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Efficient and Sustainable Cleaning: A Comparative Analysis of Cryogenic Technology

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Abstract: Dry ice blasting is a technology that has been widely studied and applied in different industrial sectors as an alternative to the use of solvent, water, or abrasive spraying methods. It is a CO_2 spraying system capable of balancing efficiency and sustainability with a wide variety of equipment available on the market. This study analyses and compares cryo-cleaning equipment manufactured by pioneering companies in the cryogenic industry. Based on data sheets, safety data sheets, and contact with manufacturers, a quantitative comparative study has been carried out. The aim of this study is to identify those with the best performance, efficiency, and adaptability to operational and environmental requirements. The results reflect the strengths and weaknesses of the equipment in terms of occupational safety and operability. These have been discussed and evaluated, recognising improvements of this technology, which is capable of removing surface layers of different natures without altering the underlying substrate.

Keywords: dry ice blasting; snow blasting; eco-efficiency; ecological transition; SDG 6; SDG 9; SDG 11; SDG 12; SDG 13; SDG 14; SDG 17

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1. Introduction

The use of dry ice blasting technology for surface cleaning has been investigated since 1945 by the US Navy as a degreasing system and was introduced into the market during the 1980s [1] for a variety of uses and applications [2]. The dry ice blasting system is based on three mechanisms that contribute to breaking the bond between the contaminant and the substrate from which it is to be removed: thermal shock by cooling the surface, kinetic energy from the use of compressed air, and sublimation of the pellets used [3]. The advantages of the system compared to other surface contaminant removal methods have been extensively analysed [4–8], with a focus on environmental and operational aspects. First is its eco-sustainability, as the CO_2 used is recycled, which reduces the use of large quantities of water and avoids the use of environmentally polluting and health-hazardous solvents. Second, it ensures surface safety, as it is not an abrasive system; the pressure required is reduced compared to other projection systems, and the pellets used have a very low hardness. Third, its versatility allows for adjustments according to the parameters used. Fourth, it is highly adaptable to sensitive surfaces and complex geometries. Finally, the system is simple, as it is not necessary to remove any residues from the surface, which is completely dry at the end of the treatment.

Cryo-cleaning is an established technology in many industries, and interest in its use continues to grow [6]. Leading dry ice blasting machine manufacturers promote the technology for its many benefits. Its characteristics make it ideal for the cleaning and maintenance of production lines and equipment in various industries, extending their useful life.

In addition, it has applications in sectors such as plastics and rubber manufacturing, metal casting, energy companies, food processing plants, surgical instrument and equipment manufacturing, printing, paint and adhesive factories, and vehicle manufacturing. It is also effective for the periodic cleaning of air conditioning systems and public transport fleets, as well as for the conditioning of private vehicles. In addition, it is useful in the remediation of the effects of fires and floods, removing smoke, carbonaceous particles, moulds, and the odours derived from these situations (see Table 1).

Table 1. Application studies of dry ice blasting and snow blasting for surface cleaning in different industrial sectors.

Industrial Sector	Need for Cleanliness	Object or Surface Treated	Type of Dirt or Waste	References
Manufacturing of plastics, rubbers, and foams	Disposal of waste in moulds and other machines in the manufacturing lines, such as mixers, extruders, and injectors	Metal and plastic surfaces	Waste mould release agents, adhesives, and synthetic polymer residues	[3,6,9–11]
Energetics	Cleaning of gas and steam turbine engines and other rotary engines and dynamoelectric machines	Metal and plastic surfaces	Oils, combustion deposits, and chemical residues	[6,11,12]
Oil	Cleaning of sucker rods, tanks, and pipelines	Metal surfaces	Heavy oils, paraffin, fouling, and asphaltenes	[11,13]
Nuclear decontamination	Cleaning of various elements in nuclear plants, e.g., electric motors, valves, ventilation ducts, pipes, machinery, and electrical equipment	Metal and plastic surfaces	Radioactive particles	[6,12]
Air conditioning	Heating, ventilation, and extraction duct maintenance	Hollow metal and plastic pipes	Grease, oil, and dust	[6,14]
Maintenance of electrical systems	Elimination of pollutants in a wide range of electrical systems	Various	Environmental dust of organic and mineral nature	[6,9,11,15,16]
Aerospace and shipping	Cleaning of engines, electrical systems, and paint stripping	Metal and plastic surfaces	Environmental dust of organic and mineral nature, soil, corrosion fouling and oxides, and old paintwork	[6,11,17–20]
Automotive	Cleaning of welding robots	Metal surfaces	Remains of slag, epoxy resin, and other adhesives	[6,21]
	Repair and overhaul of engine parts	Metal and plastic surfaces	Silicone gaskets	[3,6]
	Vehicle renewal	Bodies and metal parts	Rust and dirt in confined spaces	[22]
	Preparation of plastic surfaces of different vehicle parts for painting	Polypropylene (PP)Unsaturated glass fibre-reinforced polyester resin (SMC)Acrylonitrile butadiene styrene (ABS)	Surface dirt	[8,11,23]
	Pre-treatment to improve adhesion of epoxy and polyurethane resins and to improve the properties of galvanised surfaces	Aluminium seals, steel and titanium sheets, and galvanised surfaces	Environmental contamination, lubricants, and zinc ashes	[2,6,11,24,25]
	Paint stripping	Steel	Automotive primer and paint	[2]
	Various cleaning and processing applications	Vehicle components	Various	[26]
	Cleaning of robotic arms and workstations in automotive manufacturing	Metal and plastic surfaces	Welding residues, grease, and general soiling	[27]
Railway	Removal of pollutants from railway tracks	Metal rails	Organic leaf debris, mud, carbonaceous particles, and ferric oxides	[7,11]

Table 1. *Cont.*

Industrial Sector	Need for Cleanliness	Object or Surface Treated	Type of Dirt or Waste	References
Road maintenance	Semi-automated stripping of road markings on highways	Asphalt surfaces and other pavements	Pavement paints	[28]
Printers	Cleaning of presses, rotary presses, and other production equipment	Metal surfaces	Ink and adhesive residues	[11]
Leather tanning	Shaving or liming and de-shelling of the skin	Leather	Organic and inorganic waste	[8,29]
Food industry	Cleaning of ovens, roasters, packers, wine barrels, coffee roasting chambers, distilleries, and other elements in processing and packaging lines	Metal and plastic surfaces	Various natural organic products such as oil, waxes, charcoal, corn, coffee, and other protein wastes	[8,11,12,22,23,30]
	Disinfection of wine barrels and dairy equipment	Metal and wood surfaces	Organic and microbiological remains	[23,31,32]
Poultry industry	Cleaning of production channels	Metal and wood surfaces	Removal of organic contamination	[8,33]
Conservation and restoration of cultural heritage	Graffiti removal	Granite and architectural surfaces	Synthetic spray paint	[34]
	Marquetry cleaning	Wood	Environmental dust and varnishes	[35]
	Cleaning of metal surfaces	Aluminium, bronze, steel, brass, and copper	Environmental dusts of organic and mineral nature, corrosion, spray paint, and waxes	[36–38]
	Cleaning of ceramic objects	Ceramics	Environmental dust of organic and mineral nature	[39]
	Sculpture cleaning	Polyester and cellulose acetate butyrate (CAB)	Environmental dust of organic and mineral nature, fingerprints, and surfactant migrations	[40,41]
	Paper cleaning	Paper (cotton and wood)	Environmental dust of organic and mineral nature	[42]

Source: Own analysis based on the publications referred to in each case study.

The configuration of most commercially available dry ice blasting equipment focuses on fast, efficient, economical, and environmentally friendly cleaning [1]. This technology aims to remove hard concretions on large, regular and irregular substrates in short timeframes at a low cost and in compliance with the climate neutrality pact [43]. This approach translates into specific goals, such as ensuring worker safety or minimising the impact of the process on serial production by reducing waste and by-products derived from cleaning [6]. The management of the non-volatile residue deposited on the surface is addressed without the need for a second washing treatment or material replacement, thus eliminating associated challenges, such as those found in processes that use soaps and solvents, as well as sandblasting [44].

Several studies confirm the versatility of the system, which can be adjusted by varying the main parameters, including compressed air pressure, granule feed rate, granule size, and nozzle type [2,5,6,11]. In this way, they can be adapted to very delicate surfaces, such as electronic systems [15], even with complex geometries [12]. The range of materials to be removed is very diverse [11], both organic, e.g., heavy oils in storage tanks [13], and inorganic, e.g., corrosion layers on metals [7,36]. Furthermore, some applications demonstrate the possibility of very selective cleaning of extremely delicate materials [41]. However, they also point out the limitations of the system, including the high energy cost of the required compressors; degradation of the CO_2 pellets with use and storage, especially in lathes with high relative humidity; and the high level of noise emitted during use. This led to the recommendation that, in certain situations, they can be combined with other conventional mechanical cleaning systems [6].

Technical data are paramount to optimise costs and ensure operational efficiency in a variety of industrial contexts. Furthermore, maximising the economy in cryo-cleaning not only involves assessing the intrinsic performance of each piece of equipment according to its specific application and needs but also demands the adoption of efficient processes and practices. These must be based on a framework of optimal working conditions derived from meticulous scientific studies using specific methodologies to examine and improve the effectiveness of cryo-cleaning. This evaluation includes detailed analyses of the physico-chemical and mechanical properties of the materials to be cleaned.

While previous studies have extensively analysed the advantages of dry ice blasting, focusing on its environmental benefits [44] and operational efficiency [23,25], there is a gap in the literature regarding a standardised comparative evaluation of the currently available cryo-cleaning equipment. Leading manufacturers promote the technology for its numerous benefits, but the diversity of available equipment and their varied applications necessitate a detailed comparative analysis. Several studies confirm the system's versatility [5,6,12], allowing adjustments to the main parameters for delicate surfaces and complex geometries. However, these studies also highlight limitations such as high energy costs, degradation of CO_2 pellets, and significant noise levels [6], suggesting a need for integration with other cleaning systems.

Our study aims to fill this gap by providing an objective comparative evaluation of the cryo-cleaning equipment currently available on the market. We will use a standardised scoring system to assess their performance, efficiency, and sustainability. The specific objectives include analysing technical specifications, defining selection criteria to meet operational and sustainability requirements, comparing pre-existing and derived scores, and identifying the best-performing machines. This comprehensive evaluation will offer valuable insights for industries looking to adopt or optimise their use of cryo-cleaning technology.

The main objective of this study is to provide an objective comparative evaluation of the cryo-cleaning equipment currently available on the market through a standardised scoring system, assessing their performance, efficiency, and alignment with sustainable practices. From this main objective, the following specific objectives are also derived:

1. Analyse the technical specifications and sustainability characteristics of a selected range of cryo-cleaning equipment;
2. Define the criteria to be considered when selecting cryo-cleaning equipment to ensure that both operational and sustainability requirements are met;
3. Compare and contrast the pre-existing and derived scores of the selected equipment to assess their relative performance;
4. Identify machines that offer the best performance, efficiency, and adaptability to operational and environmental needs.

2. Materials and Methods

The methodology employed comprises a mixed and multifaceted approach, combining quantitative and qualitative methods to provide a comprehensive and detailed assessment of cryo-cleaning equipment in relation to sustainability. The type of methodology used at each step is detailed below.

2.1. Bibliographic Review (Qualitative and Systematic Methodology)

The initial phase of this study was based on a systematic and qualitative literature review. A critical analysis was conducted across 252 documents selected for their relevance in compiling and synthesising the existing body of knowledge in the field of cryo-cleaning. The spectrum of sources examined included peer-reviewed academic publications, specialised technical reports, case studies, and grey literature contributions. The search was carried out using prestigious academic databases, with Scopus as the main reference.

The selection strategy was based on an articulated set of keywords and search phrases chosen for their relevance and ability to comprehensively cover the field of study. Terms such as 'cleaning', 'cryogenic', 'dry ice blasting', 'sustainability', 'innovation', 'technical sheet', and 'report' were used to filter and retrieve relevant information. Additionally, the search was restricted to specific disciplines, such as engineering, materials science, energy, chemistry, chemical engineering, and environmental sciences, to ensure proper contextualisation of the findings.

2.1.1. Selection of Equipment

National and international companies specialising in the provision of dry ice blasting services are focused on a market that ranges from the specific design and installation of customised equipment to the sale and rental of standardised blasting machines, pelletisers, granulators, and CO_2 collectors, as well as treated and projectable raw materials. This study includes cryo-cleaning equipment from a variety of companies, featuring a wide range of features—from compact, portable units to more robust, higher-capacity solutions suitable for a range of industrial applications. Specifically, 19 units from leading brands manufactured by Karcher® (Kärcher España, Barcelona, Spain), Polartech® (Polartech, Odense, Denmark), Cold Jet® (Cold Jet, Loveland, OH, USA), Intelblast® (Intelblast SL, Barcelona, Spain), Cryoblaster® (Cryoblaster, Frontonas, France), Cryonomic® (Artimpex nv, Gent, Belgium), Cryosnow® (CryoSnow GmbH, Berlin, Germany), and White Lion® (White Lion GmbH, Hesse, Germany) were evaluated.

The companies selected for this study were chosen based on several criteria. Firstly, the companies were evaluated for their technological impact and leadership in innovation in the development of dry ice blasting devices. Karcher®, for instance, is a renowned company in the cleaning and maintenance sector, setting quality standards in domestic and industrial settings. Additionally, the reputation and use of Cold Jet® equipment by leading companies like 3M, Apple, Bayer, Frito Lay, Johnson and Johnson, Nike, and Siemens highlight the reliability and efficiency of this equipment. Furthermore, the recent patents obtained by Polar Tech® for new snow blasting and dry ice blasting equipment demonstrate their commitment to technological innovation. Companies such as Intelblast®, Cryonomic®, Cryoblaster®, and White Lion® were selected for their diversification and significant market presence, offering a variety of technologies for comparison. Finally, the fact that CryoSnow® owns national and international intellectual property rights demonstrates its relevance and ability to innovate.

2.1.2. Analysis of Equipment Data Sheets (Qualitative and Analytical Methodology)

This segment of the study is characterised by its analytical and qualitative approach, orientated towards the evaluation of the technical specifications and sustainability attributes of the cryo-cleaning equipment. A detailed and comparative assessment of their performance was achieved by analysing the relevant data sheets.

2.1.3. Collection of Data Provided by the Manufacturer (Qualitative and Exploratory Methodology)

The purpose is to collect specific and up-to-date information that is not publicly available. Direct collaboration with companies ensures that the data collected is accurate and representative of current practices and technologies. This method allows for specific and contextualised insights that may not be present in the published literature.

2.2. Comparative Analysis of Cryo-Cleaning Equipment (Quantitative Methodology)

The developed scoring system is based on a standardised scale divided into 5 segments, where value 1 is the least favourable condition and value 5 is the most favourable, allowing for direct comparisons between different models and brands. The comparative ranges were established from the data collected in Section 2.1, establishing the minimum values (α), maximum values (β), and the size of the interval (I) for each criterion. In order to provide a thorough and accurate evaluation of equipment, it is vital to take into account a range of operational factors that can influence the performance and efficiency of the equipment in question. The assessment of operational parameters must consider the requisite manoeuvrability and spatial requirements for both operation and storage. In addition, the power source must meet the defined technical requirements and offer the flexibility to be located at a convenient and appropriate site; furthermore, the evaluation of energy resources must be conducted in order to determine the available supply. The efficiency of cleaning operations and the energy demand of the process are both influenced by the pressure and volumetric air flow. The acoustic pressure level is of relevance with regard to its impact on the work environment and safety requirements. The tank capacity of a given piece of equipment determines the operational autonomy and frequency of refilling. The diameter of pellets affects the efficiency of cleaning and the applicability of the equipment on different surfaces. The consumption of dry ice and liquid CO_2 impacts the operational costs and environmental impact of the equipment, while the liquid pressure influences the efficiency of cleaning and the technical requirements of the equipment. Finally, the weight of the equipment without accessories affects its portability and ease of use. Evaluating these aspects allows for a thorough understanding of each piece of equipment, considering its technical requirements, environmental impact, and operational costs.

The specific criteria applied were as follows:

- Dimension of the equipment;
- Weight without accessories;
- Power supply;
- Power consumption;
- Sound pressure level;
- Tank capacity;
- Air pressure;
- Variability of air volume flow rate;
- Pellet size variability;
- Pellet size.

2.2.1. Scoring Methodology

The pre-existing scores come from data sheets and information provided by the manufacturers. The numerical data were normalised with respect to the maximum (β) and minimum (α) values. This normalisation allows for fair and relative comparisons between devices, regardless of absolute differences in their technical specifications.

The derived scores were calculated by applying conditional formulae to the technical characteristics of the equipment and the criteria evaluated. These rules were designed to reflect operational efficiency and sustainability, with the highest scores given to features that promote efficiency and reduce environmental impact. In this sense, some criteria with higher values could be unfavourable. For example, higher CO_2 consumption results in higher environmental impact and lower efficiency. Conversely, efficiency and cleaning capacity increase with a higher air pressure range. Therefore, the derived scores were calculated accordingly. The value of I (iota) in the formulae presented is crucial to normalise and compare different operating parameters of the cryo-cleaning equipment. This value is calculated from the minimum (α) and maximum (β) values recorded for each criterion evaluated by applying the formula below:

$$I = \frac{(\beta - \alpha)}{5}$$

This formula allows the total range of possible values for a specific criterion to be divided into five equal intervals. The purpose is to assign comparative scores based on these ranges, thus facilitating a fair evaluation between different machines.

The minimum (α) and maximum (β) values used to calculate I come from the data sheets and information provided by the manufacturers about the assessed equipment. These sources include detailed data on the technical and operational characteristics of the equipment, such as dimensions, air pressure, volumetric flow rate, sound pressure level, tank capacity, pellet size, CO_2 consumption, and weight without accessories. The information was collected from manufacturers such as Cryosnow® and Polartech®, among others.

To illustrate the calculation of I, let us consider the air pressure criterion. If the minimum and maximum values recorded are 6 and 50 bar, respectively, the I value would be calculated as follows:

$$I = \frac{(50 - 6)}{5} = 8.8 \text{ bar}$$

These ranges are applied in conditional formulas to assign scores that reflect the operational efficiency and sustainability of the equipment.

The scoring methodology uses these ranges to rank machines on a scale of 1–5. Depending on the criterion assessed, two assumptions are applied:

Assumption A: When the most favourable condition (5) is close to the minimum value (α):

$$\text{IF value} < (\alpha + \text{I});\ 5; \text{IF value} < [\alpha + (\text{I} \times 2)]; 4; \text{IF value} < [\alpha + (\text{I} \times 3)]; 3;$$
$$\text{IF value} < [\alpha + (\text{I} \times 4)]; 2;\ \text{IF value} < [\alpha + (\text{I} \times 5)]; 1.$$

Assumption B: When the most favourable condition (5) is close to the maximum value (β):

$$\text{IF value} < (\alpha + \text{I}); 1; \text{IF value} < [\alpha + (\text{I} \times 2)]; 2;\ \text{IF value} < [\alpha + (\text{I} \times 3)]; 3;$$
$$\text{IF value} < [\alpha + (\text{I} \times 4)]; 4;\ \text{IF value} < [\alpha + (\text{I} \times 5)]; 5$$

This methodology ensures a fair and uniform assessment, enabling equal comparisons between the different equipment assessed.

Missing values were addressed by excluding cells with incomplete data on key characteristics, thus ensuring that only units with complete data were included in the final assessment. This approach maintains the integrity and reliability of the analysis.

2.2.2. Validation of Assessments

Direct comparison between pre-existing and derived scores serves to validate the consistency of the assessments. Close alignment between the two sets of scores suggests a robust and accurate assessment, while discrepancies between scores may indicate the need to revise technical specifications, assessment criteria, or both. These differences may also reveal new insights that warrant further investigation.

2.2.3. Comparative Analysis

This is carried out by using graphs to support comparative analysis. Radar charts visually illustrate how each unit compares to the different criteria evaluated. These graphs facilitate the identification of patterns and trends in equipment performance. In turn, it highlights the strengths and weaknesses of each piece of equipment, providing a clear view of which is best suited to specific applications or operational challenges.

3. Results

3.1. Data Collection

The equipment selected for the evaluation of the efficiency and sustainability of dry ice blasting systems (see Tables 2 and 3) reflects different performance and formal characteristics. It presents hybrid and single-functional equipment designed for solid and liquid CO_2 spraying. The collected data encompass specific criteria such as dimensions, power supply, air pressure, air volume flow rate, sound pressure level, tank capacity, pellet diameter range, carbon dioxide consumption, and weight of the equipment without accessories.

Table 2. Equipment and characteristics for the projection of solid CO_2—unifunctional machinery.

Company	Equipment	Dimensions (L × W × H)	Power Supply	Air Pressure	Air Volume Flow Rate	Sound Pressure Level	Tank Capacity	Pellets ø	Consumption	Weight without Accessories
Karcher®	IB 15/120	1000 × 800 × 1300 mm	220–240 V	2–16 bar 0.2–1.6 MPa	2–12 m^3/min	125 dB/A	40 kg	<3 mm	30–120 kg/h	91 kg
Karcher®	IB 7/40 Adv	768 × 510 × 1096 mm	220–240 V	2–10 bar 0.2–1 MPa	0.5–3.5 m^3/min	99 dB/A	15 kg	<3 mm	15–50 kg/h	93 kg
Karcher®	IB 10/2 L2P	870 × 450 × 970 mm	220–230 V	0.7–10 bar	0.07–0.8 m^3/min	95 dB/A	0 kg	<2.5 mm	2–8 kg/h 20–60 kg/h (liquid CO_2)	92 kg
Polartech®	PT-PROi	650 × 550 × 950 mm	110–230 V	2–14 bar	0.8–9 m^3/min	60–120 dB/A	25 kg	1–3 mm	0–75 kg/h	70 kg
Polartech®	PT MINIi	410 × 470 × 480 mm	110–230 V	2–10 bar	0.6–3 m^3/min	60–120 dB/A	8 kg	1–3 mm	25 kg/h	26 kg
Cold Jet®	AERO2 PCS 60	990 × 480 × 1140 mm	110–220 V	2.8–10 bar	0.3–2.8 m^3/min	80–120 dB/A	27 kg	3–0.3 mm	<108 kg/h	114 kg
Cold Jet®	AERO2 PLT 60	990 × 480 × 1140 mm	110–230 V	2.4–17.2 bar	1.4–4.7 m^3/min	80–120 dB/A	27 kg	3–0.3 mm	0–162 kg/h	105.69 kg
Intelblast®	IBL 3000	780 × 400 × 1110 mm	230 V	2–16 bar	2–25 m^3/min	75–130 dB/A	25 kg	3 mm	25–90 kg/h	95 kg
Intelblast®	IBL 2500	700 × 500 × 900 mm	230 V	2–12 bar	2–15 m^3/min	75–130 dB/A	25 kg	3 mm	25–90 kg/h	81 kg
Intelblast®	IBL Mini	550 × 480 × 610 mm	230 V	2–12 bar	0.3–5 m^3/min	75–120 dB/A	8 kg	3 mm	10–30 kg/h	39 kg
Cryoblaster®	ATX25-E V2	800 × 580 × 1000 mm	230 V	3–15 bar	-	-	25 kg	-	0–75 kg/h	98 kg
Cryoblaster®	ATX25-P	410 × 400 × 1100 mm	230 V	3–15 bar	-	-	15 kg	-	0–65 kg/h	67 kg
Cryoblaster®	ATX Nano	460 × 460 × 980 mm	230 V	2–12 bar	-	-	8 kg	-	0–35 kg/h	52 kg
Cryonomic®	COB 62	380 × 570 × 890 mm	220–240 V	1–7 bar	0.5–4 m^3/min	77–110 dB/A	14 kg	-	20–80 kg/h	66 kg
Cryonomic®	COB 62+	380 × 570 × 890 mm	220–240 V	1–10 bar	0.5–5.5 m^3/min	77–110 dB/A	14 kg	-	20–80 kg/h	68 kg
Cryonomic®	COB 71	665 × 570 × 876 mm	220–240 V	1–12 bar	0.5–6.5 m^3/min	77–110 dB/A	30 kg	-	25–100 kg/h	90 kg
Cryonomic®	COB 71P	665 × 570 × 876 mm	220–240 V	1–12 bar	0.5–6.5 m^3/min	77–110 dB/A	30 kg	-	25–100 kg/h	95 kg
Cryonomic®	COMBI 7	665 × 570 × 876 mm	220–240 V	1–16 bar	1–13 m^3/min	77–110 dB/A	30 kg	-	25–105 kg/h	100 kg
White Lion®	WL 5000 Robby	675 × 580 × 1100 mm	230 V	1–16 bar	1–16 m^3/min		50 kg	3 mm	5–120 kg/h	92 kg

Source: Own analysis based on technical data sheets and manufacturer's safety data sheets from Karcher® [45–47], Polartech® [48–50], Cold Jet® [51], Intelblast® [52], Cryoblaster® [53–55], Cryonomic® [56], and White Lion® [57].

Table 3. Equipment and characteristics for the projection from liquid CO_2—hybrid and unifunctional machinery.

Company	Equipment	Dimensions (L × W × H)	Power Supply	Air Pressure	Air Volume Flow Rate	Sound Pressure Level	Tank Capacity	Pellets ø	Dry Ice Consumption	CO_2 Liquid Consumption	Liquid Pressure	Weight without Accessories
Cryosnow®	SJ-25	580 × 370 × 470 mm	24 V DC	5–16 bar	1–6 m^3/min	80–120 dB/A	Not applicable	Not applicable	Not applicable	0.4–1.5 kg/min	20–100 bar	25.6 kg
Cryosnow®	SJ-10	400 × 300 × 300 mm	24 V DC	2–16 bar	0.3–2 m^3/min	70–100 dB/A	Not applicable	Not applicable	Not applicable	0.1–0.3 kg/min	20–100 bar	15 kg
Cryosnow®	SJ-5	310 × 190 × 277 mm	-	2–10 bar	0.1–0.25 m^3/min	70–90 dB/A	Not applicable	Not applicable	Not applicable	0.04–0.08 kg/min	20–100 bar	7.6 kg
Polartech®	PT-PROs	650 × 550 × 950 mm	110–230 V/AC 50–60 Hz	2–10 bar	1–5 m^3/min	60–120 dB/A	Not applicable	Not applicable	Not applicable	0.25–1.5 kg/min	20–70 bar	53 kg
Polartech®	PT-PROsi	850 × 550 × 480 mm	110–230 V/AC 50–60 Hz	2–14 bar	0.8–9 m^3/min	60–120 dB/A	25 kg	1–3 mm	0–75 kg/h	0.25–1.5 kg/min	20–70 bar	70 kg

Source: Own analysis based on technical data sheets and manufacturer's safety data sheets from Cryosnow® [58] and Polartech® [50,59,60].

The Polartech®, Intelblast®, and Cryoblaster® brands showed similar dry ice consumption, ranging between 20 and 90 kg/h, suggesting comparable efficiency in resource management. In contrast, equipment from Karcher® and Cold Jet® exhibited higher consumption, ranging from 30 to 120 kg/h and less than 108 kg/h, respectively. This could be reflected in higher operating costs. This factor is crucial, especially in large-scale operations where dry ice consumption is a significant variable in the cost structure. The pellet size used by dry ice blasting equipment generally tends to use smaller diameter pellets, equal to or smaller than 3 mm. This size is shown to be consistent across several models, such as the Karcher® IB 15/120, the Karcher® IB 7/40 Adv, and the Intelblast® IBL 3000. The ability to vary pellet size can significantly influence cleaning efficiency depending on the specific application and surface to be treated.

The size and weight of the equipment also play an important role, especially in terms of logistics and storage. The Karcher® and Cold Jet® equipment is heavier and larger, potentially increasing transport and storage costs, while the mini versions of Polartech®, Intelblast®, and Cryoblaster® offer greater practicality. Polartech®'s compact model, with dimensions of 410 × 470 × 480 mm and a weight of only 26 kg, stands out in this respect, offering significant advantages in terms of manoeuvrability and storage space. On the other hand, neither the pressure nor the amount of ice projected is adjustable [50].

The tank capacity of dry ice blasting equipment plays a crucial role in the operational efficiency and duration of blasting sessions. Examining the tank capacities of different models reveals significant variations. For example, the Karcher® IB 15/120 features a robust capacity of 40 kg, which positions it as a suitable option for prolonged tasks without constant interruptions to refill pellets. In contrast, the Polartech® PT MINIi model, with an 8 kg tank, stands out for its portability and agility, making it ideal for small applications that demand flexibility and frequent travel, with a total weight of approximately 30 kg. However, neither the pressure nor the amount of ice projected can be adjusted [50]. The tank capacity impacts the cleaning duration, mobility, and total weight of the equipment.

Air pressure and volumetric flow rate are crucial aspects in the evaluation of the operational efficiency of cryo-cleaning equipment. In terms of air pressure, most equipment is in the standard range of 10–12 bar, providing adequate pressure for a wide variety of applications. However, Cryonomic®'s COB 62 model operates at a lower pressure of 7 bar, which may be sufficient for specific applications requiring a more delicate pressure. On the other hand, equipment such as Karcher®'s IB 15/20, Cold Jet®'s AERO2PLT 60, and Intelblast®'s IBL 3000 exceed this standard range, reaching pressures of up to 16–17 bar. This higher pressure can be beneficial for tasks requiring greater cleaning force, although compatibility with the surfaces to be treated should always be considered to avoid damage. As for the volumetric flow rate, which determines the amount of air that can flow through the equipment per unit of time, most of the equipment is within a range of 0.5–9 m^3/min. This range is sufficient to meet the needs of various cleaning operations, ensuring effective coverage and consistent performance. However, certain models, such as the Karcher® IB 15/20 and the Intelblast® IBL 2500 and 3000 models, offer volumetric flow rates of 12, 15, and 25 m^3/min, respectively. These higher values could translate into greater operational efficiency and a reduction in the time needed to complete cleaning tasks, especially in situations where fast and efficient cleaning of large surfaces or volumes is required.

Analysis of the sound pressure of the equipment reveals a range of 60 to 130 dB/A. Models such as the Karcher® IB 15/120 and the Intelblast® IBL Mini show sound pressure levels of 125 dB/A and 75–120 dB/A, respectively. In contrast, the Cryosnow® SJ-5 and Polartech® PT MINIi models exhibit lower levels of 70–90 dB/A and 60–120 dB/A, respectively. This disparity is crucial when considering the occupational safety environment.

The power supply of most dry ice blasting equipment operates at voltages from 220 to 230 V AC (50–60 Hz). Examples include Karcher® IB 15/120, Polartech® PT-PROi, and Cryoblaster® ATX Nano. This variability in power supply may be relevant to industries willing to adopt this type of cleaning.

When considering the technical performance of liquid CO_2 cryo-cleaning equipment, such as Cryosnow®, Polartech®, and Karcher® (see Table 3), the uniqueness of Karcher® stands out. This model is categorised as unifunctional and is distinguished by its unique ability to convert liquid CO_2 into pellets during the cleaning process, as documented in Table 1. It is noted that most models significantly reduce the total tower weight and raw material consumption per hour compared to dry ice blasting. The smaller units are compact and lightweight, while some larger models, such as the Cryoclean® SJ-25 and Polartech® PT-PROs, sacrifice portability for higher air flow and blasting capacity.

In terms of liquid CO_2 consumption, Cryosnow® and Polartech® ranged between 0.25 and 1.5 kg/min, while Karcher® has a slightly lower consumption of 0.3–1 kg/min. Notably, more compact variants of Cryosnow® further optimise consumption, ranging from 0.1 to 0.3 kg/min, and are characterised by their smaller size and lighter weight, ranging from 7 to 15 kg without accessories. Polartech®, while larger and heavier, offers additional flexibility by being able to operate with either dry ice or liquid CO_2, depending on the model selected.

In terms of air pressure, there are no significant differences between the brands. However, the volumetric air flow rates of Polartech® equipment are higher, a factor that can directly influence the operational efficiency and speed of cleaning.

The acoustic pressure of the dry ice blasting equipment reflects a significant variation between models. The Cryosnow® SJ-25 has a sound pressure level of 80–120 dB/A, while the SJ-10 and SJ-5 models exhibit ranges of 70–100 dB/A and 70–90 dB/A, respectively. The Polartech® PT-PROs and PT-PROsi show similar sound pressure levels of 60–120 dB/A. There is a disparity in noise levels that directly influences the choice of equipment in terms of safety measures and operator health.

In terms of power supply, Cryosnow® equipment operates on a 240 V DC power supply, while Polartech® models operate on power supply voltages ranging from 110 to 230 V AC. The power supply required to operate the cleaning equipment represents a specific evaluation criterion linked to the versatility and adaptability of the system to the working environment.

3.2. Comparative Analysis of Cryo-Cleaning Equipment

Scores were defined from the minimum values (α), maximum values (β), and the interval measure (I) established from the collected data (see Table 4). The highest derived scores for the different operating parameters of the devices are given for those with smaller dimensions, lower weight, and larger power supply options (see Table 5). These were rated more positively for their compatibility and ease of storage and transport, as well as their portability, versatility, and adaptability. In addition, equipment with lower energy consumption is considered to be more efficient and to have a lower environmental impact. Such equipment is also quieter, more comfortable, and safer for operators. Models with larger capacity tanks are noted for their increased autonomy. The wide ranges of pressure and air flow enable improved efficiency in cleaning work, allowing for the removal of more stubborn dirt. Finally, the possibility of using different pellet sizes offers flexibility with regard to cleaning application, with equipment that can use smaller pellets, achieving more precise cleaning on particularly delicate surfaces.

From the processed data, the strengths and weaknesses of each model are presented in Figure 1. Additionally, the average values of the data are presented in Figure 2.

Table 4. Minimum values (α), maximum values (β), and interval measurement (I).

Criterion	Unit	Minimum Value	Maximum Value	Measurement of the Interval
Dimensions	m^3	0.03	1.04	0.20
Power supply range	V	0	120	24
Air pressure range	bar	6	50	8.80
Air volume flow range	m^3/min	0	23	4.6
Sound pressure level	dB/A	93.50	125	6.30
Tank capacity	kg	8	50	8.40
Pellet range	mm	0	2.7	0.54
Pellets	mm	0.3	3	0.54
Range consumption	kg/h	0	180	36
Weight without accessories	kg	26	114	17.60

Source: own analysis, 2024.

Table 5. Scores derived from equipment in relation to sustainability and efficiency criteria.

Equipment	Dimensions	Power Supply Range	Air Pressure Range	Air Volume Flow Rate Range	Sound Pressure Level	Tank Capacity	Pellet Range	Pellets ø	Range Consumption	Weight without Accessories	Average Value
IB 15/120	1	1	3	3	1	4	1	1	3	2	2.0
IB 7/40 Adv	4	1	2	1	5	1	1	1	5	2	2.3
IB 10/2 L2P	4	1	2	1	5	1	1	1	4	2	2.2
PT-PROi	4	5	4	2	1	3	4	4	3	3	3.3
PT MINIi	5	5	2	1	1	1	4	4	5	5	3.6
PT-PROsi	5	5	4	2	1	3	4	4	5	3	3.4
AERO2 PCS 60	3	5	1	1	4	3	5	5	1	1	2.9
AERO2 PLT 60	3	5	5	1	4	3	5	5	1	1	3.3
IBL 3000	5	1	5	5	4	3	1	1	4	2	3.1
IBL 2500	4	1	3	3	4	3	1	1	4	2	2.6
IBL Mini	5	1	3	1	5	1	1	1	5	5	2.8
ATX25-E V2	3	1	4	1	5	3	1	5	3	1	2.5
ATX25-P	5	1	4	1	5	1	1	5	4	3	3.0
ATX Nano	5	1	3	1	5	1	1	5	5	4	3.2
COB 62	5	1	1	1	5	1	1	5	4	3	2.6
COB 62+	5	1	2	1	5	1	1	5	4	3	2.8
COB 71	4	1	3	2	5	3	1	5	3	2	2.9
COB 71P	4	1	3	2	5	3	1	5	3	2	2.9
COMBI 7	4	1	5	3	5	3	1	5	3	1	3.1
WL 5000 Robby	4	1	5	4	5	5	1	1	2	2	2.8

Source: Own authorship based on data sheets and safety data sheets from Cryosnow® [58] and Polartech® [50,59,60].

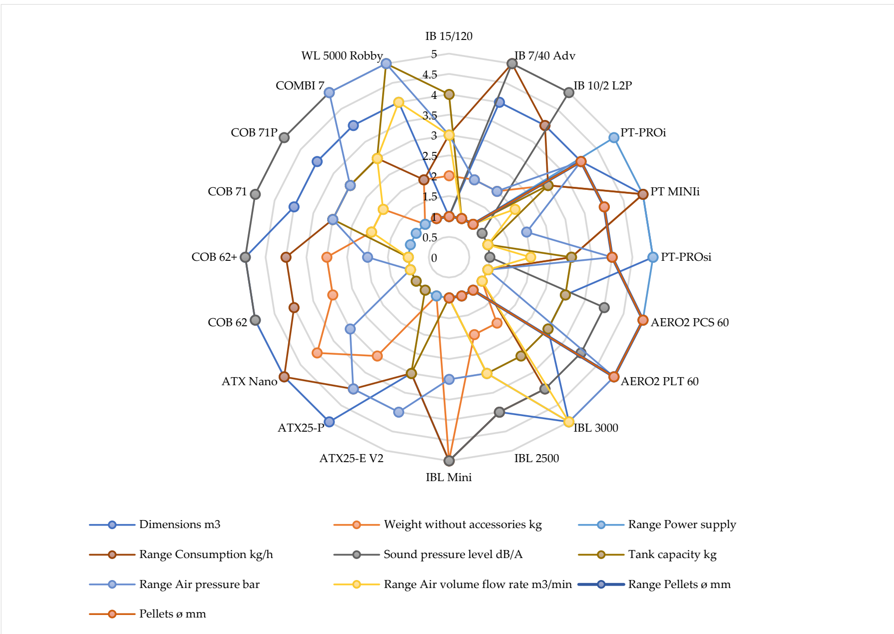

Figure 1. Comparative performance profile of cryo-cleaning equipment for each of the evaluation criteria. Source: own analysis, 2024.

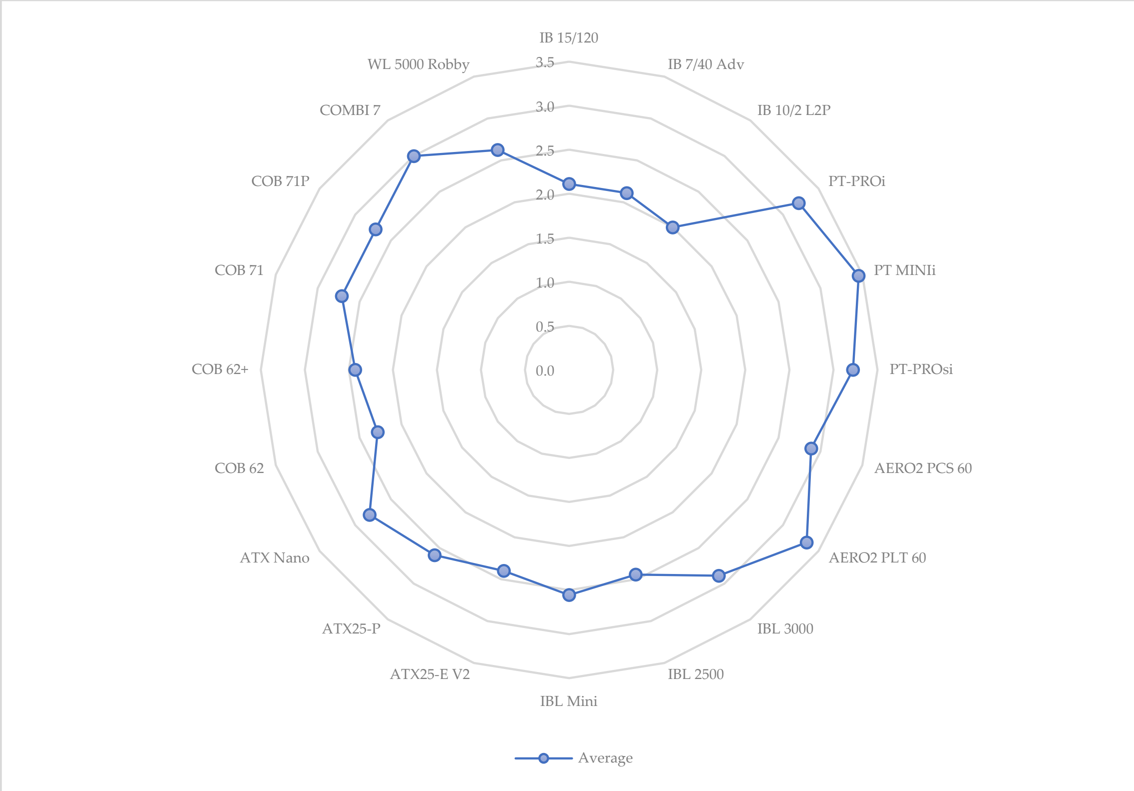

Figure 2. Average scores of cryo-cleaning equipment, taking into account all the evaluation criteria. Source: own analysis, 2024.

4. Discussion

The results reveal the technical performance of the devices, their suitability for different operational challenges, and environmental sustainability. Devices with higher scores in compact dimensions and low weight are more suitable for environments where space is limited and portability is essential. In addition, high scores in energy efficiency and low noise underline a design that is conscious of environmental impact.

On the other hand, equipment with a high tank capacity, pressure, and flow performance are more suitable for more intensive cleaning operations. These insights offer valuable guidance for selecting cryo-cleaning equipment that not only meets operational requirements but also promotes sustainable working practices.

Across the equipment analysed, the Polartech® PT-MINIi, AERO2 PLT 60, and PT-PROsi have been identified as a choice that closely aligns with the defined selection parameters. Likewise, the Polartech® PT-PROsi stands out for its ability to hybridise dry ice blasting and snow blasting systems, enhancing the versatility of the equipment for analysing the applicability and optimisation of the cryogenic method in specific sectors. Additionally, models like the WL 5000 Robby, AERO2 PCS 60, ATX Nano, ATX25-P, IB 15/120, IB 10/2 L2P, IBL 3000, COB 62+, COB 71P, and COB 71 and the solutions offered by Cryosnow® significantly contribute to the applicability of cryo-cleaning in different industrial sectors.

Intelblast®'s WL 5000 Robby and Cold Jet®'s AERO2 PCS 60 models have demonstrated efficiency in dry ice management, reflecting a commitment to environmental sustainability and operational cost optimisation. In terms of practicality, equipment such as Cryoblaster®'s ATX Nano and ATX25-P stand out for their compact and lightweight design, which streamlines transportation and reduces logistical costs.

In terms of air pressure performance, the IB 15/120 and PT MINIi models provide an optimal range for a wide variety of applications. On the other hand, Karcher®'s PT-PROsi and IB 10/2 L2P models are designed to reach higher pressures and are adapted to intensive cleaning jobs that demand more power.

In terms of volumetric air flow, equipment such as Intelblast®'s IBL 3000 and Cryoblaster®'s AERO2 PLT 60 stand out for their larger ranges, which translates into greater agility and effectiveness in cleaning, particularly in time-critical scenarios.

Versatility is also a feature of Polartech®'s COMBI 7 and COB 62+, which are capable of switching between dry ice and liquid CO_2, giving them the ability to adapt during cleaning operations.

Cryosnow® and Polartech® stand out for their moderate liquid CO_2 consumption, ranging between 0.25 and 1.5 kg/min, indicating economical and efficient operation. These brands also feature compact versions that further optimise CO_2 consumption, contributing to efficiency and reduced operating costs. Recent studies in the automotive industry compared cryo-cleaning with conventional solvent and water-based cleaning methods, revealing that cryo-cleaning can reduce cleaning time by up to 96.9% [23]. This research, carried out by the Department of Physics, Mechanics and Industrial Engineering at NOVA University in Lisbon, focused on the feasibility of using dry ice in painting processes [8]. Using Cryosnow®'s SJ-25 handheld dry ice blasting equipment, the researchers established control parameters such as operating time and CO_2 consumption, finding an average CO_2 consumption of up to 2 kg/min and an efficiency of 1 min/m^2. Compared to the dynamic wash (DW) method, which includes multiple washing and drying stages, cryo-cleaning not only has reduced costs and water consumption but also minimises the space required by implementing a robotised system, taking up only a third of the original space. Furthermore, Karcher® distinguishes itself with the ability to convert liquid CO_2 into pellets during the cleaning process without the need for a pelletiser, which could offer specialised functionality for certain applications.

The evaluation of the cryo-cleaning equipment, based on this detailed technical analysis, reveals that the Polartech® models are positioned as an outstanding choice, particularly for their balance between technical performance and resource management efficiency. Polartech®, Intelblast®, and Cryoblaster® all have comparable and moderate dry ice consumption, suggesting efficient material management. In contrast, the Karcher® and Cold Jet® machines show higher consumption, which could lead to higher operating costs. In terms of dimensions, Polartech® is favourable because of its compact design, offering notable advantages for transport and storage, potentially translating into significant logistical savings.

4.1. Future Trends and Developments

These devices represent a selection in today's cryo-cleaning market, providing comprehensive solutions to industrial operational and sustainability challenges. With individual characteristics, each device contributes to the establishment of an efficient, effective, and environmentally friendly industrial cleaning environment. However, as we delve deeper into the uses, it is crucial to recognise both the drivers that support their expansion and the barriers that limit their development [6].

4.1.1. Innovation in Energy Efficiency

Dry ice blasting offers substantial benefits, although significant challenges remain. The energy consumption of the process, associated with the costly production of the blasting material and the low efficiency of compressed air usage, stands out as a significant barrier [61]. This technology requires a source of compressed air to supply the necessary kinetic energy to the dry ice pellets. The quality and quantity of this kinetic energy, derived from the mixture of air and pellets, is a factor that influences the efficiency of the cleaning process. Producing sufficient compressed air and pellet extrusion to the required specifications is a highly energy-demanding process [62]. In addition, the availability of centralised compressed air distributions with these characteristics is not common in industrial facilities [23].

There are some initiatives that lead the way towards greater sustainability and cost reduction. In 2009, a patent was published for the acceleration of dry ice particles through a centrifugal wheel independent of compressed air [25], while other authors propose cost-saving measures and efficient use of compressors to reduce energy consumption by up to 87% in specific industrial applications [23]. Addressing these challenges requires a holistic approach involving technical innovations, industrial collaboration, and the implementation of effective energy-saving measures [12].

4.1.2. Development of Noise Reduction Technologies

In the technical and safety data sheets published by the manufacturers, the sound pressure levels to which the operator is subjected during the use of the equipment are published, as well as the required personal protective equipment (PPE) to limit the risks of exposure. Most of the machines recorded in the study reach 120 dB/A, a very high value that can cause hearing damage if appropriate protective measures are not taken. For reference, the take-off of a jet plane at a distance of 100 metres, a chainsaw, or a train horn corresponds to approximately these levels. Against this background, we found studies that demonstrate the relationship between optimal nozzle configuration and noise impact reduction, offering a promising advancement in operator comfort and safety [63]. Other research aimed at automotive tyre mould cleaning integrates numerical and experimental methods to optimise the energy and aerodynamic efficiency of the cleaning system. Considering geometrical and operational constraints to reduce noise, they evaluate various nozzle and silencer designs to minimise noise emissions without affecting system efficiency [18].

4.1.3. Future Perspectives: Demands for Sustainable and Safe Fluids

In the context of growing environmental awareness, dry ice blasting is emerging as a more sustainable option compared to conventional methods that use solvents, chemicals, or water. The use of CO_2 as a raw material, obtained as a by-product of industrial processes, may lead to a more environmentally friendly future [3]. It comes from a circular economy cycle and not from fossil fuels, so it does not contribute to increased greenhouse gas emissions. However, in the context of the urgent climate crisis [64], the adoption of cryo-cleaning requires careful and conscious analysis of its multiple applications. While cryo-cleaning promotes the efficient use of resources and the reuse of by-products [65], it is imperative to take into account the implications of greenhouse gas emissions associated with the use of CO_2 in this method.

Similarly, an emerging trend in dry ice blasting involves research into the substitution of CO_2 with eco-sustainable gases [66]. The current economic situation, resulting from the pandemic, new environmental policies, and the limitation of global energy resources, has had a direct impact on CO_2 production, resulting in a significant shortage that translates into increased costs [67,68]. Furthermore, CO_2 extraction alternatives have demonstrated low quality, which is associated with the presence of impurities [68,69].

4.1.4. Optimising the Cleaning Process

Efficiency in cryo-cleaning is directly linked to the optimisation of each stage of the process. Scientific research has analysed the ideal conditions for its application in different scenarios, examining crucial factors such as angle, distance, cryogenic gas pressure, temperature, and exposure time [3,12,70]. By adjusting these variables, it is possible not only to boost the effectiveness of cryo-cleaning but also to decrease the related costs. This approach includes careful management of resources, ranging from the amount of cryogenic material used to the total operation time. Applying cryo-cleaning in a methodical way, taking into account the particularities of each surface or material, not only minimises waste but also maximises the efficiency of the procedure.

Furthermore, the optimisation of the cryo-cleaning process involves a thorough analysis of critical elements, including the temperature of the surface to be treated, the resistance of the underlying material [35,71], possible recontamination and condensation [72]. This consideration ensures the effectiveness of the cleaning, as well as the integrity and longevity of the treated surface.

5. Conclusions

A comprehensive analysis of cryogenic cleaning systems identified a number of options that, in addition to meeting technical requirements in a variety of industrial applications, were distinguished by their efficiency and commitment to sustainability. This study provides a solid foundation for making informed and strategic decisions regarding the purchase of dry ice blasting equipment, offering a comprehensive guide based on rigorous evaluation criteria.

The selection of equipment that maximises operational efficiency while minimising environmental impact is critical. The equipment evaluated showed significant differences in energy consumption, operating pressure and cleaning performance. For example, the results showed that equipment that operates at lower pressures and uses less energy without compromising cleaning effectiveness is more sustainable and economical in the long term.

Cryogenic cleaning systems are directly aligned with several of the UN's 2030 Sustainable Development Goals (SDGs) [73], particularly those related to reducing the water footprint (SDG 6), the efficiency and sustainability of industrial infrastructure (SDG 9), creating cleaner urban environments (SDG 11), and reducing carbon emissions (SDG 13). This study highlights the importance of adopting technologies that are not only effective but also promote environmental sustainability.

The equipment selection process included a detailed evaluation of criteria such as weight without accessories, power supply, and energy consumption. The importance of these factors in choosing suitable equipment for various industrial applications was highlighted, ensuring that the equipment selected was not only efficient in terms of performance but also sustainable and easy to use.

In a context where operational efficiency and environmental sustainability are increasingly prioritised, the correct selection of dry ice cleaning equipment is crucial. This article addresses this critical need by providing a detailed framework for equipment evaluation and selection. This will contribute to the body of knowledge on dry ice blasting, supporting innovation and the adoption of sustainability practices within the sector. The methodology and analyses presented are intended to serve as a resource for future experimental research projects and developments in the field of cryogenic cleaning.

The adoption of SDG-aligned technology for cryogenic cleaning represents a significant step towards more sustainable and responsible industrial practices, promoting a positive impact on both operational efficiency and environmental protection.

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