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Comparative Life Cycle Assessment of Swarf Cleaning Methods for Sustainable Manufacturing

Georgios Karadimas*, Emanuele Pagone, Konstantinos Salonitis

Sustainable Manufacturing Systems Centre, Faculty of Engineering and Applied Sciences, Cranfield University, MK43 0AL, UK

George.karadimas@cranfield.ac.uk*

Abstract

The metal manufacturing industry faces significant environmental challenges due to high energy consumption and waste production. This study critically analyzes two advanced swarf cleaning methods including supercritical CO_2 cleaning and Cryoclean to evaluate their environmental impacts. Using Life Cycle Assessment (LCA), the research compares these methods to determine their effectiveness in reducing CO_2 emissions and overall environmental impact. The results reveal that Cryoclean is the preferred method, slightly outperforming supercritical CO_2 cleaning in minimizing carbon emissions and ecosystem damage. This makes Cryoclean the more sustainable option for most industrial applications requiring effective, residue-free cleaning. Specifically, Cryoclean reduced CO_2 emissions by approximately 5% compared to supercritical CO_2 cleaning. The study also highlights the energy and resource efficiency of these methods, emphasizing their role in promoting sustainable manufacturing practices. By providing a detailed comparison of these cleaning processes, the study offers valuable insights into optimizing swarf recycling, thereby supporting the global shift towards more sustainable industrial practices. This research underscores the importance of adopting efficient swarf cleaning technologies to enhance the sustainability of metal manufacturing and meet environmental targets.

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Keywords: Swarf Cleaning, Supercritical CO_2, Cryoclean, Life Cycle Assessment;

1. Introduction

Aerospace manufacturing faces the critical challenge of balancing stringent quality standards with pressing environmental concerns. The industry's reliance on metal components significantly contributes to high energy consumption and waste generation, with metal production accounting for approximately 40% of emissions across the entire industrial sector and consuming 10% of global energy resources [1]. This issue is further compounded by the high buy-to-fly ratio in metal component production, which leads to considerable material wastage in the form of underutilized metal, creating an alarming environmental footprint [2].

The urgency for a transition to a sustainable circular economy model within the aerospace sector has never been more pronounced. Greenhouse gas emissions have surged fivefold over the past century, intensifying the need to address resource depletion and mitigate the adverse environmental impacts associated with conventional manufacturing processes [3]. The rising demand for metal elements, particularly steel, has driven a significant increase in the use of metal cutting fluids, complicating the sustainability narrative. Recent studies indicate that the production of steel chips is escalating, leading to a concerning accumulation of waste materials that, if inadequately managed, could contribute substantially to global warming and contaminate water resources with heavy metals [4].

Despite the growing body of research focused on the recycling of steel swarf, significant gaps persist in our understanding of effective cleaning methods for this waste materia [5, 6]. Current recycling techniques often involve high energy consumption and may result in further environmental degradation. For instance, methods such as powder metallurgy and hydrometallurgy have been explored, but they present

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several drawbacks, including the requirement for small-sized swarf and the generation of hazardous wastewater [7, 8]. Moreover, traditional cleaning methods that utilize chemical agents have been shown to produce considerable global warming potential impacts, highlighting the necessity for alternative, more sustainable approaches [9-11]. This is because global steel swarf production exceeds 2 million tons annually, and improving swarf cleaning could reduce waste by 30%, significantly minimizing material losses and environmental impact [11].

Alternative methods are used for swarf cleaning. Ultrasonic cleaning utilizes high-frequency sound waves to dislodge contaminants but requires high energy input, making it less efficient for large-scale applications [12]. Chemical cleaning effectively removes oils and residues but poses environmental and regulatory challenges due to hazardous waste generation [13]. Plasma cleaning, an emerging technology, uses ionized gases to break down contaminants, offering residue-free cleaning but at a high operational cost and limited industrial adoption [13].

These methods vary in efficiency, environmental impact, and feasibility, influencing their suitability for different industries. While ultrasonic and chemical cleaning are commonly used, advancements in dry and non-toxic cleaning technologies, such as SCC and Cryo-cleaning, are gaining preference due to their lower emissions and sustainability benefits [13].

This study aims to address these research gaps by critically analyzing two advanced swarf cleaning methods: supercritical CO_2 cleaning and Cryoclean. Through the application of Life Cycle Assessment (LCA), this paper seeks to evaluate the environmental impacts of these methods, emphasizing their effectiveness in reducing CO_2 emissions and enhancing overall resource efficiency. The comparative analysis will be conducted under a unified boundary, scope, and functional unit to ensure consistency and reliability in the results.

The research methodology involves a systematic evaluation of energy consumption, carbon emissions, and potential ecosystem damage associated with each cleaning method. By providing empirical data on the environmental performance of supercritical CO_2 cleaning and Cryoclean, this study aims to contribute valuable insights into optimizing swarf recycling processes. Ultimately, the findings are expected to support the aerospace industry's transition towards more sustainable manufacturing practices, aligning with global efforts to achieve environmental targets and promote a circular economy.

2. Goal and Scope Definition

This study evaluates the environmental impacts of Supercritical CO_2 Cleaning (SCC) and Cryogenic Cleaning (Cryo-cleaning) through a Life Cycle Assessment (LCA), following ISO 14040 and ISO 14044 standards [14,15]. The goal is to assess the environmental impact of each process for industrial use. SCC uses supercritical CO_2 to remove organic contaminants, while Cryo-cleaning employs cryogenic materials like liquid nitrogen or CO_2 pellets to dislodge contaminants without chemicals. The LCA considers upstream and downstream processes, following a gate-to-gate approach, considering only the swarf cleaning process including energy consumption and environmental impact, using SimaPro software with ReCiPe methodology. Key impact categories include global warming potential (GWP), human carcinogenic toxicity, and aquatic toxicity. In addition, the functional unit (FU) is defined as the cleaning of 1 kg of metal swarf to an industrially acceptable cleanliness level for reuse in manufacturing.

The ReCiPe methodology is a robust Life Cycle Assessment (LCA) approach that translates complex environmental data into clear impact categories, such as climate change, resource depletion, and human health impacts [15]. By applying ReCiPe, this study identifies key stages within SCC and Cryo-cleaning that contribute most to environmental degradation. This approach enables targeted strategies to minimize carbon footprints and enhance the sustainability of these cleaning methods for industrial applications.

2.1. System Boundaries

Both SCC and Cryo-cleaning are compared based on cleaning efficiency, energy consumption, and environmental impact. SCC is effective for organic contaminants with moderate energy consumption, while Cryo-cleaning excels at residue-free particulate removal but requires higher energy due to cryogenic temperatures.

SCC uses supercritical CO_2, achieving 96.2% oil removal with moderate energy consumption and CO_2 recycling, reducing emissions as seen in Table 1. Moreover, Cryo-cleaning relies on cryogenic substances, providing 98.8% cleaning efficiency, but with higher energy demand for cryogenic temperature maintenance. Both methods are industrial-ready, residue-free, and environmentally favourable, with SCC suited for deep cleaning and Cryo-cleaning for surface-level contaminant removal.

Table 1. Selected metal swarf cleaning methods [16,17].

Aspect	**Supercritical Cleaning (SCC)**	**Cryogenic Cleaning (Cryo-cleaning)**
Main Agent	Supercritical CO_2	Cryogenic substances (Liquid N2, Dry Ice Pellets)
Application Focus	Non-polar contaminants, oils, and organics	Particulates, surface debris, organic contaminants
Material Impact	Penetrates deeply into porous structures	Surface-focused, non-abrasive
Environmental Impact	Low (CO_2 is recycled within the system)	Low (No harmful chemicals or solvents used)
Typical Industries	Semiconductor, aerospace, medical devices	Aerospace, nuclear, semiconductor
Cleaning Depth	High (microstructure penetration)	Surface-level

Residue	None (recycling CO_2)	None (evaporation of cryogenic material)
Energy Requirement	Moderate (CO_2 compression)	High (maintaining cryogenic temperatures)
Cleaning Efficiency	96.2% oil removal	98.8% removal efficiency
Throughput	3 hrs/batch	10 tons swarf/hr
Chemical Usage	None	None
Energy Consumption	Moderate (CO_2 compression)	High (cryogenic temperature maintenance)
Global Warming Potential	Lower GWP, no VOC emissions	Minimal waste, no chemical residue
Maturity Level	Industrial-ready	Industrial-ready

SCC is more energy-efficient, particularly when used to remove organic contaminants, offering lower global warming potential due to the recycling of CO_2 within the system [16]. Cryo-cleaning, while energy-intensive due to the cryogenic cooling required, excels in applications where non-abrasive and residue-free cleaning is critical, such as in aerospace and semiconductor industries [17]. The LCA results indicate that both methods have unique advantages: SCC reduces chemical usage and emissions, while Cryo-cleaning is highly effective for particulate removal without chemical exposure risks.

Both Supercritical CO_2 Cleaning and Cryogenic Cleaning are effective alternatives to traditional chemical-based methods, each with distinct environmental and operational advantages [18]. SCC is particularly suited for processes requiring efficient organic contaminant removal with lower energy costs, whereas Cryo-cleaning provides superior particulate cleaning without the use of chemicals, albeit with higher energy consumption [19].

Finally, this gate-to-gate LCA includes cleaning processes, energy use, emissions, and waste management. CO_2 recycling efficiency is assumed at 95%, with ±5% energy consumption variation due to industrial differences. Minor emissions (<1%) and cleaning fluid losses (<0.5%) were excluded. Energy and emissions were calculated using Ecoinvent 3.9 data with the ReCiPe methodology in SimaPro.

3. Swarf Cleaning Analysis

3.1. Process Maps

In the cleaning of metal swarf, both SCC and Cryo-cleaning offer sustainable alternatives to traditional chemical-based cleaning methods. This study focuses on evaluating the environmental and operational efficiency of these two cleaning processes using LCA methodologies. Both processes target contaminants such as oils, greases, and particulates, preparing the swarf for reuse in industrial applications.

SCC involves the use of CO_2 in its supercritical phase to dissolve and remove organic contaminants. The process map in Fig. 1 outlines the flow of CO_2 from its supply in gas form through compression, heating, and injection into the cleaning chamber, where it dissolves contaminants. After cleaning, the CO_2 is separated from the contaminants and depressurized for recovery and reuse. The efficiency of the cleaning process is influenced by factors such as CO_2 pressure, temperature, and optional solvent use.



Fig. 1. Supercritical cleaning process map.

Cryogenic Cleaning, as illustrated in Fig. 2, uses cryogenic substances such as liquid nitrogen or CO_2 pellets to freeze and dislodge contaminants from the swarf. The process involves blasting the surface of the swarf with cryogenic material, causing contaminants to become brittle and separate due to thermal shock. The subsequent waste capture and ventilation system ensures safe removal of the dislodged particles and gases. The effectiveness of Cryo-cleaning depends on the cryogenic material flow rate and the impact pressure.

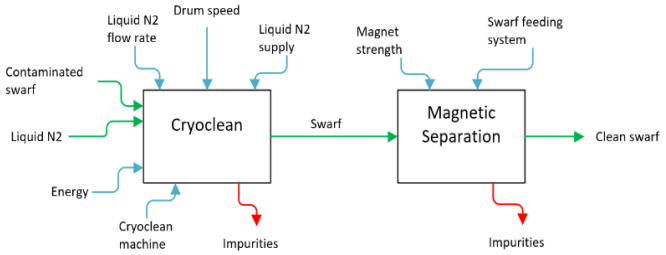


Fig. 2. Cryoclean process map.

Both SCC and Cryo-cleaning involve careful waste management and the use of environmentally friendly materials, reducing the need for harmful chemicals traditionally used in swarf cleaning. SCC's energy efficiency comes from the recycling of CO_2, whereas Cryo-cleaning requires higher energy input to maintain cryogenic temperatures but excels in the removal of particulates without chemical residues.

To ensure a more accurate comparison, both cleaning methods have been integrated with contaminant separation, as commonly applied in industrial recycling of swarf. Contaminant separation is critical for removing ferrous materials from the swarf, improving purity and making the swarf suitable for high-quality reuse in manufacturing applications.

3.2. Inventory Analysis

The inventory analysis is a critical component in the Life Cycle Assessment (LCA) of the swarf cleaning processes, aimed at quantifying the inputs and outputs at each stage of both SCC and Cryo-cleaning. Data for this analysis has been collected using standardized metrics such as the Material Utilization Factor, Energy Intensity, and CO_2 Footprint, sourced from established databases like Ecoinvent, Granta EduPack 2024, and literature. The environmental impacts at each stage are calculated using the following equations:

$$Minput = Mproduced \times Ufactor \quad (1)$$

$$Econsumed = Mproduced \times Ienergy \quad (2)$$

$$CO_2,eq = Mproduced \times ICO_2 \quad (3)$$

The equations used in this study quantify key metrics for evaluating the swarf cleaning processes. The Input Material Mass (Minput) represents the total raw material required, calculated as the product of the produced material mass (Mproduced) and the Material Utilization Factor (Ufactor), which reflects material efficiency. The Energy Consumed (Econsumed) accounts for the energy demand, determined by multiplying the produced material mass by the Energy Intensity Factor (Ienergy). Lastly, the Equivalent CO_2 Emission (CO_2,eq) evaluates the carbon footprint, derived from the produced material mass and the CO_2 Intensity Factor (ICO_2). These metrics provide a clear framework for comparing material efficiency, energy consumption, and environmental impact between the cleaning methods. The input and ouptut datta were collected fro literature and energy consumption and CO_2 emissions were calculated using process-specific data from Ecoinvent 3.9, applying the ReCiPe methodology in SimaPro.

Table 2. Cryoclean process inventory data.

Process Step	Input Data	Value	Output Data	Value	References
Degreasing	Energy (MJ)	0.014	Cleaned swarf (kg)	1.03	[22]
	Liquid N_2 (kg)	0.155	Dislodged contaminants	Varies (oil, debris)	[20]
	Swarf (kg)	1.03	Waste gases (evaporated N_2)	0.155 kg	[21]
Magnetic Separation	Energy (MJ)	0.82	Separated swarf (kg)	1	[22]
	Swarf (kg)	1.03	Ferrous waste (kg)	0.03	[21]

Table 3. Supercritical cleaning inventory data.

Process Step	Input	Value	Output	Value	References
CO_2 Supply & Compression	CO_2 (kg)	0.0093	Compressed CO_2 (kg)	0.0093	[20]
	Electricity (MJ)	16.3	-	-	[23]
Heating & Solvent Addition	Water (kg)	0.00037	Supercritical CO_2 (kg)	0.0093	[20]
	Ethanol (optional, kg)	9.6E-05	-	-	[20]
	Electricity (MJ)	0.75	-	-	[23]
CO_2 Injection into Chamber	Supercritical CO_2 (kg)	0.0093	Cleaned swarf (kg)	1	[20]
	Swarf (kg)	1	Contaminant-laden CO_2 (kg)	0.0093	[21]
Contaminant Separation	Contaminant-laden CO_2 (kg)	0.0093	Cleaned CO_2 (kg)	0.0093	[20]
	-	-	Separated contaminants (kg)	0.000054	[20]
CO_2 Depressurization & Recovery	Cleaned CO_2 (kg)	0.0093	Recycled CO_2 (kg)	0.008835	[20]
Waste Disposal	-	-	Contaminants (oil, particles, kg)	0.00075	[20]

SCC relies on the compression and heating of CO_2, which results in a higher overall energy consumption per cycle compared to Cryogenic Cleaning. However, the CO_2 is recycled within the system, significantly reducing waste and emissions, while also making the process more energy-efficient in terms of resource usage. SCC is best suited for non-polar contaminant removal, and the closed-loop recycling system ensures sustainability with minimal CO_2 loss (<5%).

Cryogenic Cleaning, although requiring less energy for cryogen delivery (0.873 MJ per cycle), depends heavily on the production and use of nitrogen, which is not recyclable. After use, the nitrogen sublimates into gas and is vented, increasing resource consumption but with lower direct energy demands. The overall energy consumption in Cryogenic Cleaning is lower than SCC due to the absence of the energy-intensive CO_2 compression stage. Cryogenic Cleaning is particularly effective for applications where residue-free, particulate cleaning is essential, though it generates slightly more solid waste than SCC.

4. Life Cycle Assessment

The environmental impacts of Supercritical CO_2 Cleaning (SCC) and Cryogenic Cleaning (Cryo-cleaning) were systematically evaluated to determine the sustainability and resource efficiency of each method in industrial swarf cleaning applications. Using the ReCiPe methodology within SimaPro 9 software, this study analyzed inventory data including energy consumption, material usage, and process-specific emissions to assess the life cycle impacts of both cleaning processes. The focus of this evaluation centers on key impact categories, namely global warming potential (GWP), human carcinogenic toxicity, freshwater toxicity, marine toxicity, and human non-carcinogenic toxicity. These categories were selected to provide a balanced view of each method's ecological and health-related impacts.

Moreover, the sections below present a comparison of SCC and Cryogenic Cleaning across these midpoint and endpoint

categories, illustrating the strengths and limitations of each process. The results provide insights into the environmental trade-offs associated with each method, highlighting areas where process optimization could further enhance sustainability and reduce environmental impact.

4.1. Midpoint Results

The midpoint analysis provides an in-depth assessment of the environmental impacts associated with Supercritical CO_2 Cleaning (SCC) and Cryogenic Cleaning, focusing on specific impact categories that represent potential ecological and human health effects. This approach allows for a granular examination of how each process contributes to key environmental stressors, such as global warming potential (GWP), human carcinogenic toxicity, freshwater toxicity, marine toxicity, and human non-carcinogenic toxicity. By isolating these impact categories, the analysis identifies areas where resource usage, energy demand, and emissions are most significant for each method. This evaluation is crucial for understanding the relative strengths and weaknesses of SCC and Cryogenic Cleaning, particularly regarding their resource efficiency, potential health risks, and overall environmental footprint.

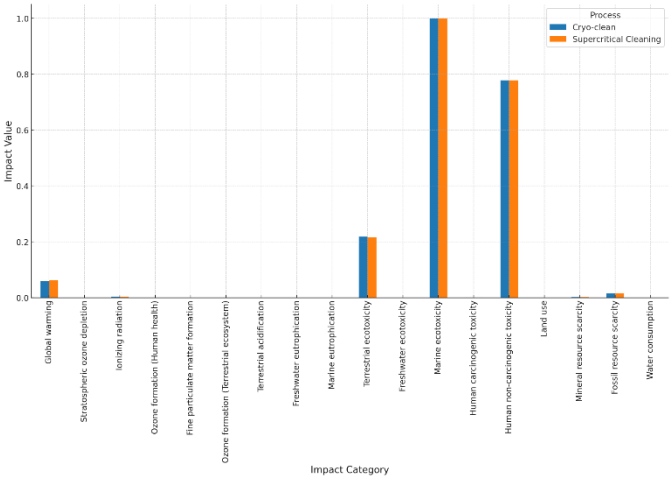


Fig. 3 Midpoint analysis results.

SCC displays a marginally higher impact in Global Warming Potential (GWP) and Human Carcinogenic Toxicity. This is primarily due to SCC's reliance on energy-intensive CO_2 compression and heating processes. Although SCC effectively minimizes chemical waste through CO_2 recycling, its energy requirements contribute significantly to greenhouse gas emissions and pose potential health risks associated with carcinogenic compounds.

In contrast, Cryo-clean exhibits a more substantial impact in the categories of Fossil Resource Scarcity and Ionizing Radiation. This reflects the environmental burden of producing and consuming nitrogen, as well as the lack of a recycling mechanism for cryogenic material, which results in single-use nitrogen consumption. Consequently, while Cryo-clean is effective in reducing direct chemical emissions, its resource usage profile indicates a more pronounced depletion of non-renewable resources.

Overall, the midpoint analysis in Figure 3 highlights the environmental trade-offs between the two methods. SCC's higher energy demand contributes to its impact on global warming and human health risks, whereas Cryo-clean's reliance on nitrogen increases its resource intensity, especially in fossil fuel depletion. These insights underscore specific areas where each method could be optimized to reduce its environmental footprint, offering pathways for improvement in energy efficiency and resource sustainability.

4.2. Endpoint Results

The endpoint analysis broadens the environmental impact assessment by examining the overarching effects of Supercritical CO_2 Cleaning (SCC) and Cryogenic Cleaning across three main areas: human health, ecosystem quality, and resource use. This analysis synthesizes the midpoint impact categories into a higher-level view, providing insights into the cumulative effects of each cleaning process on environmental and human well-being. By focusing on these endpoint categories, the analysis highlights the resource demands, potential ecosystem disruptions, and human health implications associated with each method. This approach offers a comprehensive understanding of the trade-offs involved, capturing the broader environmental implications and long-term viability of SCC and Cryogenic Cleaning in industrial applications

The endpoint results chart in fig. 4 sums the environmental impacts into the broad categories of Human Health, Ecosystem Quality, and Resource Use, providing a big-picture view of the environmental implications of each cleaning method. Supercritical CO_2 Cleaning shows higher impacts across all three endpoint categories, particularly in Resource Use. This outcome is largely due to SCC's reliance on closed-loop CO_2 compression and heating, which, while mitigating CO_2 emissions through recycling, increases resource demand and cumulative energy use.

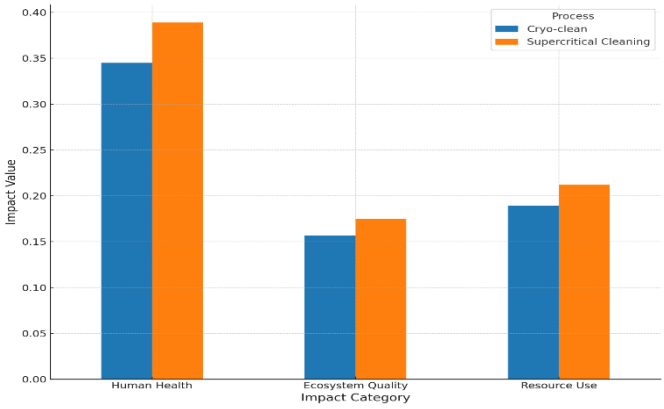


Fig. 4. Endpoint analysis results.

In addition, the chart suggests that SCC's energy profile, although beneficial for waste minimization, places a strain on resource availability, making it less sustainable in high-resource consumption environments. Conversely, Cryo-clean demonstrates relatively balanced impacts across these categories, with lower scores in Resource Use due to the single-

use nature of nitrogen. However, its lack of recycling elevates other environmental burdens, such as its fossil fuel reliance.

These endpoint results point to critical trade-offs: SCC offers sustainability benefits through CO_2 recycling, but with a heavier resource burden, while Cryo-clean's lower overall footprint in resource usage positions it as favourable in settings where resource conservation is prioritized.

5. Conclusion

This study assessed the environmental impacts of SCC and Cryo-cleaning as sustainable alternatives for swarf recycling in aerospace manufacturing. Through LCA, SCC demonstrated clear benefits in reducing Global Warming Potential (GWP) and Human Carcinogenic Toxicity by effectively recycling CO_2, minimizing emissions, and reducing chemical use. However, SCC's reliance on energy-intensive CO_2 compression and heating increases its resource demand in Resource Use, limiting its sustainability in resource-sensitive applications. In contrast, based on the comparative analysis, Cryo-cleaning is identified as the better overall option due to its superior residue-free cleaning efficiency and lower direct energy consumption, despite its reliance on single-use nitrogen. These findings position Cryo-cleaning as the preferred choice for sustainable metal manufacturing, particularly in applications prioritizing effective contaminant removal with minimal chemical usage.

Future research should focus on advancing both methods for improved energy efficiency and reduced resource dependency and include a full sensitivity analysis, allowing to assess the impact of variability in energy use and material efficiency. For SCC, optimizing CO_2 compression and recovery, potentially through enhanced solvent efficiency or alternative energy sources, could further mitigate its resource impact. For Cryo-cleaning, developing nitrogen recycling mechanisms or sourcing nitrogen from renewable production methods could reduce its fossil resource impact and improve environmental performance.

To expand the applicability of these findings, further studies should explore the scalability of SCC and Cryo-cleaning in diverse industrial settings beyond aerospace, assessing adaptability across various contaminants and substrate materials. Integrating these cleaning methods into a broader sustainable manufacturing framework aligns with circular economy principles, offering pathways to significant reductions in environmental impact and resource consumption in high-precision manufacturing sectors.

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