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Life Cycle and Hygienic Evaluation of Green vs. Traditional Cleaning Protocols in Civil Buildings

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Abstract

The transition toward low-impact facility management requires robust evidence that environmental optimization does not compromise hygienic reliability. In the professional cleaning sector, sustainability claims are often based on product substitution rather than on integrated performance validation. This study provides a dual-perspective evaluation comparing a conventional cleaning protocol with the Pfe Green system, an eco-designed approach compliant with the Italian *Minimum Environmental Criteria* (CAM, D.M. 29 January 2021), implemented in a civil building of Renault Italia S.p.A. in Rome. A combined Life Cycle Assessment (LCA) and microbiological evaluation was conducted under real operational conditions to quantify both climate-related and hygienic outcomes. The LCA, performed in accordance with ISO 14040–44 and ISO 14067 standards, demonstrated that the Green protocol achieved an approximately 30% reduction in Global Warming Potential over a 100-year horizon (GWP₁₀₀), mainly attributable to structural process optimization, including reduced detergent mass, lower laundering temperatures, improved dilution control, and energy-efficient machinery. Microbiological monitoring, conducted according to ISO 14698 and UNI EN ISO 18593, showed that both systems ensured high levels of microbial abatement, with the Green protocol exhibiting slightly higher average reductions in total viable counts (96.1% vs. 94.2%). These findings confirm that lower chemical input and eco-formulated products do not compromise hygienic performance when supported by standardized procedures and microfiber-based mechanical removal. By integrating life-cycle metrics with microbiological validation, this research proposes a replicable assessment model for sustainable cleaning services. The results demonstrate that CAM-aligned green protocols can simultaneously reduce greenhouse gas emissions and maintain hygienic effectiveness, thereby supporting evidence-based sustainable procurement and corporate environmental strategies. The originality of this study lies in the integration of life-cycle environmental assessment with real-world microbiological validation under operational conditions, providing a comprehensive framework for evaluating sustainable cleaning systems beyond product-level substitution.

Keywords: Life Cycle Assessment (LCA); sustainable cleaning systems; microbiological efficacy; CAM; facility management; GWP₁₀₀



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1. Introduction

The professional cleaning sector represents a critical yet often underexamined component of sustainable facility management. Beyond its primary function of ensuring hygienic safety, the sector exerts measurable environmental pressures through chemical production, energy consumption, textile turnover, packaging waste, and transportation logistics. As sustainability criteria increasingly shape public procurement and corporate environmental governance, cleaning services have become a strategic leverage point for reducing operational carbon footprints.

In Italy, the introduction of the Minimum Environmental Criteria (CAM; D.M. 29 January 2021) has formalized sustainability requirements within public tenders, mandating the adoption of environmentally preferable products and processes. However, regulatory compliance alone does not guarantee systemic sustainability. A central challenge persists: environmental improvements must be demonstrated without compromising hygienic standards, particularly in high-use civil environments [1,2].

Life Cycle Assessment (LCA) provides a standardized and internationally recognized framework for quantifying environmental impacts across the full service chain, in accordance with ISO 14040, ISO 14044 and ISO 14067 [3–5]. In the context of cleaning, LCA enables evaluation of upstream burdens (chemical production, textile manufacturing), core operational impacts (energy and water use by machinery and washing machines, commuting of service operators), and downstream effects (waste and wastewater treatment). While several studies have applied LCA to cleaning products [6–8], fewer investigations have assessed entire service systems under real operational conditions.

Previous studies have primarily focused on product-level assessments or isolated environmental indicators, often neglecting the integration of operational performance metrics. For example, recent contributions have evaluated cleaning agents and disinfection strategies from either an environmental or microbiological perspective, but rarely within a unified framework. This gap limits the ability to assess potential trade-offs between sustainability and hygiene. Therefore, there is a need for integrated approaches that simultaneously evaluate environmental impacts and functional performance under real-use conditions [9–14].

At the same time, microbiological monitoring remains the primary indicator of cleaning efficacy. Standardized methodologies, including ISO 14698:2003 and UNI EN ISO 18593:2018, provide objective measures of surface bioburden reduction and compliance with occupational hygiene benchmarks (ISPESL; INAIL) [15–17]. Yet environmental and hygienic assessments are rarely integrated within a unified analytical framework.

The recent literature in sustainability has highlighted the importance of coupling environmental indicators with functional performance metrics to avoid burden shifting and to ensure holistic sustainability. Nevertheless, empirical case studies that simultaneously quantify climate impact and microbiological outcomes in operational civil buildings remain limited.

The present study addresses this gap by conducting a comparative, real-world evaluation of two cleaning protocols—a conventional system and the CAM-compliant Pfo Green approach—applied within the civil premises of Renault Italia S.p.A. in Rome. The objective is twofold: (i) to quantify environmental performance through Global Warming Potential (GWP, kg CO₂e) using a cradle-to-grave LCA framework, and (ii) to assess hygienic effectiveness through standardized microbiological surface monitoring.

By integrating life-cycle modeling with microbial performance data, this research moves beyond product-level sustainability claims and proposes a systems-based validation of green cleaning services. The findings contribute to evidence-based facility management

and provide quantitative support for aligning environmental policy instruments with measurable hygienic outcomes.

The paper is structured as follows: Section 2 describes the materials and methods, including the Life Cycle Assessment framework and microbiological analysis. Section 3 presents the results of environmental and hygienic performance and discusses the findings in relation to existing literature, and Section 4 concludes with implications for sustainable facility management and future research directions.

2. Materials and Methods

2.1. Study Overview and Objectives

The study was designed to compare the Pfe Green protocol—developed by Pfe S.p.A. in compliance with the CAM (D.M. 29 January 2021)—with the conventional cleaning system used in civil environments. The objective was to (i) assess the environmental benefits of the *Green* protocol through a Life Cycle Assessment (LCA) and (ii) verify its hygienic performance through microbiological monitoring of surfaces before and after cleaning [18].

2.2. Study Site and Sampling Period

The investigation was conducted at the *Renault Italia S.p.A.* headquarters (Building IV, Via Tiburtina 1159, Rome, Italy), which represents a typical civil cleaning environment, including offices, meeting rooms, restrooms, and workshop areas. The total surface area analyzed was 3270 m² (Figure 1).



Figure 1. Plan of Building IV of Renault Italia's headquarters in Rome (RM).

Field data collection covered two consecutive four-week periods. The Traditional protocol was applied from 9 May to 6 June 2025, followed by the *Green* protocol from 9 June to 7 July 2025.

Both protocols were applied under identical operational conditions, frequencies, and surface typologies to ensure methodological consistency and comparability.

2.3. Life Cycle Assessment

The LCA was conducted in accordance with ISO 14040:2021 and ISO 14044:2021, following the four-phase framework consisting of goal and scope definition, life cycle inventory (LCI), life cycle impact assessment (LCIA), and interpretation [3–5,19].

2.3.1. Goal and Scope Definition

The goal of this study was to compare the environmental performance of a conventional cleaning protocol and the Pfe Green system under real operational conditions, with particular focus on climate change impacts.

The functional unit was defined as 1 m² of surface maintained clean for 1 year, representing the service provided under standard conditions.

The system boundaries covered the full life cycle (“cradle-to-grave”) of the cleaning service, including upstream processes such as the production and transport of cleaning agents, textiles, packaging, and durable equipment; core processes related to on-site service execution, including energy consumption, water use, chemical application, and operator transport; and downstream processes involving waste management and wastewater treatment.

Common elements shared by both protocols, such as personal protective equipment (PPE) and consumables unaffected by the protocol change, were excluded according to cut-off criteria ensuring $\geq 99\%$ impact coverage, in line with ISO 14044 requirements for system completeness and relevance [3].

2.3.2. Life Cycle Inventory (LCI)

Primary site-specific data on material and energy consumption were collected through direct measurements, including calibrated balances, water and energy meters, structured inventory tracking, and standardized field checklists.

Secondary data were obtained from certified Carbon Footprint of Product (CFP) and Environmental Product Declaration (EPD) datasets, as well as from the Managed LCA Content 2025.1 (Sphera, 2025) database.

Data quality met ISO 14044 and PCR requirements, with proxy datasets contributing less than 10% of the total calculated environmental impact.

All input and output flows were quantified and normalized to the functional unit to ensure consistency and comparability between the analyzed systems.

A detailed overview of the Life Cycle Inventory (LCI), including the main quantified input and output flows, units, data sources, and modeling assumptions for the Traditional and Green protocols, is reported in Table S1 (Supplementary Materials).

2.3.3. Life Cycle Impact Assessment (LCIA)

The environmental impact category considered in this study was the Global Warming Potential over a 100-year time horizon (GWP₁₀₀), expressed in kg CO₂-equivalent and calculated using IPCC AR6 characterization factors [20,21].

Modeling was performed using the LCA for Experts (Sphera 2025) software suite, and results were normalized to the functional unit defined by cleaning services PCR to enable direct comparison between protocols [21].

2.3.4. Interpretation

The interpretation phase was conducted in accordance with ISO 14044, with the objective of identifying the main contributors to environmental impact and evaluating differences between the two cleaning protocols.

Results were analyzed considering consistency with the goal and scope definition, data quality, and completeness of the system boundaries. Sensitivity considerations were quali-

tatively assessed, particularly in relation to key parameters such as chemical consumption, textile systems, and operator transport.

The interpretation focused on identifying the main drivers of GWP reduction and ensuring that conclusions were supported by the inventory and impact assessment results.

Particular attention was given to the modeling of operator transport, which represents a relevant contribution to the overall environmental impact of service delivery [22]. In the Traditional protocol, daily commuting was performed using a conventional internal combustion engine vehicle, whereas in the Green protocol, an electric vehicle was adopted. Transport distances were assumed to be identical for both scenarios, and emissions were calculated using appropriate emission factors derived from LCA databases. For the electric vehicle, the Italian electricity mix was considered [23]. These assumptions were integrated within the core operational phase and normalized to the functional unit.

2.4. Microbiological Assessment

Microbiological sampling and analysis were carried out following ISO 14698:2003 and UNI EN ISO 18593:2018 standards, and in accordance with INAIL (2017) and ISPESL (2009) guidelines [15–17,24].

2.4.1. Sampling Plan

Sampling points were selected to represent areas characterized by different contamination risk levels, including offices, meeting rooms, restrooms, and workshop zones. Both RODAC contact plates and sterile swab techniques were employed. RODAC plates containing Tryptic Soy Agar (TSA) were used for total aerobic mesophilic counts, while selective culture media—Mannitol Salt Agar, MacConkey Agar, and Sabouraud Dextrose Agar—were used to support the detection and isolation of specific microbial groups [8,25,26].

2.4.2. Sampling and Analysis Procedure

Contact plates were pressed against target surfaces for 30 s under standardized pressure using calibrated applicators. Swab samples were collected from 10 cm × 10 cm delimited surface areas using pre-moistened neutralizing buffer swabs to ensure recovery of residual microorganisms without disinfectant interference [27]. Following sampling, culture plates were incubated at 30 ± 1 °C for 48 h, and colonies were enumerated and expressed as colony-forming units per square centimeter (CFU/cm²).

Microbiological performance was expressed as the percentage reduction in total viable counts (TVC) after cleaning relative to baseline pre-cleaning values.

2.5. Data Integration and Statistical Analysis

Environmental and microbiological data were analyzed separately and comparatively to evaluate correlations between reduced GWP and hygienic performance. Microbiological reductions were expressed as mean ± standard deviation (SD), calculated from replicate measurements across sampling points per category ($n \geq 3$). Statistical differences between protocols were evaluated using Student's *t*-test (two-tailed, $\alpha = 0.05$), after verification of data normality.

3. Results

3.1. Environmental Performance (LCA Results)

The comparative Life Cycle Assessment demonstrated that the Pfe Green cleaning protocol achieved a substantial reduction in climate change impact relative to the traditional system, expressed as Global Warming Potential (GWP₁₀₀, kg CO₂e).

The system boundaries (“cradle-to-grave”) incorporated the production, use, and end-of-life phases of consumables, textiles, equipment, and utilities.

Across the full life cycle, the Green protocol yielded an average decrease in total GWP of 33%. This reduction was primarily attributable to structural process optimizations within the service chain, in particular to a change in the transport mode of service operators. Thanks to the adoption of an electric car for daily commuting, it was possible to reduce emissions by 283 kg CO₂e for each year of service provided.

The adoption of microfiber textiles, characterized by extended service life, made it possible to avoid 129 kg of CO₂e emissions per year.

Moreover, the optimized use of detergents and disinfectants—achieved through reduced chemical concentrations and improved dilution control—significantly lowered upstream impacts associated with formulation, packaging, and transport. Additionally, reduced washing temperatures in laundry operations (40 °C versus 60 °C) contributed to lower energy consumption, while maintaining hygienic performance. Finally, the implementation of energy-efficient machinery, including Eco-mode scrubber-dryers (e.g., Fimap GL PRO), further decreased the overall environmental burden.

The relative contributions of key life-cycle stages are shown in Figure 1, which provides a conceptual summary of the LCA results and highlights the proportional impact of upstream, core, and downstream phases.

Life Cycle Inventory Results

The life cycle inventory (LCI) was constructed in accordance with ISO 14040 and ISO 14044 principles, ensuring completeness, transparency, and coherence between the defined functional unit and all quantified input/output flows [28–30]. For each unit process included within the system boundaries, a specific flow was determined and normalized to the functional unit defined as 1 m² of representative surface maintained clean for one year. This normalization enables direct comparability between the Green and Traditional protocols independently of building size and operational scale.

The inventory analysis revealed substantial structural differences between the two cleaning systems, particularly in relation to chemical consumption, textile use, and energy demand associated with laundering operations.

Chemical Consumption

A marked reduction in total cleaning chemical use was observed under the Green protocol. For surface cleaning products, the annual site consumption per square meter was significantly lower than in the Traditional system. The most evident difference concerned floor detergents: the Traditional protocol required 2.48×10^{-2} kg/m²·year of “Velvet,” whereas the Green protocol required only 5.25×10^{-4} kg/m²·year of “Ultra Green,” corresponding to a reduction of approximately two orders of magnitude. This difference is attributable to improved dilution control, concentrated formulations, and optimized dosing procedures.

Similarly, overall annual chemical consumption at the building scale was reduced from 155.1 kg/year (Traditional) to 72.4 kg/year (Green), corresponding to a reduction of more than 50%. This decrease directly affects upstream impacts (raw material extraction, formulation, packaging production, and transport) and downstream burdens, including packaging waste generation [31].

In the laundry system, although the Green protocol employs a slightly higher total mass of detergents for textile reconditioning, this increase is offset by replacing disposable textiles with reusable microfiber systems. Therefore, the higher detergent input must be interpreted within a broader circular-use perspective rather than as an inefficiency, as it supports material reuse and reduces the throughput of single-use textiles.

Textile Systems: Reusable vs. Disposable

The most structurally significant difference between protocols concerns textile materials.

The Traditional protocol relies heavily on disposable dry-sweeping gauzes (7842 units/year, corresponding to $2.40 \text{ units/m}^2\cdot\text{year}$), representing the dominant material flow within this category. In contrast, the Green system replaces these single-use materials with reusable microfiber fringes (2.3 units/year at the site level, equivalent to $6.97 \times 10^{-4} \text{ units/m}^2\cdot\text{year}$).

This transition from disposable to reusable textiles radically alters the service's material intensity profile. While reusable textiles require periodic laundering (thus shifting part of the environmental load toward energy and water use), the dramatic reduction in material throughput substantially decreases upstream impacts related to production, packaging, and transport, and end-of-life impacts due to waste transport and treatment.

The adoption of reusable microfiber textiles is supported by previous studies demonstrating their superior durability and cleaning efficiency compared to disposable materials, as well as their reduced life-cycle environmental impact when properly managed through controlled laundering processes [9,32–34]. This approach aligns with circular economy principles by reducing material throughput and waste generation.

This inventory shift explains why textile-related emissions emerge as one of the principal contributors to impact in reduction in the comparative LCA results.

Laundry Energy and Water Demand

The inventory data highlight a clear difference in washing parameters between protocols. Both systems perform 228 annual washing cycles; however, the Green protocol operates at 40°C , resulting in 757.3 MJ/year of energy use ($2.32 \times 10^{-1} \text{ MJ/m}^2\cdot\text{year}$), whereas the Traditional protocol operates at 60°C , resulting in 999.7 MJ/year ($3.06 \times 10^{-1} \text{ MJ/m}^2\cdot\text{year}$).

This corresponds to a reduction of approximately 24% in laundry energy demand under the Green protocol. The lower washing temperature represents a key operational optimization, reducing electricity consumption without compromising hygienic performance, as demonstrated in the microbiological assessment.

Conversely, water consumption for laundry is slightly higher in the Green protocol ($16.812 \text{ m}^3/\text{year}$ vs. $14.843 \text{ m}^3/\text{year}$). This increase is attributable to the higher number of reusable textiles undergoing reconditioning. However, when expressed per functional unit, the difference remains marginal (5.14×10^{-3} vs. $4.54 \times 10^{-3} \text{ m}^3/\text{m}^2\cdot\text{year}$) and contributes minimally to total GWP.

Mechanical Equipment Energy Demand

Energy consumption from mechanized cleaning equipment was comparable between systems but still slightly lower under the Green protocol.

Specifically, annual energy demand for scrubber-dryer operations was 98.23 MJ/year ($3.00 \times 10^{-2} \text{ MJ/m}^2\cdot\text{year}$) when operated in Eco mode, compared with 101.72 MJ/year ($3.11 \times 10^{-2} \text{ MJ/m}^2\cdot\text{year}$) under Normal mode in the Traditional system.

Similarly, carpet cleaning energy demand was lower under the Green protocol due to reduced operating time (13.9 h annually vs. 33.1 h in the Traditional protocol), despite the Green machine model having a higher instantaneous power draw. Although the absolute differences are modest relative to chemical and textile flows, these operational optimizations contribute cumulatively to the overall reduction in GWP.

Wastewater Generation

Wastewater generation closely follows water consumption patterns. Annual wastewater production amounted to $19.035 \text{ m}^3/\text{year}$ ($5.82 \times 10^{-3} \text{ m}^3/\text{m}^2\cdot\text{year}$) under the Green protocol and $17.066 \text{ m}^3/\text{year}$ ($5.22 \times 10^{-3} \text{ m}^3/\text{m}^2\cdot\text{year}$) under the Traditional protocol.

The slightly higher wastewater production in the Green system reflects increased laundering activity associated with reusable textiles. However, when evaluated within the full life-cycle perspectives, this increment remains environmentally secondary compared with the avoided impacts related to disposable textile production and chemical manufacturing.

In both systems, the core operational phase, including energy and water consumption and service operators' transport, represented the largest share of total emissions ($\approx 75\text{--}80\%$), followed by the upstream phase ($\approx 15\text{--}20\%$), including detergents and textiles manufacturing, while the downstream phase accounted for less than 5% of total GWP.

Under the Green protocol, these proportions shifted toward lower upstream contributions by substituting high-impact chemical products with eco-formulated alternatives certified under ISO 14067. This structural rebalancing of life-cycle contributions confirms that material input optimization is a critical driver of climate impact mitigation within service-based systems.

Waste management and recycling practices further supported environmental improvements. The incorporation of partially recycled materials in packaging (50% HDPE; 84.5% paperboard) and the recovery of textile materials ($\approx 98\%$ recycling rate) reduced the environmental footprint of end-of-life stages.

Tables 1 and 2 summarize the absolute and percentage variations in Global Warming Potential (GWP₁₀₀) between the Green and Traditional protocols, disaggregated by service scenario and macro-impact category.

Table 1. Service GWP changes for different scenarios.

System	$\Delta\%$ GWP Green vs. Traditional	Δ GWP Green vs. Traditional	M.U.
Reduction in GWP of service per square meter per year	−33.0%	−139	g CO ₂ e/m ² year
Reduction in GWP of service by site year		−454	kg CO ₂ e/site year
Reduction in GWP of service per site for the duration of the contract (36 months)		−1.363	kg CO ₂ e/site contract (3 years)

Table 2. GWP variations by macro-aspect of the analyzed protocols.

Aspect	$\Delta\%$ GWP Green vs. Traditional	Δ GWP Green vs. Traditional	M.U.
Operator transport	−32.1%	−283.0	kg CO ₂ e/site year
Textiles	−136.8%	−128.9	kg CO ₂ e/site year
Energetic consumption	−31.7%	−43.6	kg CO ₂ e/site year
Chemical consumption	−26.1%	−30.2	kg CO ₂ e/site year
Water consumption	2.3%	0.04	kg CO ₂ e/site year
Waste water treatment	5.4%	0.9	kg CO ₂ e/site year
Production and end of life machinery and equipment	38.4%	30.5	kg CO ₂ e/site year

Overall, the Pfe Green protocol demonstrated compliance with the CAM environmental performance criteria, confirming that eco-designed cleaning systems can substantially reduce GHG emissions while maintaining equivalent operational performance under real-use conditions.

These findings align with those reported in prior sustainability research on service-based LCA optimization [1,2], further substantiating the central role of life-cycle thinking in enabling evidence-based decarbonization strategies within the professional cleaning sector and supporting the transition of facility services toward climate neutrality.

3.2. Microbiological Performance

Microbiological monitoring provided a quantitative assessment of cleaning efficacy under real operational conditions. Sampling points were selected to ensure representativeness of different contamination risk levels and included office desks, meeting tables, restroom fixtures, corridors, and workshop floors. This distribution allowed evaluation across both high-touch surfaces and low-contact areas, reflecting heterogeneous patterns of microbial deposition.

Baseline and Post-Cleaning Microbial Load

Before cleaning, total viable counts (TVC) on Tryptic Soy Agar (TSA) confirmed the expected variability in microbial burden according to surface type, frequency of use, and human traffic density. High-contact surfaces such as tables, seating areas, and sanitary fixtures exhibited the highest baseline contamination, whereas corridor floors and less frequently used areas showed comparatively lower counts.

Following application of both cleaning protocols, a marked reduction in microbial load was consistently observed across all sampled environments. In all cases, post-treatment counts were substantially reduced relative to baseline levels and fell within the acceptability thresholds indicated by Italian occupational hygiene guidelines for civil environments (ISPESL, 2009) [17].

The Traditional protocol achieved a high overall percentage reduction in TVC, while the Green protocol showed a slightly higher mean reduction across most surfaces. Although differences between protocols were limited in magnitude and should be interpreted cautiously, the overall trend indicates equivalent and, in several cases, marginally improved performance of the Green system, as illustrated in Figure 2.

Surface-Specific Trends

A more detailed surface-level analysis reveals important patterns. High-touch surfaces, including desks, tables and restroom fixtures, exhibited consistently strong microbial reductions under both protocols. In these areas, the Green protocol often showed slightly lower residual counts, suggesting effective removal efficiency despite lower chemical mass input [35,36].

Workshop areas presented the highest residual contamination in both systems. This finding is likely attributable to intrinsic surface characteristics such as porosity, persistent organic residues, and mechanical soil embedding, rather than to deficiencies in cleaning formulation. The comparable behavior of both protocols in these zones reinforces the interpretation that environmental characteristics, rather than chemical aggressiveness, drive the presence of residual microbes.

Collectively, these observations indicate that cleaning efficacy is primarily influenced by mechanical action, microfiber performance, and standardized procedures rather than by detergent concentration alone.

Although the difference was not statistically significant ($p > 0.05$), the *Green* protocol consistently exhibited slightly higher microbial reduction across most surfaces, particularly on high-touch areas such as tables, handles, and restroom fixtures.

The only exception was observed in workshop zones, where residual contamination remained relatively higher ($\approx 2.5 \times 10^2$ CFU/25 cm²). This residual bioburden is plausibly attributable to intrinsic surface characteristics and persistent soil embedding rather than to protocol inefficacy, as comparable patterns were observed under both treatments.

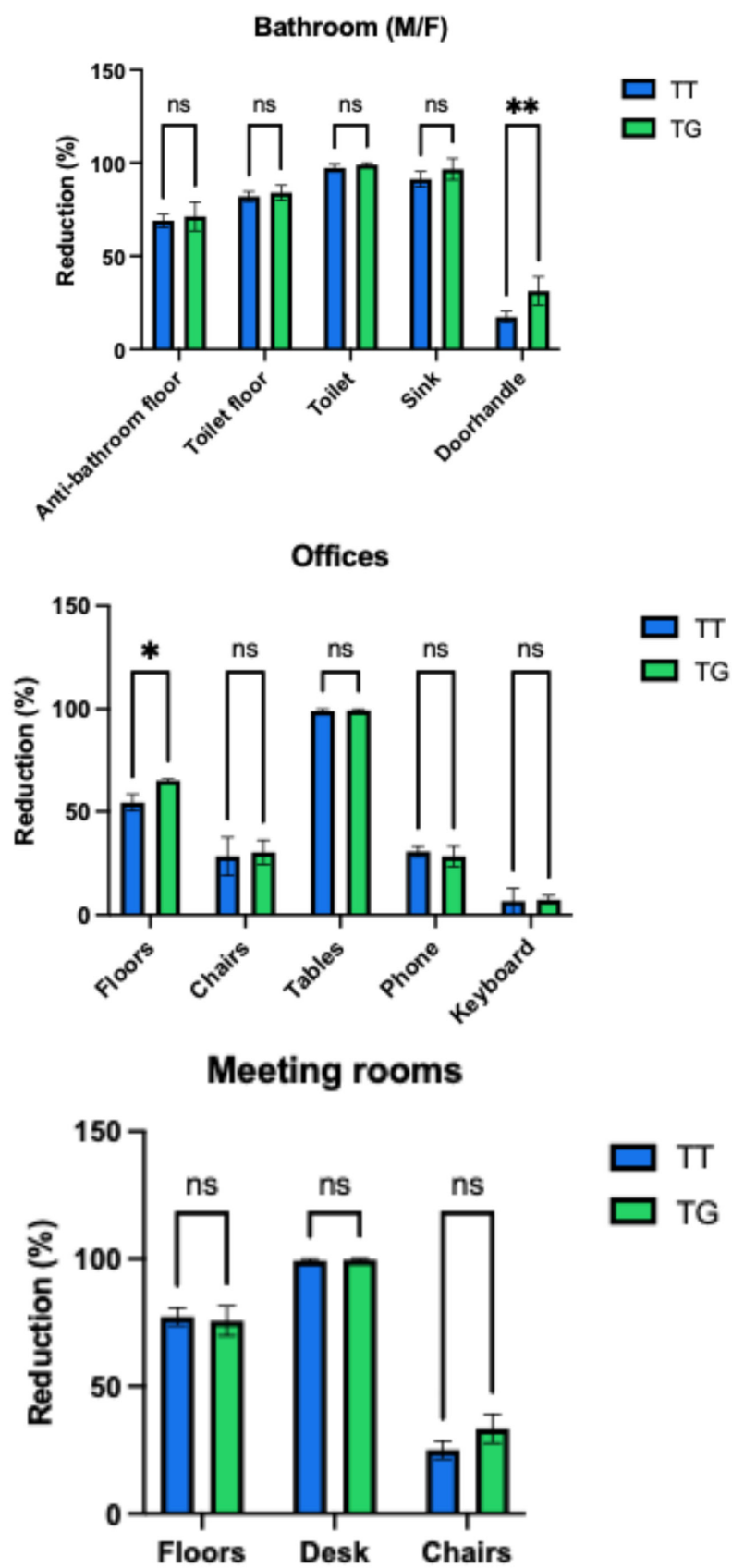


Figure 2. Cont.

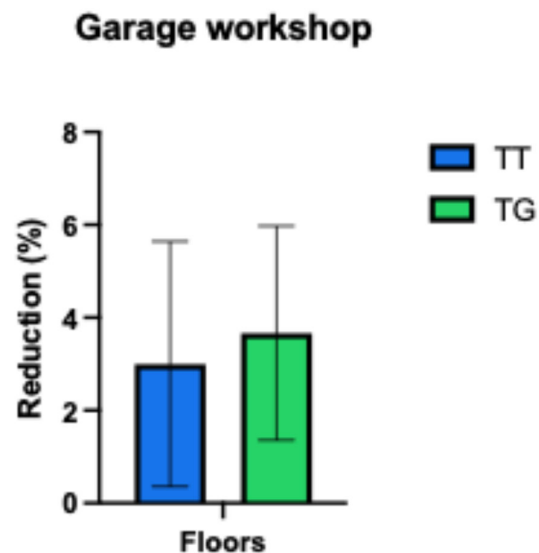


Figure 2. Percentage reduction in total viable counts (TVC) on Tryptic Soy Agar (TSA) across representative surface categories following application of the Traditional (blue) and Green (green) cleaning protocols. Values are expressed as mean percentage reduction relative to pre-cleaning baseline levels; error bars represent standard deviation. Statistical comparisons between protocols were performed using Student's *t*-test ($p < 0.05$); ns (not significant, $p \geq 0.05$), * ($p < 0.05$), ** ($p < 0.01$). Both protocols achieved substantial microbial abatement, with the Green protocol showing consistently comparable or slightly higher reductions across most surface types.

Interpretation and Comparative Insights

The microbiological findings demonstrate that reduced chemical mass, lower washing temperatures, and eco-formulated detergents do not compromise hygienic performance when appropriate operational protocols are followed. This result is particularly relevant in the context of sustainable procurement frameworks such as the Italian CAM, which require that environmentally preferable cleaning systems guarantee performance equivalent to conventional practices.

From a mechanistic perspective, effective microbial reduction appears to depend predominantly on the efficiency of mechanical removal processes, the structural properties of microfiber materials, accurate dilution control and pre-impregnation systems, and the standardization of application time and surface coverage, as well as adequate operator training and procedural consistency. These determinants likely exert a greater influence on bioburden reduction than the intrinsic chemical strength of detergents alone [37,38].

Importantly, when considered alongside the Life Cycle Assessment results, the microbiological outcomes confirm the absence of an environmental–hygiene trade-off. The Green protocol achieves a substantial reduction in Global Warming Potential while maintaining microbiological effectiveness across diverse environmental contexts. This dual validation—environmental and hygienic—supports the feasibility of transitioning toward lower-impact cleaning systems without compromising indoor hygiene quality, thereby aligning operational practice with sustainability principles and evidence-based facility management.

Overall, the convergence of environmental and microbiological evidence strengthens the argument that sustainability in professional cleaning services should be assessed at the system level rather than at the level of individual product substitution. The results further corroborate CAM requirements stipulating that green cleaning protocols must ensure performance equivalent to or greater than conventional systems. When considered together, the LCA and microbiological outcomes demonstrate that the Pfe Green approach achieves

environmental improvement without trade-offs in hygienic quality, thereby fulfilling the core principles of sustainable service provision.

3.3. Integrated Sustainability Perspective

The integration of life-cycle metrics and microbiological quality indicators highlights the multidimensional nature of sustainability in the cleaning sector. By combining climate-impact quantification with standardized hygienic validation, the present study advances a comprehensive evaluation framework that bridges environmental science and applied microbiology.

From an operational standpoint, the Pfe Green protocol exemplifies a systemic approach to sustainability through the combined implementation of eco-formulated detergents with certified Carbon Footprint of Product (CFP), optimization of laundering processes via reduced temperature cycles and pre-impregnation systems, and structured performance verification based on integrated LCA and microbiological assessment.

Such integration enables quantitative documentation of environmental and hygienic co-benefits, which can be strategically employed in public tenders and corporate ESG reporting. The demonstrated alignment between environmental impact mitigation and maintained hygienic efficacy underscores the strategic value of LCA-informed decision-making in service design, procurement policies, and sustainable facility management strategies.

It is important to note that the present study focused on climate change as the primary impact category. However, the inclusion of additional environmental indicators, such as water scarcity, eutrophication, and human toxicity, would likely further amplify the differences observed between the two protocols, particularly in relation to chemical consumption and wastewater emissions.

4. Conclusions

This study presents an integrated environmental and microbiological evaluation of two professional cleaning protocols applied in a civil building context. Through the combined application of Life Cycle Assessment (LCA) and standardized microbiological monitoring, the research provides a dual-performance framework capable of simultaneously quantifying climate impact and hygienic efficacy under real operational conditions.

The Pfe Green system demonstrated a mean reduction of approximately 30% in life-cycle greenhouse gas (GHG) emissions, expressed as Global Warming Potential over a 100-year horizon (GWP₁₀₀), when compared with the conventional method. This reduction was primarily driven by structural process optimizations, including a more sustainable daily commuting mode, substitution of disposable textiles with reusable microfiber systems, lower-temperature laundering cycles, improved detergent dilution control, and the adoption of energy-efficient equipment. Importantly, these environmental improvements were not achieved through a reduction in service frequency or coverage, but rather through systemic redesign of material and energy flows within the cleaning process.

From a hygienic perspective, both protocols achieved microbial reductions fully compliant with Italian occupational hygiene benchmarks for civil environments. Notably, the Green protocol showed consistently comparable—and in several high-touch surface categories, marginally superior—reductions in total viable counts (TVC), despite the use of lower chemical mass inputs and eco-formulated detergents. Although the differences between protocols were not statistically significant ($p > 0.05$), the observed trend supports the conclusion that mechanical removal efficiency, microfiber performance, standardized procedures, and operator training represent the dominant determinants of microbial abatement, rather than detergent aggressiveness alone.

The integrated interpretation of environmental and microbiological outcomes demonstrates the absence of a trade-off between ecological optimization and hygienic performance.

This finding is particularly relevant within the framework of the Italian Minimum Environmental Criteria (CAM), which require that environmentally preferable systems ensure performance equivalence to conventional practices. The results confirm that compliance with CAM environmental standards can be achieved without compromising indoor hygiene quality.

Beyond the specific case study, this research contributes methodologically by validating a replicable assessment model based on internationally recognized ISO standards for both environmental impact (ISO 14040–44; ISO 14067) and microbiological control (ISO 14698; UNI EN ISO 18593). Such an integrated approach strengthens the scientific credibility of sustainability claims in facility management and supports transparent reporting within Environmental, Social and Governance (ESG) frameworks.

In conclusion, the findings substantiate that eco-designed cleaning systems, when properly implemented and performance-verified, represent a credible and scalable pathway toward reducing the carbon footprint of professional cleaning services without compromising hygienic safety. Future investigations should expand this dual-assessment model to healthcare, educational, and industrial settings, incorporate additional environmental impact categories (e.g., water scarcity, human toxicity, particulate matter formation), and evaluate long-term performance stability through longitudinal monitoring.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/su18094250/s1>, Table S1: Life Cycle Inventory (LCI) of the Traditional and Green cleaning protocols. Inventory flows were quantified for the Renault Italia S.p.A. case study and normalized to the functional unit of 1 m² of representative surface maintained clean for 1 year. Primary data were obtained from direct measurements and structured field records, while background processes were modeled using CFP/EPD datasets and the Managed LCA Content 2025.1 database.

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Abbreviations

The following abbreviations are used in this manuscript:

AIB	Association of Issuing Bodies
CAM	Minimum Environmental Criteria (Criteri Ambientali Minimi)
CFP	Carbon Footprint of Product
CFU	Colony Forming Units
CO ₂	Carbon Dioxide
CO ₂ e	Carbon Dioxide Equivalent
EPD	Environmental Product Declaration
ESG	Environmental, Social and Governance
GHG	Greenhouse Gas
GLO	Global (dataset reference in LCA database)
GMP	Good Manufacturing Practices
GWP	Global Warming Potential
GWP ₁₀₀	Global Warming Potential over 100 years
HDPE	High-Density Polyethylene
HFCs	Hydrofluorocarbons
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
MCA	MacConkey Agar
MJ	Megajoule
MSA	Mannitol Salt Agar
PCR	Product Category Rules
PFCs	Perfluorocarbons
PPE	Personal Protective Equipment
RE	Renewable Energy
SDA	Sabouraud Dextrose Agar
SDS	Safety Data Sheet
SDGs	Sustainable Development Goals
SF ₆	Sulfur Hexafluoride
TSA	Tryptic Soy Agar
TVC	Total Viable Count
TT	Traditional Treatment
TG	Green Treatment
UNI	Ente Nazionale Italiano di Unificazione

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