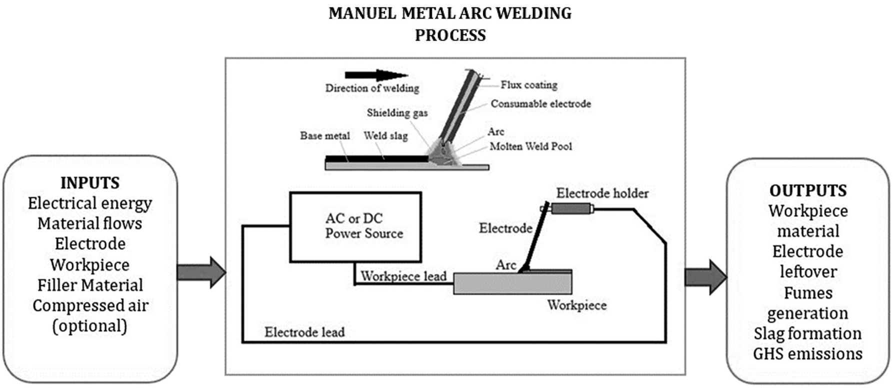
Figure 2. Overview of the framework and method used in this study



Figures 3.
MMAW system boundary

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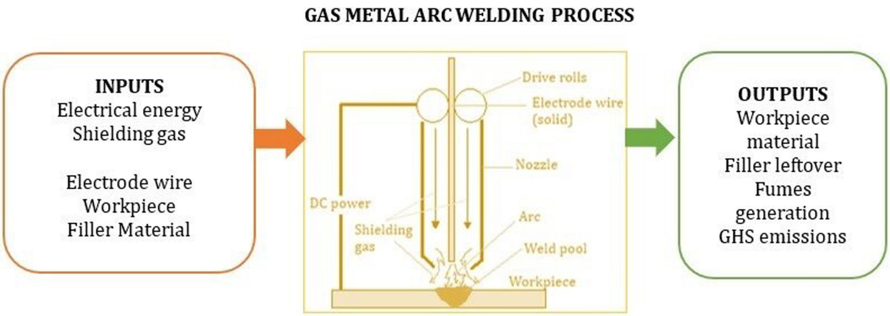

Figures 4.
GMAW system boundary

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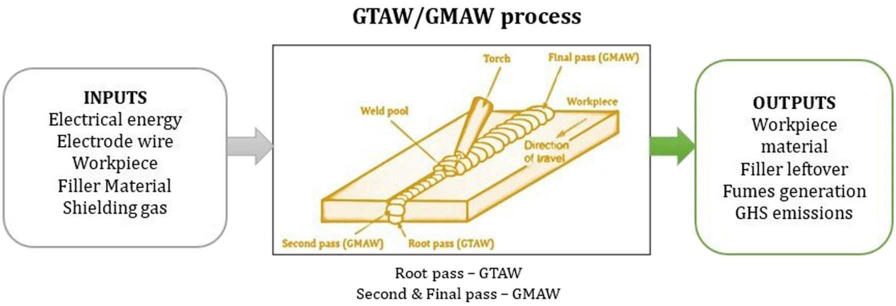

Figures 5.
GTAW/GMAW system boundary

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process, which include the consumable raw materials such as base metal, filler, shielding gas, and electrical energy as process inputs, as well as emission production, waste of raw materials, and consumable electrodes, without considering machinery.

The inventory data for the inputs and outputs of each welding process is obtained in the inventory analysis stage and it is based on the given system boundaries and the selected functional unit. The chemical compositions of the materials used (base metal and filler material) are obtained from the producer's data sheets. Fume emissions are calculated by using the emission rates representative processes from the reference literature (Rahmati *et al.*, 2022; Favi *et al.*, 2019; Knott *et al.*, 2023). Iron oxide fumes, nitrogen oxides, ozone, and carbon monoxide are selected as direct emissions into the environment. Electricity consumption is calculated using measured values and the equipment's wall-plug efficiency of 80%. To determine the amount of filler material used for MMAW, electrodes were weighted, and unused stubs were gathered. For GMAW and GTAW, the wire length and feed rate were measured.

To compare the impact of welding technologies on the metal industry, four factors were chosen: global warming potential (GWP100), eutrophication potential (EP), acidification potential (AP), and stratospheric ozone depletion (SOD).

Life cycle assessment

Life cycle assessment is an advanced tool for assessing the environmental impact of products and processes (Sangwan *et al.*, 2016; Alkahla and Pervaiz, 2017). It is a standardized methodology (ISO 14040), that is divided into four phases: goal and scope definition, life cycle analysis, life cycle impact evaluation, and iterative interpretation. In this article, this structure is adopted for the welding processes. The objectives of this LCA study are to demonstrate the ecological effects contributed by all the inputs and outputs of the chosen welding processes and to compare them. To compare the impact of welding processes, four indicators are chosen: global warming potential (GWP 100), eutrophication potential (EP), acidification potential (AP), and stratospheric ozone depletion (SOD). The functional unit is a 1m long weld seam of a 10 mm thick metal plate. The analysis was conducted using open-source software openLCA 1.11.0 and the Idemat2021 data set. To determine the environmental impacts, the CML2001 methodology is adopted.

Welding experiment details and data collection

Welding was carried out with three types of technologies: MMAW, GMAW, and a combination of GTAW and GMAW. The butt-welded joints are done to investigate the influence of different welding technologies and their different process parameters on the environment. The base metal for this study was non-alloyed structural steel with the designation S235JR, along with the appropriate filler material (wire and rods, shown in Table 1). Basic information on material and joint preparation is provided in Table 1.

The consumed material's chemical composition is known and sourced from the manufacturer. Welding samples were done on eighteen plates with a V-edge preparation and dimensions of 10 × 150 × 350 mm. All the plates were welded in a flat position. Three pairs of plates were used for each welding technology and were welded with varying parameters. Visual inspection of weld surface defects is the primary method for evaluating welding quality on industrial sites (Yan *et al.*, 2023). Therefore, a visual inspection was done to ensure that the welds were done properly. Figure 6 shows some of the successfully welded specimens using these three different welding technologies.

Basic data	MMAW	GTAW + GMAW	GMAW
Groove preparation	V (ISO 9692–1) $\alpha = 60^0$, d = 10 mm, c = 2 mm, b = 3 mm	V (ISO 9692–1) $\alpha = 60^0$, d = 10 mm, c = 2 mm, b = 3 mm	V (ISO 9692–1) $\alpha = 60^0$, d = 10 mm, c = 2 mm, b = 3 mm
Base material	S235 RJ	S235 RJ	S235 RJ
Filler material	ISO 2560-A E 35 0 RR 12	ISO 14341-A G 42 4 C/M 3Si1	ISO 14341-A G 42 4 C/M 3Si1

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Table 1.
Basic data of material and joint preparation

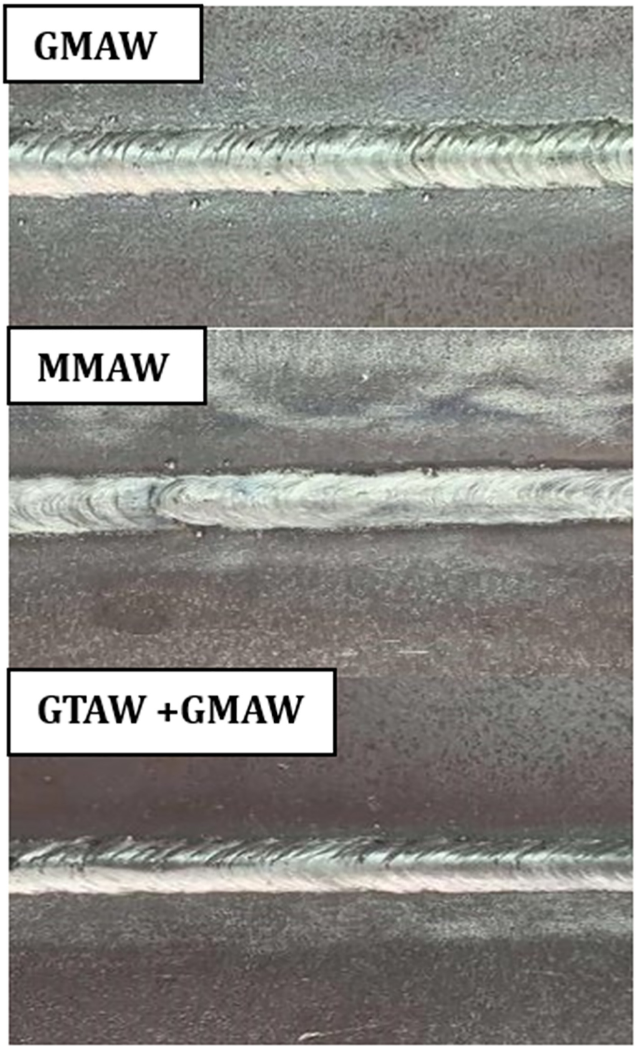

Figure 6.
Welded specimens using GMAW, MMAW, and GTAW + GMAW process

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After completing the welds successfully, several readings were collected, and the average value was reported and used in this study. Tensile and hardness test specimens with standard dimensions were prepared to measure the physical performance category indicators, as shown in Figure 7. A summary of the welding process parameters is shown in Table 2.

The welding time and process parameters are used to calculate electricity consumption and filler material consumption. The energy required for effective deposition efficiency can be calculated using the equation from the research paper (Sproesser *et al.*, 2016b). The fumes for all welding processes were calculated and used from the reference table in the article written by Quecke *et al.* (2023). The collected life cycle inventory data are summarized for all three technologies in Table 3.

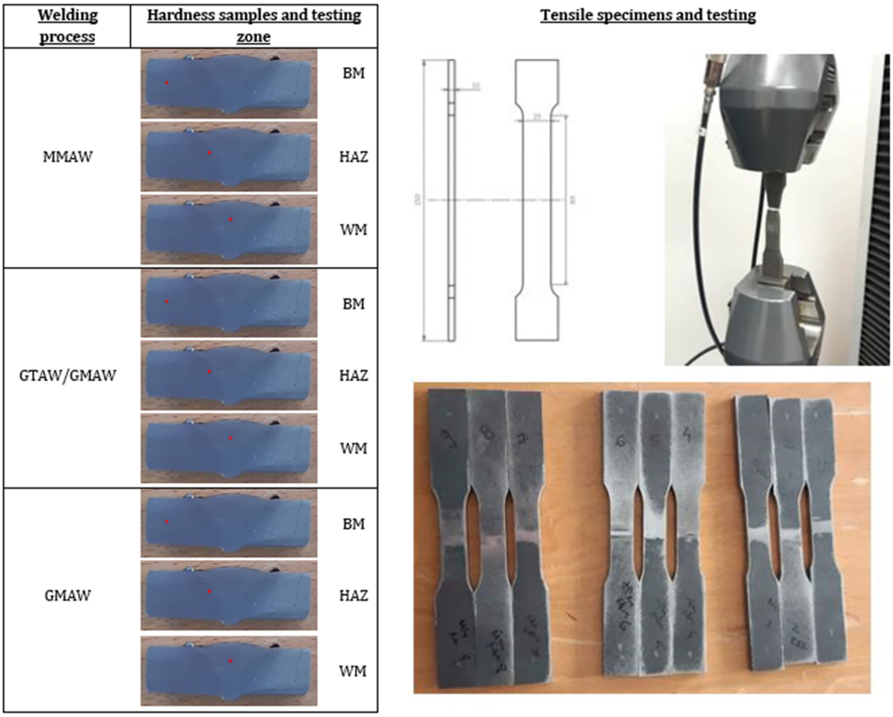

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Figure 7. Tensile and hardness testing samples

Welding process parameters	MMAW	GTAW + GMAW	GMAW
Wire feed rate in m/min	–	9	8.55
Welding speed in mm/s	3	5.7	6.1
Average power P_w in kW	4	9	8
Type of shielding gas	–	GTAW: 100% Argon GMAW: 82% Argon 18% CO_2	82% Argon, 18% CO_2
Contact tube to workpiece distance in mm	–	18	16
Number of passes	3	3	3
Welding fume emission (g)	4	5.5	6
Filler material consumption (g)	1,080	1,200	950
Shielding gas consumption (l/min)	–	10 + 11	12

Source(s): Table created by authors

Table 2. Welding process parameters

Results and discussions

Physical performance and environmental impact are the categories selected to evaluate and calculate the necessary indicators as input parameters for the assessment. In terms of physical performance, the indicators considered were yield stress and hardness. The tensile testing machine recorded the load and the extension values that were later used to calculate the stress and strain values for each sample. Figure 8 shows the yield stress results for each specimen, while Figure 9 shows the hardness test results for three specific locations: base metal (BM), heat-affected zone (HAZ), and weld metal (WM).

The yield stress obtained from welded specimens is greater than the yield stress of the base material, and all specimens are fractured in the base metal, indicating an overmatched welded joint. The decrease of yield stress in MMAW may be associated with the presence of voids, slag, or other defects. Also, it can be a result of grain growth. The hardness varies in the different zones of the welded joints within each welding case. For the MMAW and GMAW processes, the hardness value in the weld zone rises slightly, whereas, for GTAW + GMAW, this occurs in the HAZ zone. This may be related to structural changes in the weld during solidification, as well as the formation of defects caused by increased welding speed or current (see Figure 6).

The LCA analysis was conducted using the inventory data calculated and collected during the welding process. Figure 10 shows the results obtained on global warming potential (100 years), acidification, stratospheric ozone depletion, and eutrophication, which are chosen to demonstrate the environmental burdens caused by welding processes, for each plate separately.

According to the results, MMAW is the most damaging to the environment and contributes more than the other two welding processes. GMAW contributes the least when compared to both processes used in this investigation. The variations arise from differences in energy and material consumption. In MMAW, the most important compound that affects eutrophication and acidification is titanium dioxide, which accounts for nearly half of the

Table 3. Life cycle inventory data for the welding process

LCA input/output	MMAW	GTAW + GMAW	GMAW
Filler material consumption (g)	1,080	567	950
Shielding gas consumption (l/min)	–	180	323
Rutile consumption (g)	220	–	–
Energy consumption (kWh)	4.3	1.2	1.8
Welding fume emission (g)	19	3	5.2
Slag (g)	500	–	–
Electrode butt (g)	110	–	–

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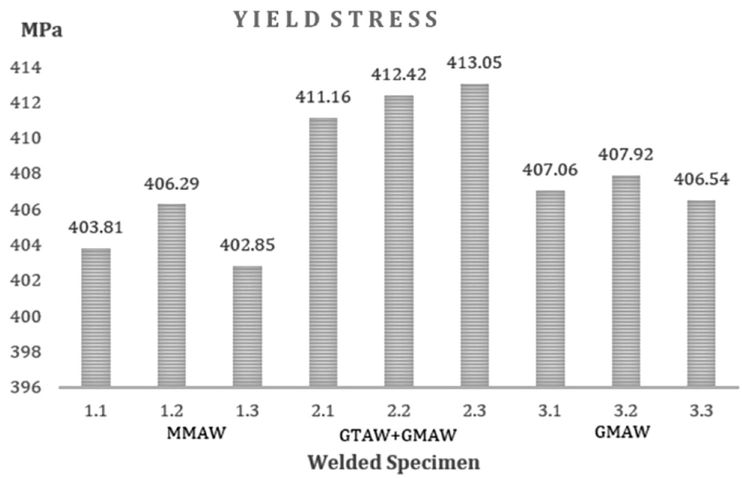

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Figure 8. Yield stress value for all tested specimens

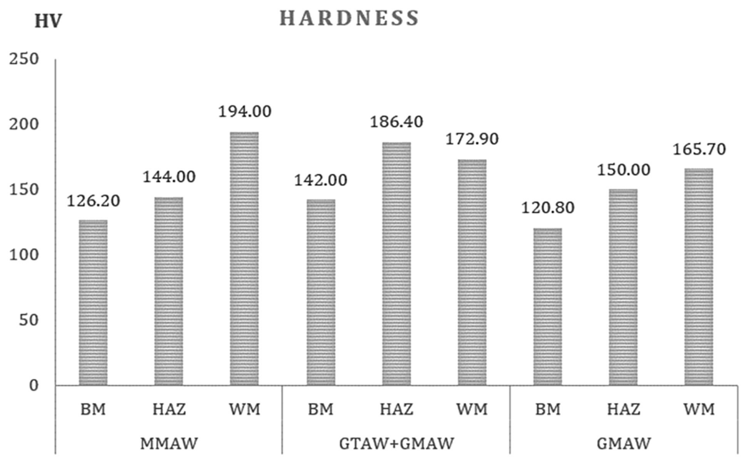

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Figure 9.
Hardness value for all tested specimens

coating. GMAW produces more fumes than MMAW and GTAW, possibly due to impurities in low-quality filler materials (Jamal *et al.*, 2020). There is a minor, almost negligible difference in the results obtained for each plate welded with different parameters. This is due to the welder's use of minimal variations in current and voltage and similar gas flow. Also, the material used is consistent, contributing significantly to the overall results.

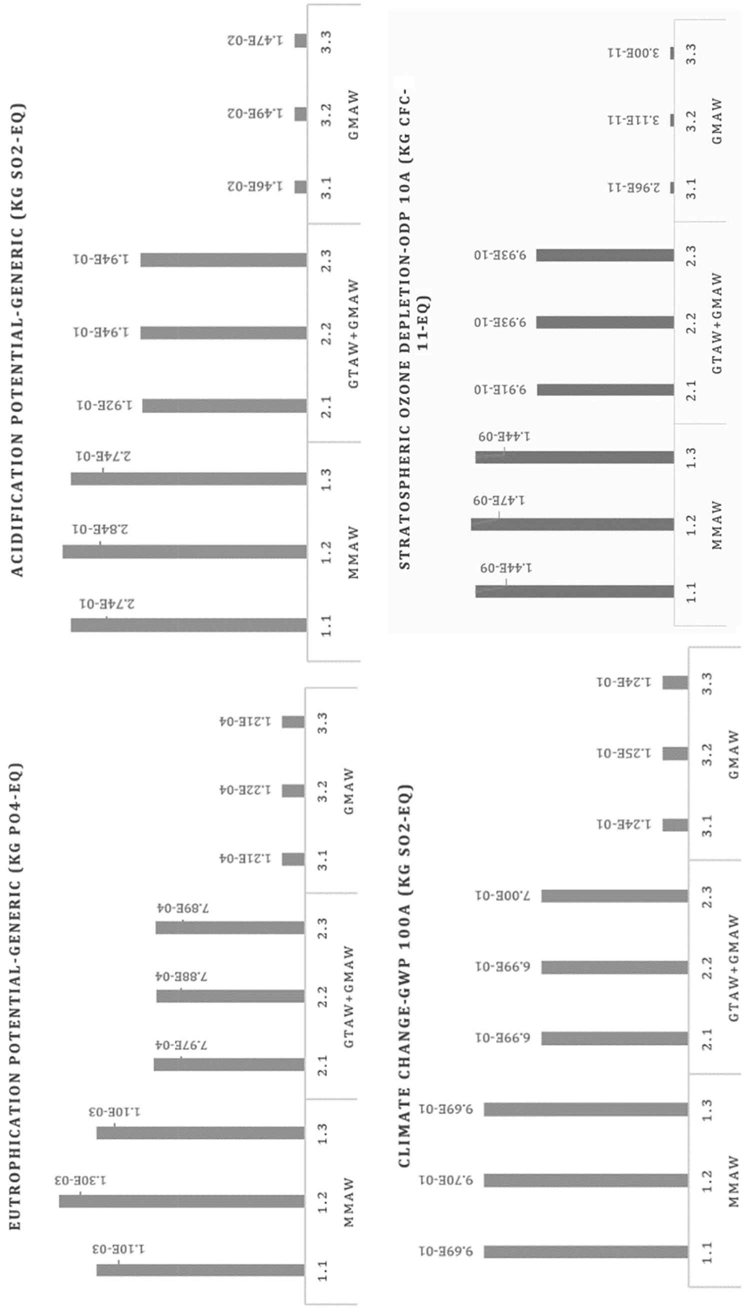
After analyzing all relevant indicators and findings of this study, it can be concluded that MMAW has the worst environmental impact. The combined processes demonstrate improved physical performance and a lower environmental impact than MMAW. This is because MMAW consumes more electrical energy and filler material. This process has lower efficiency, and the arc reaches extremely high temperatures that easily decompose the materials while emitting ultraviolet and infrared rays, and ion radiation which are very damaging to health and the ecosystem.

Conclusion

The current study characterizes the sustainability of welding processes based on a literature review and focuses on the LCA methodology approach for environmental impact assessment of commonly employed welding processes. The study relies on available literature and experiments to determine input parameters. The research has resulted in several conclusions:

(1) Sustainability is a useful methodology that can be applied to a variety of products and processes to reduce environmental impact, increase profits, and satisfy society. The triple-bottom-line theory, which addresses the social, environmental, and economic aspects of sustainability, is recommended by literature as a suitable method to perform a successful sustainability assessment. It is also recommended that the technological advancement category be added, as this is crucial for the long-term growth and competitiveness of manufacturers.

(2) The most important phase in implementing sustainability is to define the range of the sustainability assessment of the process, the categories, and indicators that should be relevant and measurable. This will prevent missing significant elements of the process that affect the quality and reliability of the assessment. The decision on a welding



Source(s): Figure created by authors

Figure 10.
Comparison of the environmental impact of different welding processes with varying parameters

process should be based on achieving effective high-quality welding for structural integrity but at the same time protecting the worker and environment.

(3) Welding process performance needs to be further investigated through LCA and SLCA analysis, and each performance should be scored and weighed by defined criterion. It is possible to compare the outcomes within each category and the values obtained on the assigned indicators can provide information on the advantages and disadvantages of a specific process used in production.

(4) LCA methodology is a promising technique that can give a fast overview of the effect on environmental sustainability. Several software packages and methodologies are available that can give reliable results. In this study, openLCA 1.11.0 is used, and it is observed that changes in the parameters of welding processes result in small changes in the output of the LCA analysis. The higher the welding current, the greater the material is melting; consequently, higher energy and material consumption contribute to higher pollution. Also, it should be acknowledged that the more the input data is used the more punctual the result will be. Factors such as mass and power source consumption, the amount of electricity used, the welding time, and the welder's experience and skills all contribute to the complexity of the analysis and results outcome. Collecting input data is a key stage, therefore experimental work is crucial, and accurate calculations and measurements should be applied.

(5) MMAW, GMAW, and GTAW/GMAW are commonly used welding processes that need further investigation into their influence on important matters such as global warming, acidification, eutrophication, and ozone depletion. In this study, results show a certain difference in the environmental burden of these welding processes that are affected not just by the process itself but also by the parameters used during the welding procedure. The findings indicate that MMAW is the most harmful process to the environment, while GMAW has the least impact. When physical performance was tested, the GTAW + GMAW process exceeded the other processes in yield stress, but the hardness was with minor differences. However, in terms of environmental impact, this process outperforms GMAW.

(6) Since the welds were only visually inspected, there is a chance that internal defects influenced the results. Also, the overall outcome may change if new equipment is used. Modern power electronics (inverter–based technology) can generate more productive, smoother, and more efficient output than traditional transformer-based sources (Alkahla and Pervaiz, 2017). The power sources for the welding in this study are outdated and use more energy. Innovative technology can deliver a more efficient and consistent supply of output power. As a result, the industry is strongly encouraged to avoid using outdated equipment and instead invest in new, more efficient equipment. On a long–term basis, this investment will save money, and by incorporating sustainability practices, they will protect the environment and their employees' health.

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