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ORIGINAL ARTICLE

Technical, environmental, and economic feasibility investigation of an innovative dry washing process for metal degreasing

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Abstract
Industrial washing is essential in manufacturing and many other technological fields. Nowadays, steam washing is the most common technique. However, it involves chemical solvents which are potentially noxious for the environment and difficult to be disposed of. Therefore, there is a growing demand for alternative washing techniques that would ensure low operating costs, extensive productivity, high efficiency, environmental sustainability, good compatibility with different materials, and safe operating conditions. A fluidized bed (FB) represents a promising alternative to satisfy market requirements. In this study, a prototype of FB machine for the degreasing of pressure vessels was designed, built, and compared to the current solvent washing machine. The scope of the work is to assess the technical, environmental, and economic feasibility of a FB device for industrial washing. The analysis of variance (ANOVA) was carried out to detect the process parameters influencing the cleaning. The optimal process parameters were identified based on the experimental results. Life cycle assessment (LCA) and cost analysis were performed to evaluate environmental impacts, and operating costs. The results confirmed the validity of FB technology as an alternative to current washing techniques thanks to its higher cleanness, minor environmental impact and costs, and comparable productivity.

Keywords Industrial washing · Fluidized bed · Life cycle assessment · Life cycle cost · Sustainable manufacturing

1 Introduction

Metal processing, surface treatments, assembly of electronic devices, and many other industrial practices need surface cleaning processes to ease their execution. Hence, over the years, industries pursued the exploration of suitable particle removal systems; the effort led to the development of several methods, well resumed in [1]. These processes, however, are inefficient or non-effective, require the use of chemicals, and present many disadvantages.

Among the methods for industrial washing of metal components, solvent washing is one of the most frequently used; for this purpose, industries exploit large solvent or water washing machines that use surfactants or iso-paraffin detergents. Nonetheless, these machines have generally a high energy absorption, considerable water consumption, and extended cycle times. Steam washing is the most common technique; indeed, the vapour degreasing technique is more effective than the aqueous or semi-aqueous process. However, solvents have a strong negative impact on the environment, and current regulations for the disposal of exhausted solvents are very severe [2]. Moreover, they are highly volatile substances, and occupational exposure occurs through solvent vapour inhalation [3, 4]. Since solvents are toxic to human health [5], metallic cleaning requires compliance with health and safety standards and environmental protection [6–8]. The growing awareness of the risks associated with chemicals drives organizations to carry out social responsibility initiatives and deploy considerable research efforts to face specific environmental problems [9–11]. An innovative method for life cycle impact assessment that includes exposure scenarios were described by Golsteijn et al. [12]. In [13, 14], Kikuchi et al. confirmed the importance of reducing solvent emissions for risk mitigation in metal degreasing by a practical method for risk-based decision-making. Advanced

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washing methods [15, 16] and recovery systems of wastewater [17–19] have been developed in the past decade. Moreover, increasing market competition is forcing companies to look for new solutions [20, 21].

Laser cleaning represents a green and effective alternative to solvent washing, which has progressively become an entrenched cleaning process for a range of artefacts [22] because of appealing properties such as versatility and simplicity of the device operation in addition to the lack of hazardous chemicals [23, 24]. However, while the oxide removal through a laser beam is already present in the literature, studies on the lubricants removal, such as oil and grease, lack [25]. Despite several reports on laser cleaning effectiveness, its industrial application to metal is not widespread as the findings of these studies indicate that the laser cleaning outcomes are heavily case-dependent [22]. In general, the removal mechanism is a function of the grease layer thickness, its light absorbance, and the laser light fluence [25]. Parameters such as pulse frequency, power, scan speed, pulse time, and hatch strongly influence the laser cleaning results.

The ultra-sonic process, where high-frequency sound waves up to 120 kHz hit the components [26], is a viable alternative. The process exerts cavitation, which occurs when microscopic bubbles collapse or implode, mechanically scouring the part to be cleaned and displacing or loosening the contaminant. Despite ultrasonic are thorough processes as the microbubble penetration is high, excessive power densities may cause crystal damage [26], while lower densities are more suitable for gross and not precision cleaning of optics [27], not adequately removing particles less than about 25 um [1]. Disadvantages also include the high noise level produced [28] and a non-homogeneous outcome on the samples since the bubble float up; as a result of the latter phenomenon, the top only receives a few percentage of the energy produced [1].

A method regularly used in the automotive industry, foundry, and several other industrial applications is the dry ice blasting [29–32]. The cleaning mechanism is connected with the kinetic energy of dry ice particles. Dry ice causes thermal shock to the substrate and contaminant layer; shrinkage differences could lead to shear stresses due to thermal shock, and the low temperature causes contamination embrittlement. [33]. Dry ice blasting has also been studied as a pre-treatment process, despite not being established in industrial practice yet. The main barrier to the dry ice blasting spreading is the dry ice degradation which afflicts the process's effectiveness. The lower the dry ice particle mass, the less the energy; furthermore, dry ice particles may shatter, increasing the sublimation rate, reducing the removal rate, and increasing ice consumption [31]. In addition, high-level noise intensity limits application as well as the increment of the CO_2 level, which require adequate ventilation and worker protection [34, 35]. Also, dry ice blasting is a line-of-sight process, i.e. the exit of the nozzle must point directly to the polluted surface [31].

A fluidized bed (FB) is an automated, environmentally friendly, non-contact technique based on bubbling fluidization and offers a viable alternative to traditional cleaning methods [36, 37]. Low operating temperatures with no need for lubricants or chemicals at any stage of the process make FB highly environmentally friendly and safe. Environmental emissions are at ambient temperature and free of atmospheric pollutants. Moreover, FB is perfectly suitable for removing lubricant and organic residues even on complex-shaped surfaces as the fluidized particles surround the components. Thanks to these advantageous characteristics, FB has found many applications in the chemical and metallurgical engineering industry. It has been applied successfully for surface finishing, deburring, polishing [38–40], and coating [41, 42]. Several studies propose FB technology for post-process finishing treatments [43–47]. In the present paper, it was used for metal degreasing of pressure vessels related to airbags for the automotive industry. A diaphragm seals the pressure vessel; in fact, the surface preparation improves the adhesion of bonded interfaces [48]. Therefore, the sealing surfaces require thorough cleaning to prevent gas leakage from the weld bead [49].

The work focuses on the evaluation of an innovative technology for industrial washing, with performance comparable to current industry standards (i.e. solvent washing), lower environmental impact, energy savings, and shorter cycle time. The study involves the design of a device for the industrial washing of vessels, considering dimensions and power requirements. In addition, the paper aims to define the ideal media for removing particles adhering to the surface of the samples processed. Finally, the aim is to identify the ideal operating conditions; therefore, the effect of the operational parameters on the cleaning performance was investigated using the analysis of variance (ANOVA). The optimal conditions for oil removal were identified based on the experimental results, evaluating the samples' cleanness in terms of wettability by employing standard markers.

Additionally, life cycle assessment (LCA) and cost analysis were carried out to assess the effectiveness of the proposed technology in terms of environmental impact, resource consumption, and cost compared to solvent washing. The results demonstrated the capability of FB as a method to replace the traditional cleaning system while optimizing resource consumption and reducing adverse effects on the environment at once.

2 Materials and methods

2.1 Materials and equipment

A prototypal device was designed, manufactured, and tested to achieve a low-consuming and environmentally friendly industrial washing process. In FB technology, a solid

Table 1 AISI 1513 steel composition

Element	Fe	C	Mn	P	S
Weight%	98.35–98.8	0.10–0.16	1.10–1.40	Max 0.04	Max 0.05

granular bed is fluidized by means of an air jet, driven at the appropriate speed by a fan. The fluidized particles impact the surface of the samples, which are placed in rotation in the processing media, removing the grease particles. The design and implementation phases consisted of 6 stages, listed below:

- Conceptual design;
- Computer-aided design by using SOLIDWORKS;
- Critical design review (CDR);
- Definition of BOMs (bills of materials) and procurement;
- Manufacturing;
- Assembling

These steps were aimed at realizing a device capable of processing 21 vessels simultaneously. This size allows obtaining the productivity of the current treatments, which is a washing process using water and solvents, of 1140 components per hour with a reduction in cycle-time from 30 to 1 min. The substrate undergoing the fluidized bed washing was a vessel made of AISI/SAE 1513 carbon steel (UNS G15130), produced by Osim Plocco S.r.l., whose composition and geometrical features are resumed in Table 1 and Fig. 1. The industrial washing

Table 2 Experimental plan for the choice of media

Scenario	Abrasive media	Duration, min	Blower frequency, Hz	Rotation speed, rpm
1	Polypropylene	5	12	28
2	Acetal (re-milled)	5	18	28
3	Polyvinil chloride, PVC	5	18	28
4	Glass (Ø 2.5 mm)	5	24	28
5	Glass (Ø 1.6 mm)	5	8	28
6	Walnut shell	5	16	28

process aimed at removing residues of oil, grease, and metal shavings from previous transformation processes.

2.2 Experimental investigation

The present study considers several control factors and levels to evaluate and characterize the prototypal device performance through experimental tests. Preliminary activities were accomplished to select the best type of media for performing the innovative industrial washing, as resumed in Table 2. Despite the rotation speed of the sample within the powder being kept constant at 28 rpm, each material requires a different blower frequency due to different densities and particle dimension. The frequencies were chosen on the basis of preliminary experimental work and correspond to the lowest frequency that can

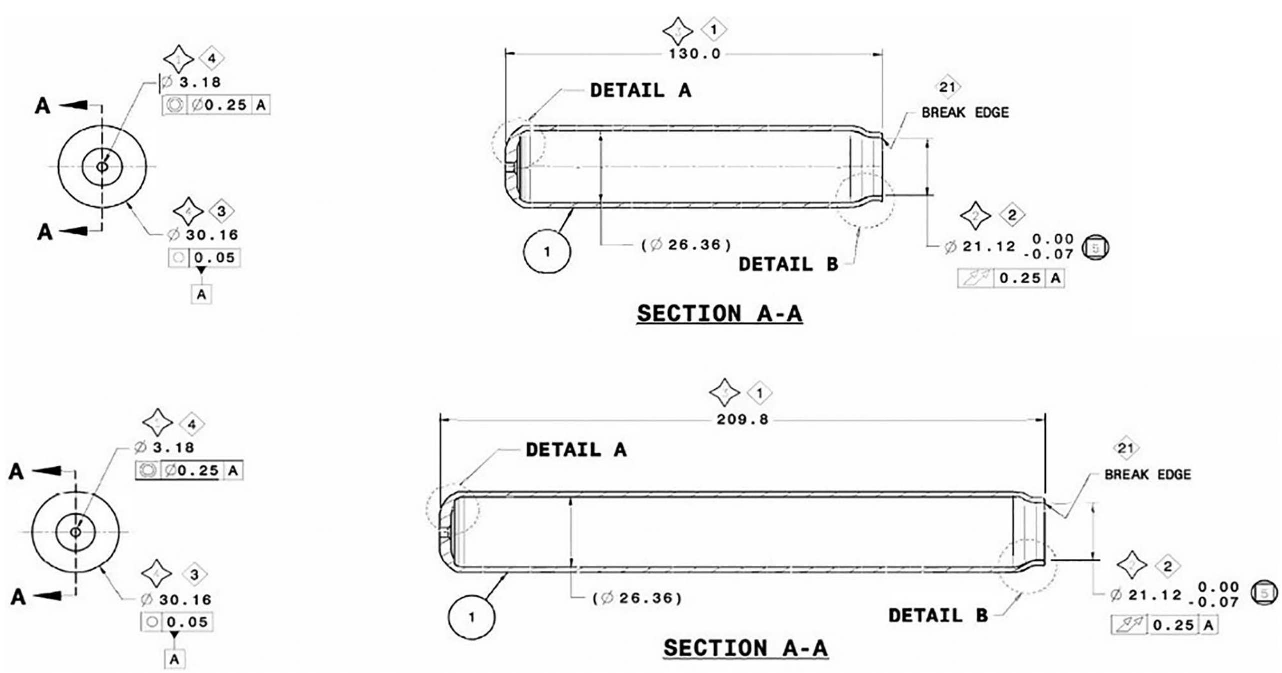


Fig. 1 Vessel representation

generate fluidisation of the abrasive particles. The process parameters were investigated to assess the optimal configuration and achieve higher performance. The variables considered for the process characterization are resumed in Table 3.

Standardized markers for wettability tests were exploited to assess the process's effectiveness. These standard markers allow measuring the surface tension of the material. The test is valid if the ink evenly spreads in a continuous line, which means that the surface tension of the substrate is the same as the ink used for the test or higher. Instead, the check fails if the ink separates in drops and the line is discontinuous. In fact, it means that the material surface tension is lower than those of the ink used for the test. The markers comply with the ASTM D2578-67 standard. Used scorers have a surface tension ranging from 32 to 50 dynes/cm. The samples are acceptable if they have a surface tension higher than 34 dynes/cm. The ANOVA was performed to study the effect of the control factors on the cleanness of samples. The surface tension was selected as the response variable. It was chosen with a significance of 95% so that a controlling factor is considered statistically significant when the p-value is lower than 0.05.

2.3 Life cycle analysis

The LCA is currently the univocal standardized methodology which allows for quantitatively evaluating the environmental impacts generated by a product, a process, a service, an activity, or generally, a system from a lifecycle perspective. In fact, previous studies (e.g. [50, 51]) demonstrate that such methodology represents a valuable tool to support the decision-making toward the selection of existing or the development of new efficient and environmentally sustainable industrial products and processes.

ISO 14040 describe the LCA methodology, while ISO 14044 has been used to perform the environmental evaluation of the proposed metal washing device. The four different phases suggested by the standard have been followed in the present study:

Table 3 Control factors and levels adopted in the experimental tests (using glass spheres Ø 2,5 mm)

Control factor	Label	Levels	Unit
Duration	t	1; 2; 3	min
Blower frequency	F	35; 40; 45; 50	Hz
Rotating speed	s	10; 20; 30; 40	rpm

- Goal and scope definition: this step requires the analysis objective, functional unit, and spatial and temporal boundaries definition;
- Life cycle inventory (LCI): this is the step where the system under analysis is subdivided into unit processes and, for each, an input/output (I/O) analysis is performed to collect all the relevant data to be considered for the environmental assessment;
- Life cycle impact assessment (LCIA): during this step, the input/output flows are used to calculate the impact indicators at both midpoint and endpoint levels;
- Result interpretation: the last step consists of the interpretation and critical review of results in order to identify the most pivotal flows/phases/items and eventually set corrective strategies.

The LCA study has been carried out with the support of the SimaPro 8.0.5.13 software tool.

2.4 Cost estimation

Cost analysis has been performed by following the activity-based costing (ABC) approach [52] that, through a hierarchical framework and the split of contributions, allows for accurately analysis of industrial processes from the operating costs point of view, discovering the most relevant causes, as well as set the most effective corrective and efficiency improvement strategies [53, 54].

The ABC methodology foresees the following steps:

- Segmentation of the process in elementary activities;
- Cost estimation of every single activity by using relevant parameters (e.g. energy quantity and cost, raw materials quantity, and cost);
- Combination of the unitary costs to derive the total cost of the process;
- Breakdown of costs to evaluate the contribution of each process step or parameter.

The cost assessment has been carried out through a dedicated Microsoft Excel spreadsheet and exploiting input data measured or derived from industrial sources.

3 Results and discussion

3.1 Design of the prototypal FB machine

The device exploits a granular media placed at the bottom of a cylinder, suspended through a fan. Dry cleaning is performed by dipping the vessels, clamped on a shaft, into a fluidized bed of abrasive media at a low rotational speed. The particles impact the substrate undergoing the process at different contact angles, removing the contaminants adherent to the surface. The airflow transports the pollutants, which are disposed of through a filter. In addition, it is fundamental that the impurities do not adhere to the abrasive particles and do not fragment so that they can have a long-term effect.

The prototype design aims at matching the productivity of conventional industrial solvent washing, set at 1140 units per hour. From this, it was possible to determine the minimum number of vessels to be processed simultaneously with cycle times of one minute. The samples are placed in the fluidization chamber and moved through a kinematic system; it consists of a central shaft and satellites rotating and revolving, which accommodate the vessels.

For each satellite, the sample number was determined on the base of the vessel dimension, considering a spacing that guarantees the correct circulation of the powder. It allowed the dimensioning of the working section, which was minimized by implementing a central solid core. The cross-section of the fluidization chamber with the component holder is shown in Fig. 2. The configuration proposed allows the presence of 7 satellites simultaneously and, therefore, the washing of 21 vessels per minute with a productivity of 1260 components per hour.

The design process led to a prototypal fluidized bed device implementation with a fluidization chamber diameter of 250 mm. CAD schematic of the fluidized bed is reported in Fig. 3, while the geometrical features of the prototypal device are reported in detail in Table 4.

Setting the height of the fluid bed as a function of the size of the vessels allows the estimation of the pressure drops to fluidise the media and then size the blower, based on the constants and equations shown in Table 5.

3.2 Experimental investigation

Regarding the media evaluation, Fig. 4 highlights the results obtained. It shows that scenarios 1, 4, 5, and 6 offer the best results, while 2 and 3 fail the test.

Despite the positive results, walnut shells and polypropylene presented drawbacks that do not allow the media to be used in an industrial environment. The latter showed impurities on its surface, causing a frequent media replacement. The former undergoes a wear process that releases dust within the fluidized bed, which adheres to the sample's surface. The most suitable powder for this application is the 2.5-mm glass sphere. Irrespective of the impact angle, the spheres slide over the surface, increasing the contaminant

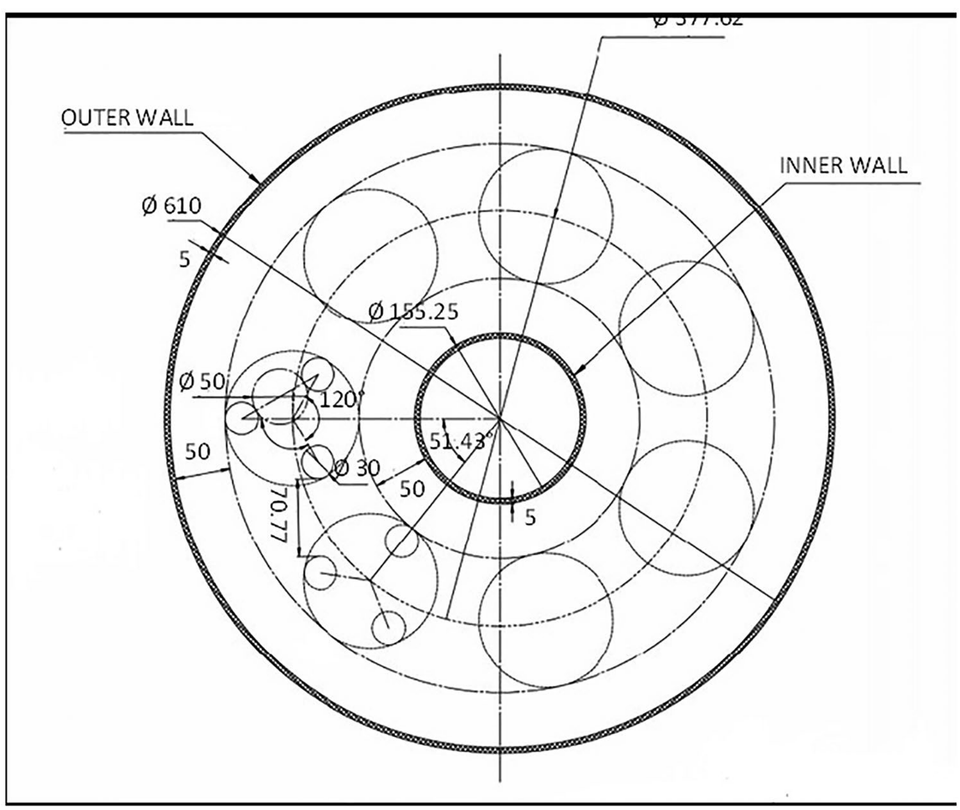


Fig. 2 Schematic of the fluidization chamber (cross-section of component holder)

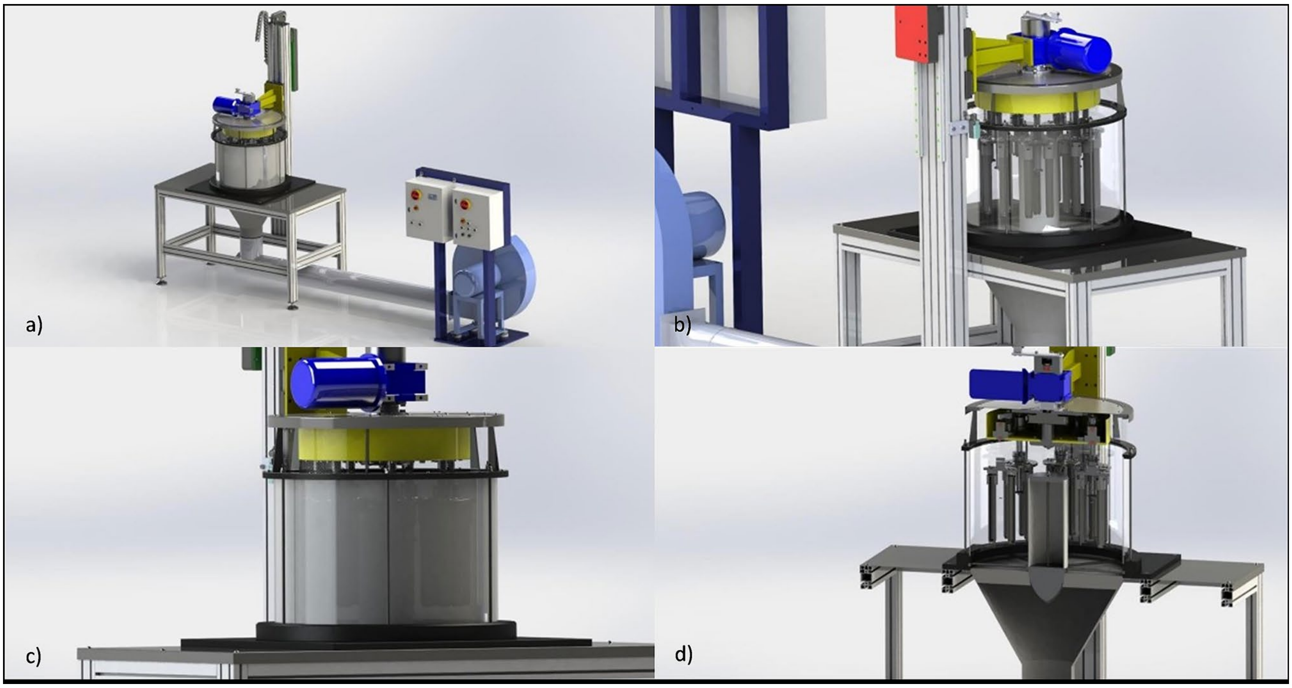


Fig. 3 CAD schematic of the prototype FB machine: **a** general scheme; **b** vessel gripping system; **c** fluidization chamber; **d** fluidization chamber cross-section

removal efficiency. Also, this behaviour reduces the risk of mechanical damage to the treated surface. The contaminant, once removed, does not stick to the glass surface but is transported by the airflow to filtration devices where it can be collected and disposed of, according to the current industrial standards. Therefore, they were selected to determine the FB's best performance.

Figure 5 reports the cleanness results achieved with the different scenarios adopted in the experimental tests.

Table 4 Main features of the FB prototypal device

Feature	Type/Value	Unit
Positioning of vessels	Manual	-
Locking mechanism of vessels	Magnetic	-
Handling of vessels	Epicycloidal	-
Diameter of external cylinder	600	mm
Diameter of internal cylinder	150	mm
Diameter of the rotating apparatus	125	mm
Minimum distance vessel to sidewalls	50	mm
Minimum distance vessel to vessel	70	mm
Resting height of the bed	50–200	mm
Height of the fluidized bed	100–400	mm
Height of the cylindrical chamber	400	mm
No. of vessels per rotating apparatus	3	-
No. of rotating apparatuses	7	-
No. of vessels per cycle	21	-

The underlying hypotheses for the ANOVA have been confirmed by the residues graphical analysis, not reported for the sake of briefness. The ANOVA results are summarized in Table 6, which shows the *p*-value and *F*-value of the control factors and their interactions (the significative ones highlighted in bold). The main effect plot and interaction plot are reported in Figs. 6 and 7, respectively.

From the table, all control factors affect the cleanness of samples and the interaction $F \times s$ is statistically significant. Also, the reliability index of the regression model is high ($R^2 = 93.67\%$), demonstrating a sound fitting. As can be inferred from the main effect plot, the surface tension increases with the increase in rotating speed, duration, and blower frequency up to 45 Hz. Whilst, a further blower frequency increase to 50 Hz leads to a decrease in the surface tension. The latter is due to the lower density of the fluidized bed. The higher the blower frequency, the greater the height of the fluidized bed and, in turn, the smaller the number of collisions per unit of volume. As a consequence, the level of cleanness decreases.

The results from the interaction plot show that low rotational speeds produce samples with a low surface tension value, independently of the blower frequency. The effect of rotational speed increments on the cleanness increases with higher blower frequency (up to $F = 45$ Hz). However, the highest blower frequency of 50 Hz causes a decrement in performance, reducing the abrasive media density instead. It is due to the speed of collisions which depends

Table 5 Blower sizing

Constants			
Name	*Label*	*Value*	*Unit*
Dry air constant	R	287.058	J kg^{-1} K^{-1}
Gravity acceleration	g	9.80665	m s^{-2}
Ambient pressure	P_0	101,325	Pa
Ambient temperature	T_0	288.15	K
Ambient density	ρ_0	1.225	kg m^{-3}
Glass density	ρ_{glass}	2400	kg m^{-3}
Steel density	ρ_{steel}	7900	kg m^{-3}
Air viscosity	μ_0	1.78E−05	Pa s
Sutherland's constant	S	110.4	K
Input			
Name	*Label*	*Value*	*Unit*
Delta fan pressure	$P_1 - P_0$	2823	Pa
Delta fan temperature	$T_1 - T_0$	30.00	K
FB inlet pressure	P_1	104,148	Pa
FB inlet temperature	T_1	318.15	K
Void fraction	ε	0.40	-
FB height	H	0.20	m
Particle diameter	d	2.50E−03	m
Particle density	ρ_p	2400	kg m^{-3}
radius of the external FB chamber	R_1	0.300	m
radius of the internal FB chamber	R_2	0.075	m
Computations			
Name	*Equation*	*Value*	*Unit*
FB inlet air density	$\rho_1 = {}^{P_1}/_{RT_1}$	1.140	kg m^{-3}
FB inlet viscosity	$\mu_1 = \mu_0 \left({}^{T_1}/_{T_0}\right)^{3/2} {}^{(T_0+S)}/_{(T_1+S)}$	1.92E−05	Pa s
FB pressure drop	$\Delta p = (1-\epsilon)(\rho_p - \rho_1)Hg$	2823	Pa
Speed	$v = {}^{(-b+\mathrm{rad}q(b^2-4ac))}/_{2a}$	1.03076	m s^{-1}
FB section	$A = \pi(R_1{}^2 - R_2{}^2)$	0.265	m^2
Flow rate	$Q = Av$	0.273	m^3 s^{-1}

on the workpiece rotation speed and the particles' speed. Therefore, as the blower frequency decreases, a higher density of the fluidized bed is obtained, but the particles' speed decrease. Thus, a low blower frequency ($F = 35$ Hz) produces a less effective impact with too low energy to remove the oil.

The response optimization method was then implemented. It provides a desirability function ranging from 0 to 1, where the optimization is achieved by maximizing the assumed value of this function. In this study, the duration was held to its minimum to ensure maximum productivity, while other factors were not bound to maximize the surface tension. The response optimization, which results are presented in Table 7, provides the following solution: $t = 1$ min, $F = 45$ Hz, $s = 40$ rpm.

It is worth noting that in these conditions, the FB process allows achieving a 43.48 dynes/cm surface tension that is much higher than the current process and comparable productivity, which settles at 34 dynes. Figure 8 depicts a comparison among not-treated vessels, solvent-washed vessels, and the FB best case, resulting from the optimization.

3.3 Environmental and cost assessments

3.3.1 Goal, functional unit, and system boundaries

The objective of these assessments is the environmental and cost performance quantification and comparison of two different but comparable processes for the metal dry-washing:

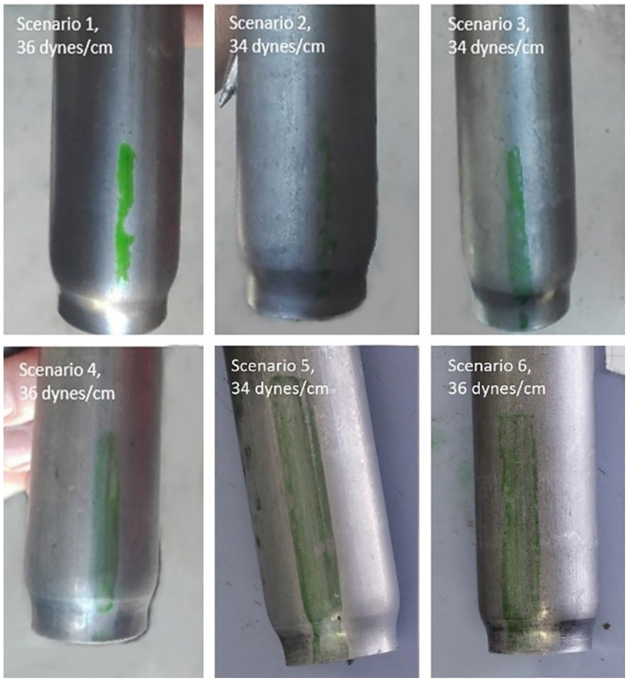


Fig. 4 Wettability of vessels in relation to the type of media

(i) the standard solvent-based washing and (ii) the proposed dry washing based on the fluidized bed.

The functional unit considered in the studies is defined as "the complete washing of a metal vessel with the geometric features reported in Fig. 1 and a length of 209.8 mm (large vessels) or 130 mm (small vessels)."

The system boundaries considered in the present analyses include only the operation of the two different machines that exploit the compared washing processes with the related input/output flows. The upstream and downstream phases, including the vessel manufacturing and related material used, are considered out of boundaries in the present environmental and cost assessments.

The standard solvent-based process is realized by exploiting a dedicated washing machine that uses an organic solvent for its washing cycle. The device can contemporarily process 280 small vessels or, alternatively, 540 large vessels. The washing cycle lasts 30 min, requires water and organic solvent, and consumes electric energy. Furthermore, the machine must be maintained by following a weekly maintenance plan to remove sludge and a monthly maintenance plan to clean the machine filter through sodium

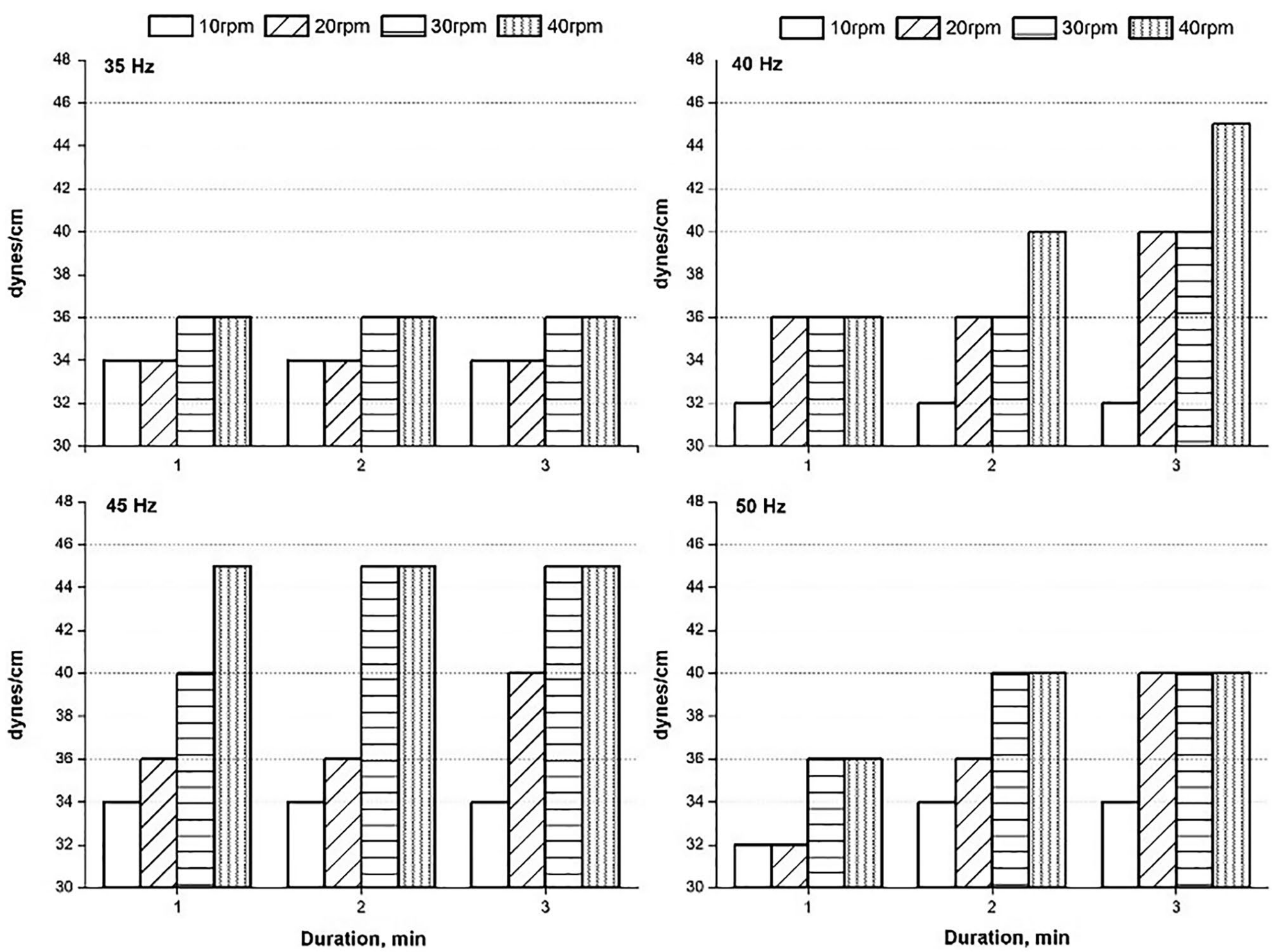


Fig. 5 Wettability test results

Table 6 ANOVA results

		Surface tension (dynes/cm)	
Source	*DF*	*F-value*	*p-value*
Duration, *t* (min)	**2**	**12.05**	**0.000**
Blower frequency, *F* (Hz)	**3**	**20.15**	**0.000**
Rotating speed, *s* (rpm)	**3**	**38.44**	**0.000**
$t \times F$	6	2.24	0.086
$t \times s$	6	1.09	0.404
$\boldsymbol{F \times s}$	**9**	**5.14**	**0.002**
R^2	(%)	93.67	

bicarbonate dissolved in water. An operator is required to load and unload the vessels in/from the washing machine, start and stop the cycle, and perform the maintenance operations needed.

The innovative fluidized bed-based process, instead, is realized through the use of the equipment described above. In this case, the machine is able to clean 21 vessels (small or large) in a cycle that lasts 1 min. Only electric energy is required for the fans functioning and movement system integrated with the developed machine. Also, in this case, a single operator is needed.

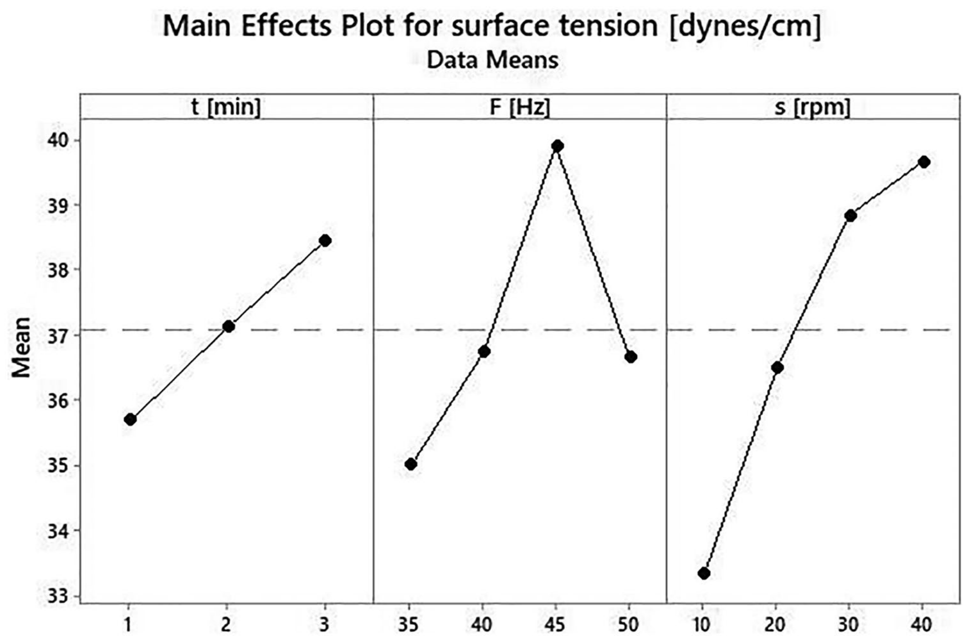


Fig. 6 Main effect plot for surface tension

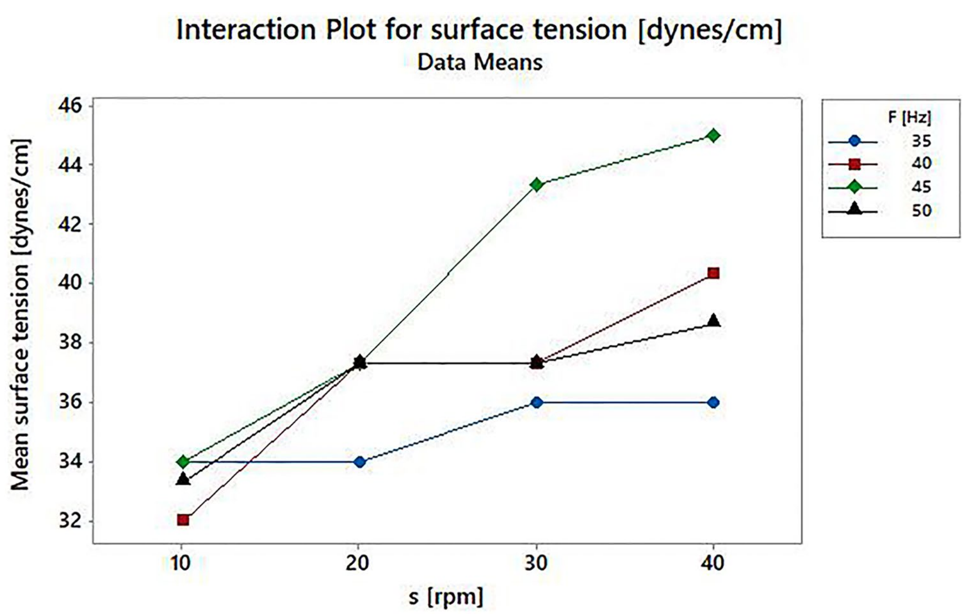


Fig. 7 Interaction plot for surface tension

Table 7 Response optimization

Response	Target	Lower	Upper	Estimated value	Desirability
Surface tension (dynes/cm)	Maximum	32	45	43.48	0.88

3.3.2 Inventory data

The used inventory data include primary data, mainly measured from the industrial processes, and secondary data, derived from the LCI database. Specifically, the Ecoinvent 3.1 database system model "allocation, default" version has been used as the secondary data source.

The following assumptions have been made during the collection of relevant data:

- Data related to substances used in the solvent-based washing process have been derived by measuring the quantity used for a single washing cycle.
- Data related to the energy consumption of the solvent-based washing process have been derived on the basis of historical data about the consumption of the machine for each washing cycle.
- Data related to weekly and monthly maintenance of the solvent-based washing machine have been derived from average historical data.
- Data related to the energy consumption of the FB based washing process have been measured through a power analyser.
- All the data related to the chosen functional unit have been derived by considering the number of vessels that it is possible to clean with a single washing cycle: (i) 540 pieces for small vessels washed with the solvent-based process, (ii) 280 pieces for large vessels washed with the solvent-based process, and (iii) 21 pieces for small/large vessels washed with the fluidized bed-based process.
- Data about the unitary costs of energy, substances, and labour have been derived from relevant literature data.
- No impacts and costs have been associated with the powder bed and its maintenance since the useful life of the powder bed before its substitution is much greater than the temporal boundaries of the functional unit (i.e. a single cycle of 1 min); thus, its contribution to the total impact and cost is negligible.
- Impacts and costs related to equipment in both the process variants have not been considered, since their service lives are much longer than a single washing cycle; thus, as demonstrated by previous studies [55], they contribute with negligible contributions.

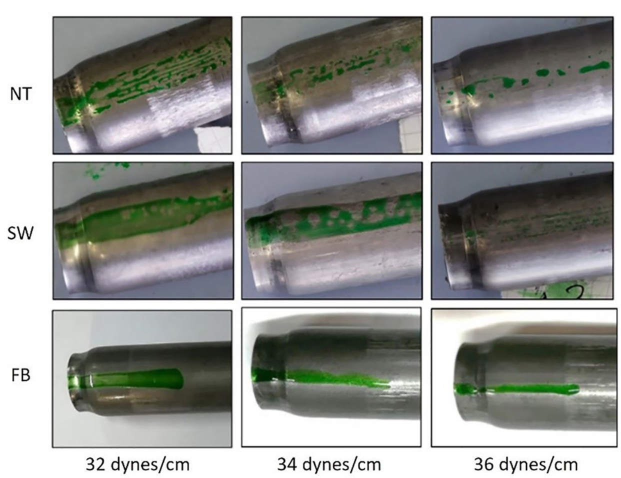


Fig. 8 comparison among not-treated (NT) vessels, solvent-washed (SW) vessels, and the FB washing best case (t = 1 min, F = 45 Hz, s = 40 rpm)

The inventory data and unitary costs used to perform the environmental and cost assessment are reported in Tables 8 and 9, respectively.

3.3.3 Environmental results

Among the large variety of available impact assessment methods and indicators, this study considered three methodologies for the quantification of the environmental impacts, widely used in the context of manufacturing processes [55, 57–61]:

- Cumulative energy demand (CED) that focuses on energy aspects by quantifying the direct and indirect energy consumption over the considered functional unit through an energy harvesting approach [62];
- Global warming potential (GWP) that allow the quantification of the contribution of the considered processes to climate changes due to direct and indirect emissions of CO_2 and non-CO_2 gases in a time horizon of 100 years. The impact assessment method defined in 2007 by the Intergovernmental Panel on Climate Change (IPCC) has been adopted in the present study [63];
- ReCiPe 2008 impact assessment methodology, providing the opportunity to have a comprehensive view of the potential environmental impacts and their causes considering a sufficiently large set of indicators [64]. The 18 midpoint impact categories, calculated according to the hierarchist (H) perspective, and the endpoint damage categories, calculated by considering an average (A) weighting set and the European normalization factor, have been considered.

Considering the first two indicators (i.e. CED and GWP), the results show a common trend (Figs. 9 and 10): the fluidized bed process is the most environmentally

Table 8 Inventory data for washing of one vessel (large or small)

Solvent-based washing			
I/O flow	*Quantity*		*Source*
	Small vessels	*Large vessels*	
Solvent (tetrachloroethylene)	0.00039 l	0.00074 l	Estimated from cycle consumption
Water	0,093 l	0,18 l	Estimated from cycle consumption
Electric energy	0.0074 kWh	0.014 kWh	Measured
Sludge (weekly removal)	0.00002 kg	0.00003 kg	Estimated from cycle company historical data
Sodium bicarbonate (monthly maintenance)	0.00001 kg	0.00002 kg	Estimated from cycle company historical data
Water (monthly maintenance)	0.00003 l	0.00006 l	Estimated from cycle company historical data
No. of pieces per cycle	540	280	-
Cycle time	30 min	30 min	-
Labour	1 operator	1 operator	-
Fluidized bed-based washing			
I/O flow	*Quantity (small/large vessels)*		*Source*
Electric energy	0.002 kWh		Measured
No. of pieces per cycle	21		-
Cycle time	1 min		-
Labour	1 operator		-

sustainable one, with total impacts of 22.49 kJ in terms of CED and 1.26 gCO2eq in terms of GWP. The calculated environmental savings with respect to the other processes are the following:

- About −87.8% and −89.4% with respect to the solvent washing of large vessels, in terms of CED and GWP, respectively;
- About −76.5% and −79.6% with respect to the solvent washing of small vessels, in terms of CED and GWP, respectively.

The dominant flow for all the compared processes is the electric energy consumed during the washing, representing more than three-quarters of the total impacts for CED and GWP indicators. The higher consumption of the solvent washing machine with respect to the fluidized bed machine (0.0074 kWh/cycle for solvent washing of large vessels vs 0.014 kWh for solvent washing of small vessel against 0.002 kWh for fluidized bed washing) is a determinant of the sustainability rank among the three compared processes. Instead, the other contributions (i.e. water for washing, weekly and monthly maintenance) represent less than 1% and can thus be considered negligible.

Table 9 Unitary costs

I/O Flow	Unitary cost	Source
Electric energy	0.16 €/kWh	Eurostat [56]
Solvent (perchloroethylene)	2.4 €/l	Company historical data
Water	1.26 €/m^3	Company historical data
Sodium bicarbonate	4.4 €/kg	Company historical data
Labour	25 €/h	Company historical data

To better understand the environmental impacts and the related causes, a broader set of midpoint indicators has been considered. Table 10 reports the results obtained for the three processes considering the 18 ReCiPe midpoint impact categories, while Fig. 11 illustrates a normalized comparison among the three processes. The normalization has been applied by dividing each value by the maximum value obtained in each impact category so that the most impactful scenario has an impact of 100% and the percentage savings can be easily and visually identified.

The most evident outcome from the ReCiPe midpoint analysis is that the fluidized bed process leads to relevant savings for all the impact categories. For almost all the impact categories (15 out of 18), the percentage savings are in the range of 84.7–99.9% in comparison with the large vessel solvent washing and between 70.5 and 99.8% in comparison with the small vessel solvent washing.

Among them, the highest savings have been obtained in the case of ozone depletion for which the calculated impact in case of fluidized bed is smaller than 2 and 3 orders of magnitude in comparison to the other processes (1.66E−10 kg CFC-11 eq., 1.23E−07 kg CFC-11 eq., and 6.42E−08 kg for fluidized bed, large vessel solvent washing, and small vessel solvent washing, respectively). This result is mainly due to the avoided use of tetrachloroethylene, an organochlorine compound featuring

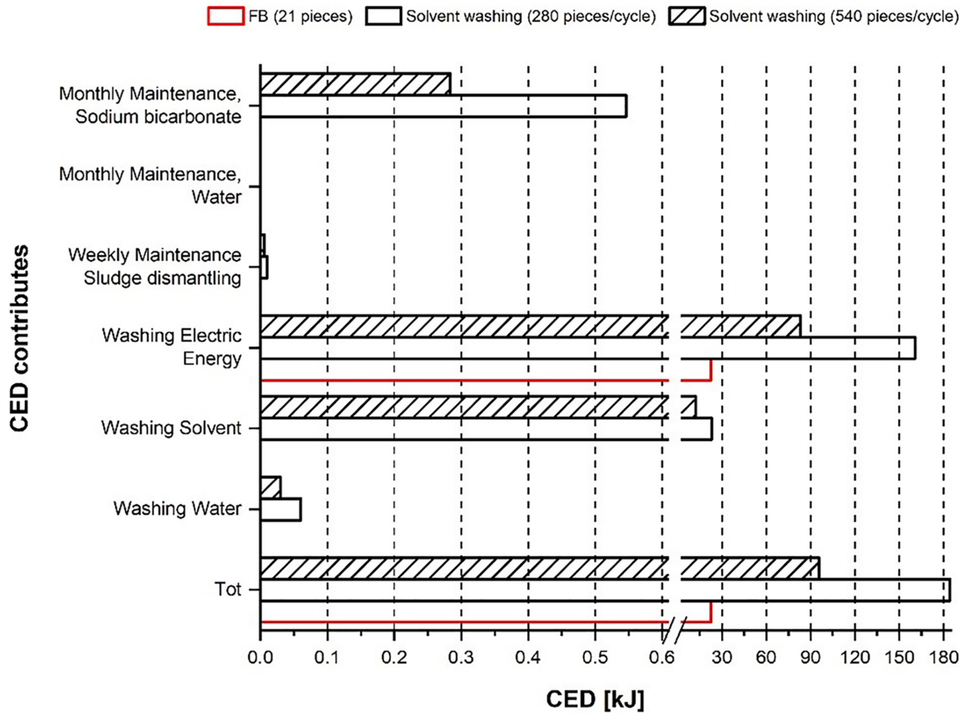


Fig. 9 LCIA in terms of CED (left)

a long atmospheric lifetime and pretty high ozone depletion potential and thus could affect stratospheric ozone [65].

The three exceptions concern the marine ecotoxicity, freshwater ecotoxicity, and metal depletion indicators, for which the observed savings for the fluidized bed process are in the range of 15.3–46.6% in comparison with the small vessel solvent washing and in the range of 56.1–72.4% in comparison with the large vessel solvent washing. For such impact categories, the synergy between the lower percentage contribution of the electric energy consumption (dominant

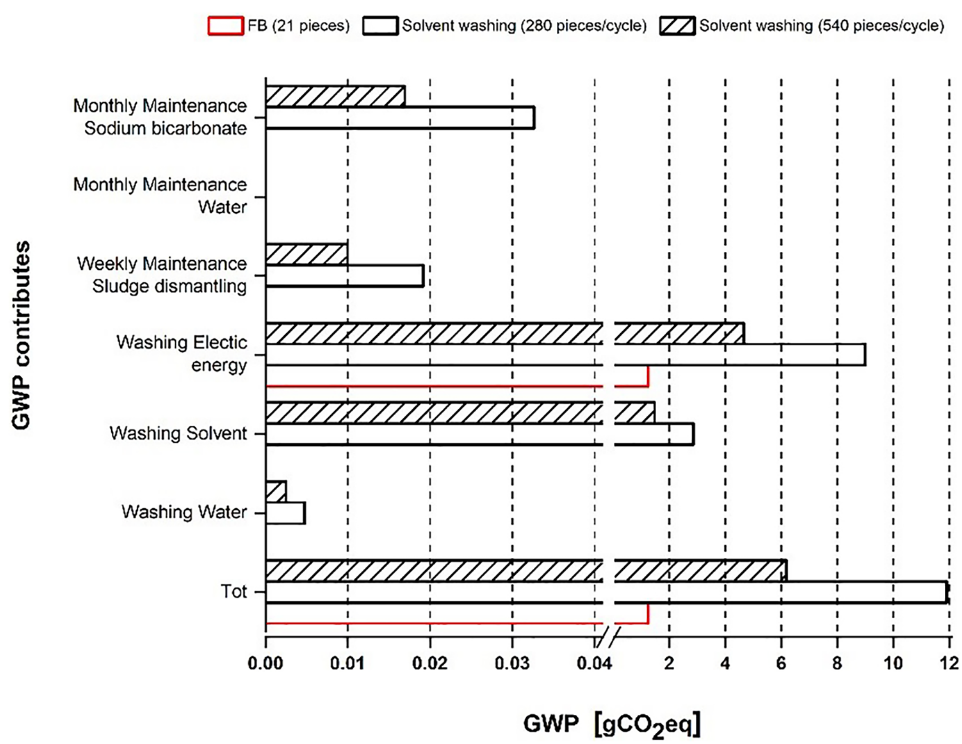


Fig. 10 LCIA in terms of GWP

Table 10 ReCiPe midpoint results

ReCiPe midpoint	Fluidized bed	Solvent washing (large vessels)	Solvent washing (small vessels)
Climate change (kg CO^2 eq)	1.26E−03	1.19E−02	6.18E−03
Ozone depletion (kg CFC-11 eq)	1.66E−10	1.23E−07	6.42E−08
Terrestrial acidification (kg SO_2 eq)	4.81E−06	4.46E−05	2.31E−05
Freshwater eutrophication (kg P eq)	2.22E−07	1.45E−06	7.51E−07
Marine eutrophication (kg N eq)	1.49E−07	1.32E−06	6.85E−07
Human toxicity (kg 1,4-DB eq)	2.33E−04	2.08E−03	1.08E−03
Photochemical oxidant formation (kg NMVOC)	2.84E−06	2.91E−05	1.51E−05
Particulate matter formation (kg PM10 eq)	1.49E−06	1.54E−05	8.02E−06
Terrestrial ecotoxicity (kg 1,4-DB eq)	5.01E−08	9.45E−07	4.90E−07
Freshwater ecotoxicity (kg 1,4-DB eq)	3.79E−05	1.09E−04	5.64E−05
Marine ecotoxicity (kg 1,4-DB eq)	3.29E−05	7.49E−05	3.88E−05
Ionising radiation (kBq U235 eq)	2.11E−04	1.52E−03	7.86E−04
Agricultural land occupation (m2a)	2.97E−05	2.10E−04	1.09E−04
Urban land occupation (m2a)	4.07E−06	2.90E−05	1.50E−05
Natural land transformation (m^2)	1.92E−07	1.37E−06	7.12E−07
Water depletion (m^3)	8.33E−06	2.63E−04	1.36E−04
Metal depletion (kg Fe eq)	3.46E−05	1.25E−04	6.49E−05
Fossil depletion (kg oil eq)	3.77E−04	3.15E−03	1.63E−03

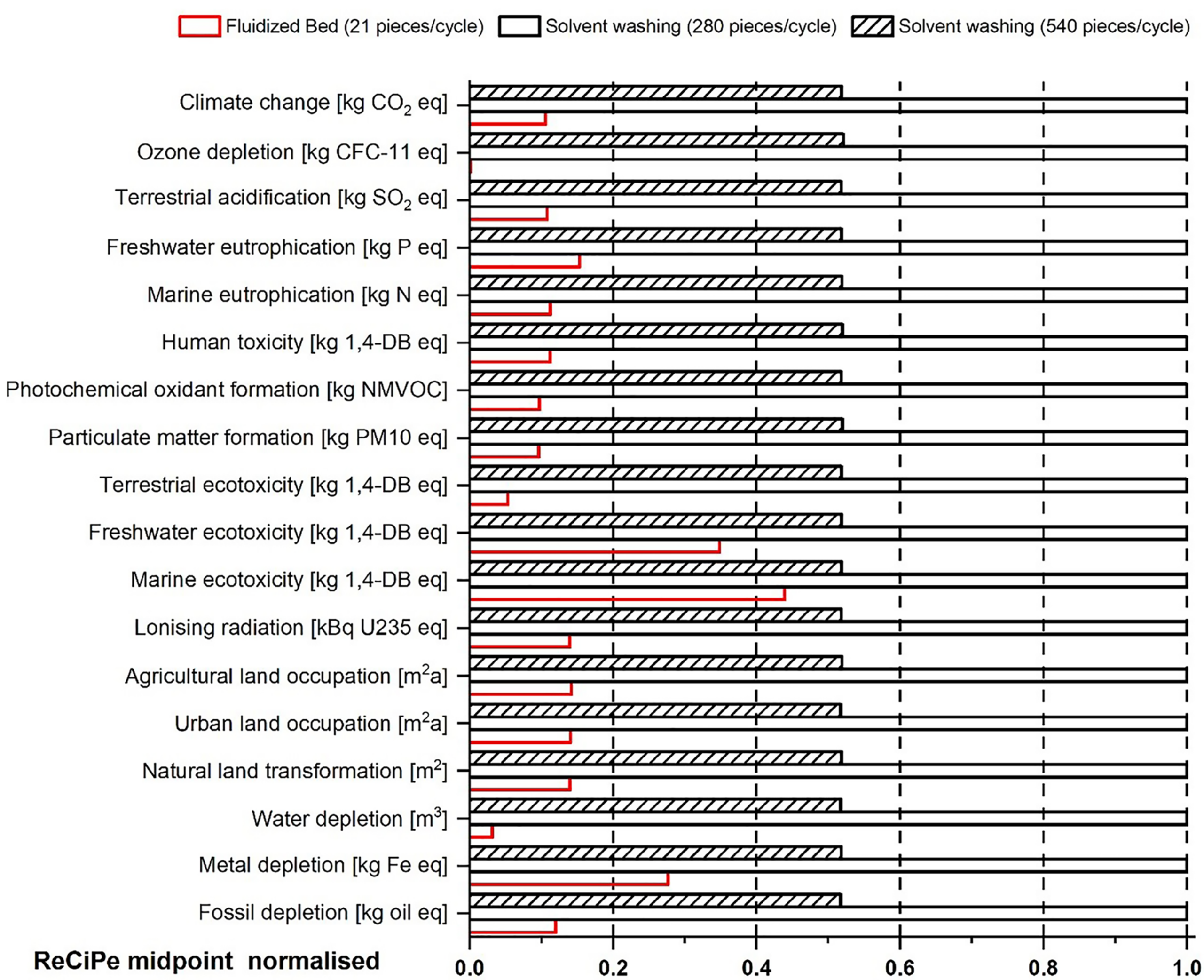


Fig. 11 Comparison (normalized) among the three process alternatives considering the ReCiPe midpoint impact categories

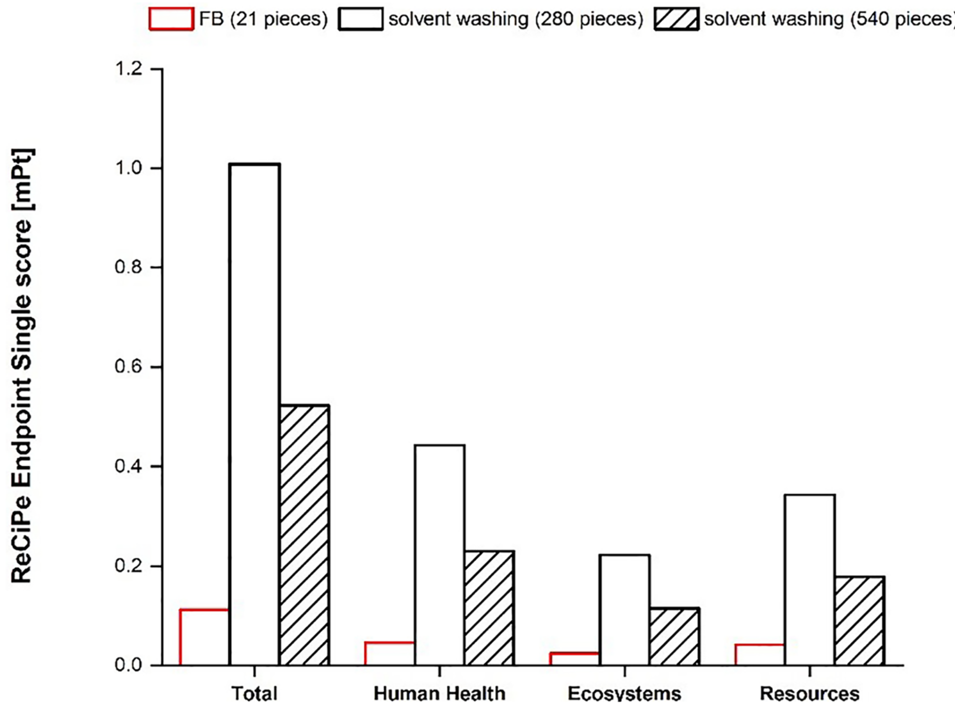


Fig. 12 ReCiPe endpoint results

flow) and the higher percentage contribution of the sodium bicarbonate used for the monthly maintenance in case of solvent washing processes (up to 27.4% in case of freshwater ecotoxicity) determines a lower difference among the three processes, particularly between the fluidized bed process and the small vessel solvent washing that differ for only 15.3% in case of marine ecotoxicity. This result can be explained by considering the high level of water toxicity potential of sodium bicarbonate, as demonstrated in several literature studies [66–68].

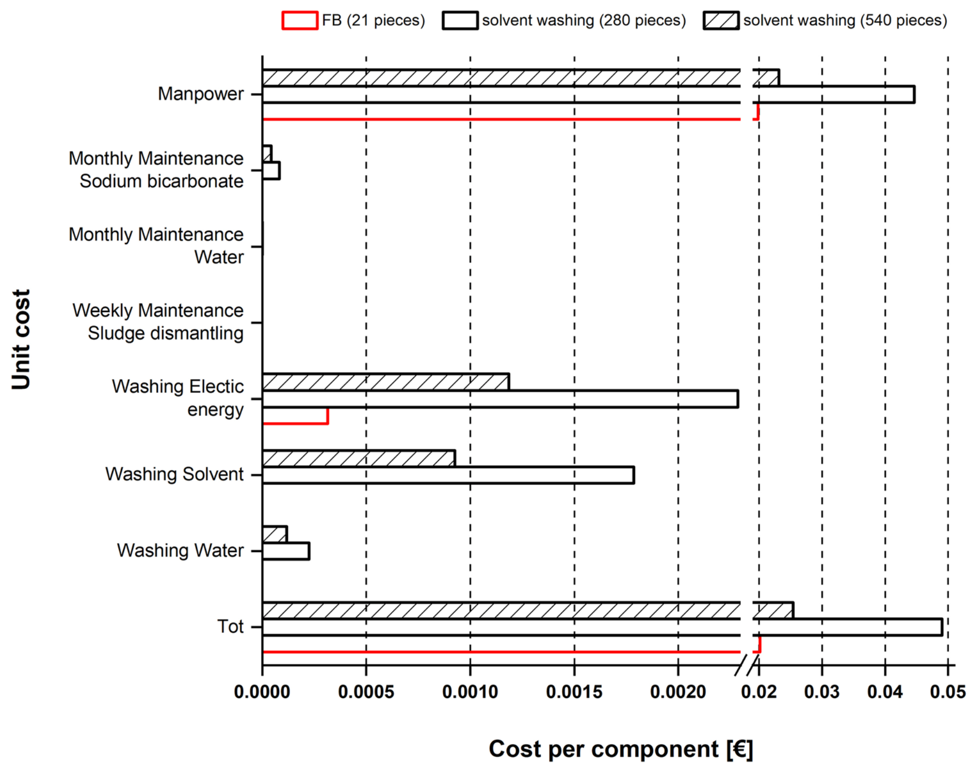
The last environmental assessment has been performed at the endpoint level. Results reported in Fig. 12 confirmed the trend observed with the other indicators previously discussed: the fluidized bed can be considered the most environmentally sustainable solution for washing metal vessels. Among the three ReCiPe endpoints, the most relevant are human health and resources which represent a little less than 80% of the total impacts for all the three considered processes, as depicted in Fig. 12. This is not surprising and can be explained by the fact that the electric energy and solvent consumptions are the dominant flows.

3.3.4 Cost results

A comparison of the overall operating costs of the compared washing processes is illustrated in Fig. 13. The cost analysis proves that FB is the most economically convenient alternative, with a decrease in the unit costs both in the case of small and large vessels. The saving in comparison with the solvent washing is almost 3 cents per piece (corresponding to 59%) for large vessels and more than 0.5 cents per piece (or 21%) for the small vessel. Highlighting the contributions split, the dominant flow for all the process alternatives is the labour which represents approximately 91% in the case of solvent washing and even the 98% in the case of FB. Although the developed FB prototype is capable of processing only 21 pieces per cycle, thanks to the short processing time, the labour cost per piece is reduced to less than 2 cents, while in the case of solvent is about 2.3 cents for small vessels and about 4.5 cents for large vessels. The same considerations can be done for the electric energy cost that is reduced by almost one order of magnitude (0.03 cents for FB vs 0.2 cents for solvent washing large vessels vs 0.1 cents for solvent washing small vessels). Another observable cost saving in the case of the FB process is related to the avoided use of solvent, while the other contributions for solvent washing processes (i.e. water, weekly, and monthly maintenance) are negligible.

It is worth noticing that the scale-up of the machine to increase the number of pieces being processed at the same time, and the future possibility of automating the loading–unloading phase may further increase the cost-saving per piece compared to the current FB process, thanks to the further reduction of the cycle time and the apportion of total costs among a high number of pieces.

Fig. 13 Cost analysis



4 Conclusions

The work proposed deals with the design and characterization of a prototypal device for a novel fluidized bed treatment addressed at the industrial cleaning washing process. The new process implemented was then compared with the current cleaning washing to assess performance and environmental impact through an experimental investigation and an LCA and operating cost analysis.

The design leads to implementing a device for the treatment of 21 vessels with a treatment cycle of 1 min, reaching comparable productivity with the current washing process applied. The outcome from the prototypal device confirmed the effectiveness of the fluidized bed as an alternative to current industrial cleaning techniques. The results showed values higher than the required industrial standard of 34 dynes/cm, with a mean surface tension of 36 dynes/cm. The experimental test carried out allowed defying the best processing parameters such as media typology, blower frequency, rotating speed, and treatment duration. In these conditions (2.5 mm glass spheres, $t=1$ min, $F=45$ Hz, and $s=40$ rpm), the FB process achieved a 43.48-dynes/cm expected surface tension and comparable productivity. Also, the prototypal device produces a neglectable environmental impact due to low resources consumption and the FB design, which do not allow the contaminants to be dispersed in the environment. This is confirmed by the LCA and cost assessment, where the FB treatment has the lowest CED, GWP, and ReCiPe scores. The ReCiPe midpoint evaluation shows that the percentage savings are in the range of 84.7–99.9% for the large vessel solvent washing while between 70.5 and 99.8% for the small vessel. The CED e GWP saw a decrement of −87.8% and −89.4% for the large vessel, while of −76.5% and −79.6% for small vessels. Also, the operating cost per piece is reduced of the 55% and 13% for large and small vessels, respectively.

In conclusion, the fluidized bed dry washing process is a valuable option for metal component treatments, which can be profitably exploited in industrial environment. With respect to the other processes, it allows reaching high cleanness level cutting at the same time the environmental impact; indeed, a low pollutant emission level is associated to this process as well as the dispersion of hazardous substances before, during, and after the operations. Scaling up of the developed FB machine, as well as the investigation of the compatibility with other materials, could be future directions of research toward the full industrial exploitation of the proposed metal dry washing process.

Author contribution The work was conceived by Gianluca Rubino. The prototype design and sizing were carried out by Gianluca Rubino. The data collection was carried out by Gianluca Rubino, Gabriele Baiocco, and Erica Menna. All authors contributed to the data analysis. The process optimization was performed by Gianluca Rubino, Erica Menna, and Gabriele Baiocco, while the life cost analysis and the cost analysis were performed by Marco Marconi. The first draft of the manuscript

was written by Erica Menna, Gabriele Baiocco, and Marco Marconi while the final writing by Erica Menna and Gabriele Baiocco.

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Declarations

Competing interests The authors declare no competing interests.

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