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Life Cycle Assessment of Sanitary Ware: Quantifying Environmental Impact

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Abstract

Reducing environmental impacts is a key challenge for the sanitary ware industry, which needs to effectively balance economic performance with environmental sustainability. In this study, life cycle assessment (LCA) was applied to quantify the environmental impacts associated with sanitary ware production in China. A Monte Carlo uncertainty analysis was further conducted to evaluate the uncertainty of the LCA results under the assumption that the inventory data followed normal distributions. The results show that the product manufacturing stage is the dominant contributor to the overall environmental impact, accounting for 79.90%. At this stage, human carcinogenic toxicity, freshwater ecotoxicity, marine ecotoxicity, freshwater eutrophication, ozone formation impacts on terrestrial ecosystems, and ozone formation impacts on human health are mainly attributable to electricity consumption. In contrast, fossil resource scarcity, terrestrial ecotoxicity, and global warming are primarily associated with the combined consumption of electricity and natural gas. The Monte Carlo simulation results show that the coefficient of variation of greenhouse gas emissions is below 10%, indicating a relatively low level of uncertainty. The uncertainty is mainly attributed to differences between domestic and international production conditions, as well as the limited accuracy of raw material transport distance data. Future research should focus on establishing regional background databases for raw materials and developing data quality standards for activity data, thereby further improving the reliability of environmental impact accounting for sanitary ware.

Keywords

Life Cycle Assessment, Sanitary Ware, Environmental Impact, Uncertainty Analysis

1. Introduction

China is one of the world's leading producers of sanitary ware, and its annual output has ranked first globally for many years. However, the industry is characterized by high energy consumption and substantial environmental emissions, with manufacturing processes that have raised significant environmental concerns. At the same time, as an important building finishing material, sanitary ware plays a key role in improving the health and comfort of residential environments. In the context of the global transition toward carbon neutrality, the sanitary ware industry needs to accelerate energy-saving and consumption-reduction measures to support high-quality development.

Life cycle assessment (LCA) is a widely used method for identifying, quantifying, and evaluating material and energy inputs and environmental emissions associated with a product, system, or service throughout its life cycle. It also supports the identification of potential improvement opportunities. In recent years, extensive LCA studies have been conducted on major construction materials such as cement and concrete [1]-[6], whereas studies focusing on the environmental impacts and emission reduction technologies of sanitary ware remain comparatively limited. Desole *et al.* [7] reported that energy and material consumption during the production stage of sanitary ware contributed substantially to environmental impacts, and that the introduction of photovoltaic systems combined with water recycling could markedly reduce these impacts. Buonomo *et al.* [8] reported that the application of solar systems to the drying process of sanitary ceramics in Italy could reduce global warming potential (GWP) by 4%, with an estimated annual reduction of 180 t CO_2 emissions across the industry. Xian *et al.* [9] showed that the carbon abatement cost of sanitary ceramic manufacturers, approximately 7437 - 13,635 CNY/t CO_2, was significantly higher than that of architectural ceramics, approximately 2064 - 3072 CNY/t CO_2. For sanitary ceramic manufacturers, expanding intermediate inputs was identified as the most economically viable emission reduction strategy. Martini *et al.* [10] demonstrated that incorporating recycled materials into the body formulation could reduce the firing temperature of sanitary ceramics by 80˚C - 100˚C, thereby improving product environmental performance and reducing greenhouse gas emissions.

Taking sanitary ware produced in China as the research object, this study adopts a LCA approach, with ISO 21930:2017 as the primary reference, to systematically assess the environmental impacts and uncertainty associated with its life cycle. The results are intended to provide evidence-based support for the green and low-carbon transition of the sanitary ware industry.

2. Methodology

2.1. Study Object and Functional Unit

Sanitary ware products manufactured by six representative Chinese manufacturers were selected for this study. The functional unit was defined as 1 kg of sanitary ware.

2.2. System Boundaries

Following the provisions of ISO 21930:2017 regarding system boundary delineation for construction products, and considering that sanitary ware, as a basic construction material, requires integration with other components before use [11], this study adopted a cradle-to-gate system boundary. Therefore, the assessment covered three stages: raw material extraction and processing, transportation of raw materials to the manufacturing plant, and sanitary ware manufacturing. Downstream processes, including transportation after the factory gate, on-site installation, use, and end-of-life treatment, were excluded from the system boundary.

2.3. Assessment Tool and Life Cycle Inventory

LCA software is commonly used to quantify the environmental impact of products or services. Considering the operational convenience, database coverage, and methodological completeness of mainstream life-cycle assessment software, SimaPro Analyst 9.6.0.1 was selected as the analytical tool. The ReCiPe 2016 Midpoint (H) V1.09 method was applied to quantify and assess the life-cycle environmental impact of sanitary ware. The life-cycle inventory was compiled using primary field data as the main data source and background data as supplementary data sources. Data directly related to the manufacturing process and obtainable through field investigation, including raw material formulations, transport schemes, and energy consumption in production processes, were collected through field surveys of representative manufacturers. General background parameters, such as environmental emissions associated with fossil energy consumption and electricity use, were obtained from authoritative databases, including the Ecoinvent 3.10 database.

3. Results and Discussion

3.1. Life Cycle Inventory Analysis

Primary data were collected according to the cradle-to-gate system boundary established in accordance with ISO 21930:2017. The inventory covered raw material extraction and processing, transportation of raw materials to the manufacturing plant, and product manufacturing. A life cycle inventory was compiled using the collected data, as shown in **Table 1**. With respect to raw material inputs, the production of sanitary ware involves more than ten types of raw materials, including quartz, feldspar, kaolin, dolomite, zinc oxide, and gypsum. Because publicly available domestic and international literature provides limited information on the extraction and production processes of these raw materials and data traceability is difficult, the corresponding data were obtained directly from the Ecoinvent database. Given that the Ecoinvent database does not fully cover all raw material types involved in this study, missing data were substituted by datasets for products with similar extraction characteristics and comparable emission profiles during processing. The raw material formulation was derived from statistical analysis of actual production data collected from the surveyed manufacturers. For raw material transportation, transport modes and distances were calculated based on procurement data from the surveyed manufacturers. In the product manufacturing stage, energy consumption data, including natural gas, diesel, and electricity, were compiled by cross-checking the energy consumption statistics, equipment operating power, operating time, and environmental impact assessment reports of the surveyed manufacturers. The environmental impact factors corresponding to these energy inputs were obtained from the Ecoinvent database.

Table 1. Life cycle inventory data for sanitary ware.

<table>
<tr><td rowspan="10">Raw material inputs</td><td>Raw material</td><td colspan="2">Amount (kg)</td><td>Raw material</td><td colspan="2">Amount (kg)</td></tr>
<tr><td>Quartz</td><td colspan="2">337.01</td><td>Zhangcun clay</td><td colspan="2">49.12</td></tr>
<tr><td>Sandstone</td><td colspan="2">68.62</td><td>Zhangwu clay</td><td colspan="2">41.72</td></tr>
<tr><td>Datong soil</td><td colspan="2">71.47</td><td>Purple kibushi clay</td><td colspan="2">159.75</td></tr>
<tr><td>Feldspar</td><td colspan="2">232.52</td><td>Trona</td><td colspan="2">101.2</td></tr>
<tr><td>Talc</td><td colspan="2">16.08</td><td>Suzhou clay</td><td colspan="2">115.54</td></tr>
<tr><td>Zircon sand</td><td colspan="2">4.21</td><td>Limestone</td><td colspan="2">5.45</td></tr>
<tr><td>Kaolin</td><td colspan="2">72.52</td><td>Dolomite</td><td colspan="2">1.9</td></tr>
<tr><td>Ball clay</td><td colspan="2">105.06</td><td>Zinc oxide</td><td colspan="2">1.82</td></tr>
<tr><td>Flint clay</td><td colspan="2">30.11</td><td>Gypsum</td><td colspan="2">29.9</td></tr>
<tr><td rowspan="10">Raw material transport</td><td>Raw material</td><td>Mode</td><td>Distance (km)</td><td>Raw material</td><td>Mode</td><td>Distance (km)</td></tr>
<tr><td>Quartz</td><td>Waterway</td><td>450</td><td>Zhangcun clay</td><td>Waterway</td><td>1200</td></tr>
<tr><td>Sandstone</td><td>Waterway</td><td>600</td><td>Zhangwu clay</td><td>Maritime</td><td>1500</td></tr>
<tr><td>Datong soil</td><td>Waterway</td><td>1200</td><td>Purple kibushi clay</td><td>Waterway</td><td>1200</td></tr>
<tr><td>Feldspar</td><td>Road</td><td>350</td><td>Trona</td><td>Waterway</td><td>900</td></tr>
<tr><td>Talc</td><td>Waterway</td><td>900</td><td>Suzhou clay</td><td>Waterway</td><td>600</td></tr>
<tr><td>Zircon sand</td><td>Waterway</td><td>450</td><td>Limestone</td><td>Waterway</td><td>900</td></tr>
<tr><td>Kaolin</td><td>Road</td><td>200</td><td>Dolomite</td><td>Waterway</td><td>450</td></tr>
<tr><td>Ball clay</td><td>Waterway</td><td>600</td><td>Zinc oxide</td><td>Road</td><td>100</td></tr>
<tr><td>Flint clay</td><td>Waterway</td><td>1200</td><td>Gypsum</td><td>Road</td><td>200</td></tr>
<tr><td rowspan="2">Manufacturing energy inputs</td><td colspan="3">Electricity (k·Wh)</td><td colspan="2">Natural gas (m³)</td><td>Diesel (kg)</td></tr>
<tr><td colspan="3">666.14</td><td colspan="2">192.08</td><td>1.91</td></tr>
</table>

3.2. Environmental Impact Assessment Results

3.2.1. Characterization Results

In LCA, characterization results are obtained by applying characterization models to convert inventory data into quantitative indicators for different environmental impact categories. These results are commonly expressed in equivalent units, thereby enabling comparison of the contributions of different resource inputs and emissions to the same environmental issue. For the global warming impact category, for example, carbon dioxide is typically used as the reference substance, and results are expressed as carbon dioxide equivalents (CO_2 eq). Using GWP factors, emissions of greenhouse gases in the inventory, such as carbon dioxide, methane, and nitrous oxide, are converted into equivalent carbon dioxide emissions. Characterization results directly represent the absolute magnitude of environmental impacts generated by a construction product at different life cycle stages and therefore serve as absolute measures of environmental impact.

Table 2 presents the characterization results for the environmental impact of sanitary ware across three stages: raw material extraction and processing, raw material transportation, and product manufacturing. The results were calculated using the ReCiPe 2016 method based on the life cycle inventory data listed in Table 1.

Table 2. Characterization results of the environmental impact of sanitary ware.

Environmental impact category	Unit	Raw material extraction	raw material transportation	product manufacturing
Global warming	kg CO_2 eq	5.5831E−02	7.0500E−02	1.3269E+00
Stratospheric ozone depletion	kg CFC11 eq	1.5295E−08	4.4280E−08	1.7746E−07
Ionizing radiation	kBq Co-60 eq	2.4896E−03	9.7140E−04	1.0522E−02
Ozone formation impacts on human health	kg NO_x eq	2.1087E−04	6.0960E−04	2.3690E−03
Fine particulate matter formation	kg $PM_{2.5}$ eq	9.9010E−05	1.3340E−04	1.2584E−03
Ozone formation impacts on terrestrial ecosystems	kg NO_x eq	2.1082E−04	6.2330E−04	2.4542E−03
Terrestrial acidification	kg SO_2 eq	2.2348E−04	3.6190E−04	2.8439E−03
Freshwater eutrophication	kg P eq	1.7572E−05	7.2190E−06	3.3418E−04
Marine eutrophication	kg N eq	1.2823E−06	8.4580E−07	1.4452E−05
Terrestrial ecotoxicity	kg 1,4-DCB	1.0764E+00	1.2389E+00	3.0287E+00
Freshwater ecotoxicity	kg 1,4-DCB	2.6370E−03	1.1987E−03	3.4937E−02
Marine ecotoxicity	kg 1,4-DCB	4.4426E−03	2.7550E−03	4.7202E−02
Human carcinogenic toxicity	kg 1,4-DCB	1.7714E−02	1.4020E−02	1.1225E−01
Human non-carcinogenic toxicity	kg 1,4-DCB	6.4679E−02	2.8096E−02	7.8440E−01
Land use	m^2·a crop eq	6.4639E−03	4.7941E−03	2.0355E−02
Mineral resource scarcity	kg Cu eq	7.1462E−03	2.1160E−04	1.1055E−03
Fossil resource scarcity	kg oil eq	1.5253E−02	1.9920E−02	3.4145E−01
Water consumption	m^3	1.1546E−03	1.4155E−04	2.1101E−03

3.2.2. Normalization Results

Characterization results are not directly comparable across different environmental impact categories; therefore, normalization is required. Normalization enables the quantitative comparison of environmental impact indicators and facilitates the identification of the relative contribution of each impact category within the defined life cycle boundary. In this study, the environmental impact of sanitary ware was normalized. The normalized environmental impact results for each life cycle stage are presented in **Table 3**, and the total normalized values are shown in **Figure 1**. The normalized life cycle environmental impact results in **Table 3** and **Figure 1** show clear differences among impact categories. The categories are ranked in descending order as follows: human carcinogenic toxicity, freshwater ecotoxicity, marine ecotoxicity, freshwater eutrophication, fossil resource scarcity, terrestrial ecotoxicity, Ozone formation impacts on terrestrial ecosystems, global warming, ozone formation impacts on human health, terrestrial acidification, fine particulate matter formation, ionizing radiation, human non-carcinogenic toxicity, water consumption, land use, stratospheric ozone depletion, marine eutrophication, and mineral resource scarcity.

Table 3. Normalized environmental impact results for each life cycle stage of sanitary ware.

Environmental impact category	Raw material extraction	raw material transportation	product manufacturing
Global warming	7.0222E−06	8.8000E−06	1.6589E−04
Stratospheric ozone depletion	2.5696E−07	7.3940E−07	2.9617E−06
Ionizing radiation	5.2088E−06	2.0164E−06	2.1986E−05
Ozone formation impacts on human health	1.0301E−05	2.9650E−05	1.1514E−04
Fine particulate matter formation	3.9013E−06	5.2150E−06	4.9175E−05
Ozone formation impacts on terrestrial ecosystems	1.2331E−05	3.5130E−05	1.3825E−04
Terrestrial acidification	5.4760E−06	8.8250E−06	6.9294E−05
Freshwater eutrophication	2.7196E−05	1.1106E−05	5.1461E−04
Marine eutrophication	2.7985E−07	1.8390E−07	3.1392E−06
Terrestrial ecotoxicity	7.1029E−05	8.1460E−05	1.9903E−04
Freshwater ecotoxicity	1.0507E−04	4.7630E−05	1.3812E−03
Marine ecotoxicity	1.0257E−04	6.3300E−05	1.0906E−03
Human carcinogenic toxicity	1.7251E−03	1.3610E−03	1.0894E−02
Human non-carcinogenic toxicity	2.0785E−06	9.0090E−07	2.5083E−05
Land use	1.0473E−06	7.7626E−07	3.2919E−06
Mineral resource scarcity	5.9506E−08	1.7650E−09	9.1993E−09
Fossil resource scarcity	1.5614E−05	2.0280E−05	3.4850E−04
Water consumption	4.3309E−06	5.3140E−07	7.9185E−06

Nine major environmental impact categories were identified for further analysis according to their contribution rankings. The proportional contributions of the three life cycle stages-raw material extraction and processing, raw material transportation, and product manufacturing-were then examined. The results show that these three stages contribute 11.17%, 8.93%, and 79.90% to the overall environmental impact, respectively. This indicates that the product manufacturing stage is the dominant source of environmental impacts over the life cycle of sanitary ware. To further identify priority stages for emission reduction, the raw material extraction and processing stage and the product manufacturing stage were selected for detailed analysis, given the relatively simple energy consumption and emission profile of the raw material transportation stage. The associated environmental emissions were further analyzed and normalized, and the results are shown in Figures 2-5.

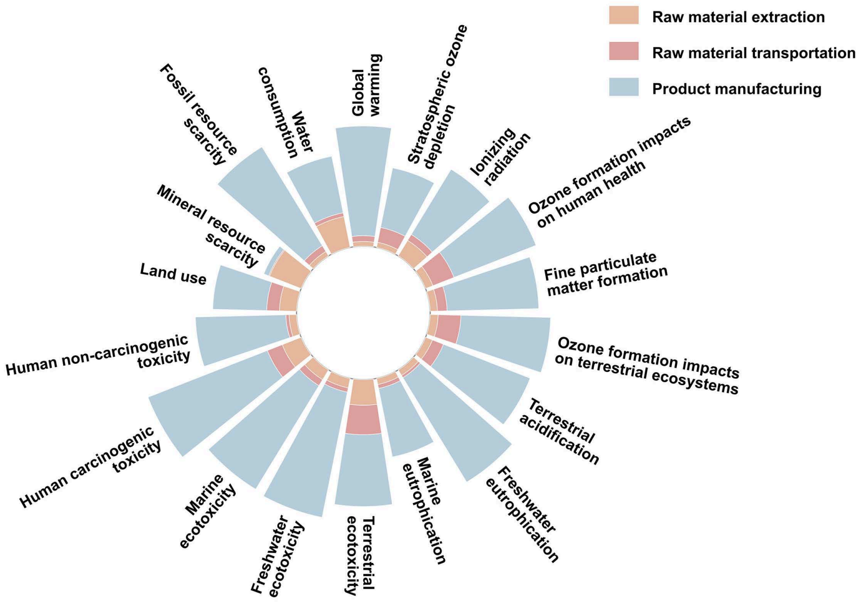

Figure 1. Total normalized environmental impact of sanitary ware.

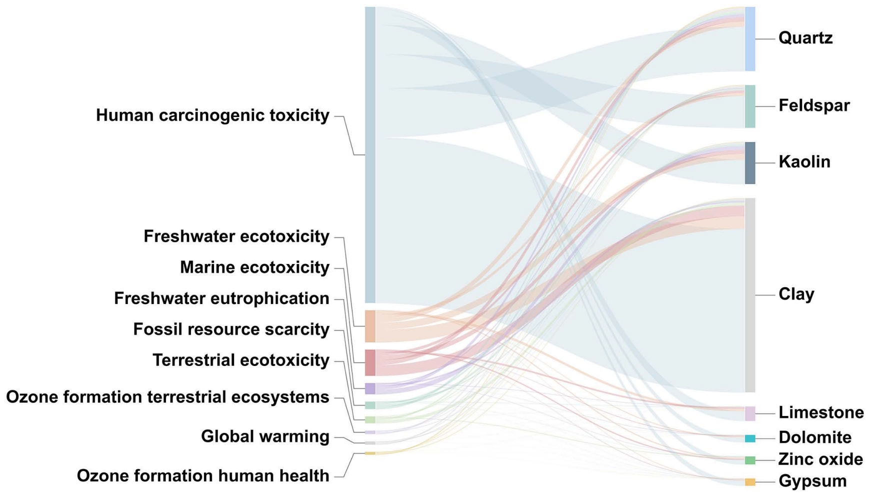

Figure 2. Contribution of raw material extraction and processing to different environmental impact categories.

As shown in Figure 2, during the raw material extraction and processing stage, human carcinogenic toxicity, freshwater ecotoxicity, marine ecotoxicity, and terrestrial ecotoxicity are mainly associated with the extraction and consumption of clay. Freshwater eutrophication, fossil resource scarcity, and global warming are primarily attributed to the processing and consumption of quartz sand and kaolin. In contrast, ozone formation impacts on terrestrial ecosystems and ozone formation impacts on human health are mainly attributable to the extraction and consumption of quartz sand. Figure 3 further indicates that clay makes the largest contribution to the overall environmental impact, accounting for 52.39%.

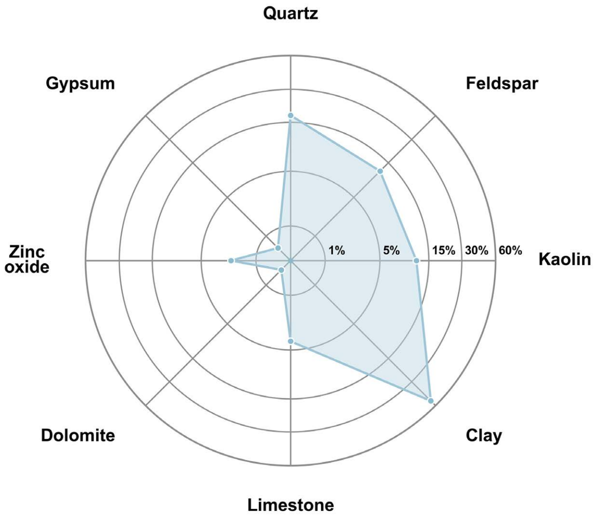

Figure 3. Contribution of raw material extraction and processing to the overall environmental impact.

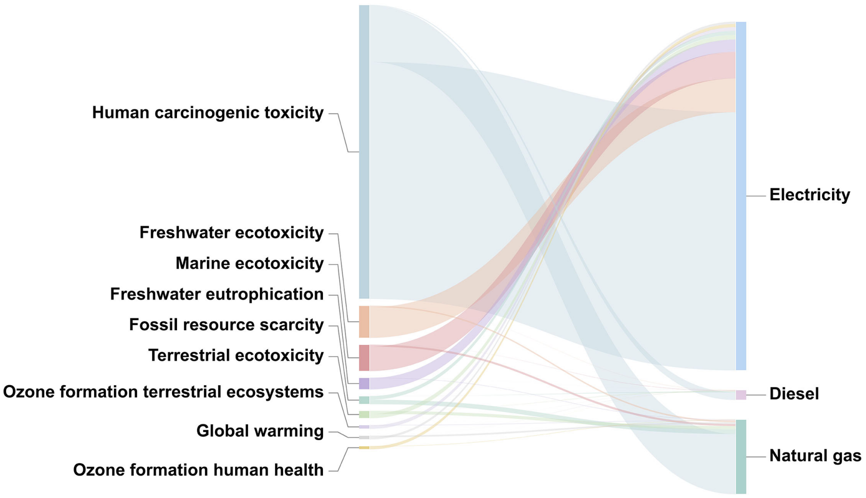

Figure 4. Contribution of product manufacturing to different environmental impact categories.

As shown in Figure 4, during the product manufacturing stage, human carcinogenic toxicity, freshwater ecotoxicity, marine ecotoxicity, freshwater eutrophication, ozone formation impacts on terrestrial ecosystems, and ozone formation impacts on human health are mainly attributable to electricity consumption. Fossil resource scarcity, terrestrial ecotoxicity, and global warming are primarily associated with the combined consumption of electricity and natural gas. Figure 5 further shows that electricity accounts for the largest share of the overall environmental impact, reaching 82.19%, and is therefore identified as the dominant contributor at this stage. These results indicate that, during the product manufacturing stage, the dominant contributor to the overall environmental impact is consistent with the major sources identified for different environmental impact categories.

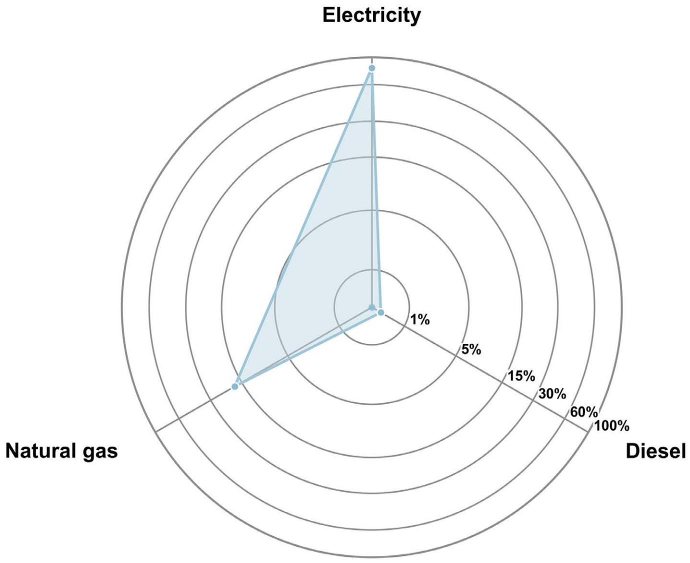

Figure 5. Contribution of product manufacturing to the overall environmental impact.

The preceding analysis indicates that two primary strategies can effectively reduce the overall environmental impact of sanitary ware: reducing energy consumption during the manufacturing stage and optimizing the production formulation. Among these, reducing energy consumption during manufacturing represents the primary mitigation pathway. Replacing conventional energy sources with renewable or low-carbon energy, particularly by increasing the share of renewable electricity, is expected to yield substantial environmental benefits. In addition, the use of raw materials with high environmental burdens should be reduced, and low-carbon alternative materials with comparable technical performance should be further developed and adopted.

3.3. Uncertainty Analysis

Several sources of uncertainty are associated with the environmental impact assessment of sanitary ware. The main sources of uncertainty include data on raw material extraction and processing, raw material consumption, transport modes and distances for raw materials, and energy consumption. Data on raw material and energy consumption were supported by relatively detailed records and were therefore considered relatively reliable. Although data on raw material extraction and processing were obtained from the widely used Ecoinvent database, these data may not fully represent actual production conditions in China. In addition, the limited precision of transport distance data may also increase uncertainty in the results. To evaluate the reliability of the assessment results, uncertainty analysis was conducted using Monte Carlo simulation. Given the multiple environmental impact indicators involved in this study, GWP was selected as a representative impact category for the uncertainty assessment. GWP is one of the most widely used environmental impact categories in international LCA studies and is also a major impact category in the production of sanitary ware. It therefore provides a suitable basis for evaluating how variations in model parameters and input data affect the overall environmental impact results.

Under the assumption that all parameters followed normal distributions, 100,000 Monte Carlo iterations were performed. The probability distribution of the GWP results, expressed as kg CO_2 eq, was generated as a histogram, as shown in Figure 6. The simulation results show that the 95% confidence interval for the GWP results is 1.2381 - 1.6695 kg CO_2 eq, and the coefficient of variation (CV) is 7.56%. A coefficient of variation below 10% indicates a relatively low level of uncertainty in the assessment results.

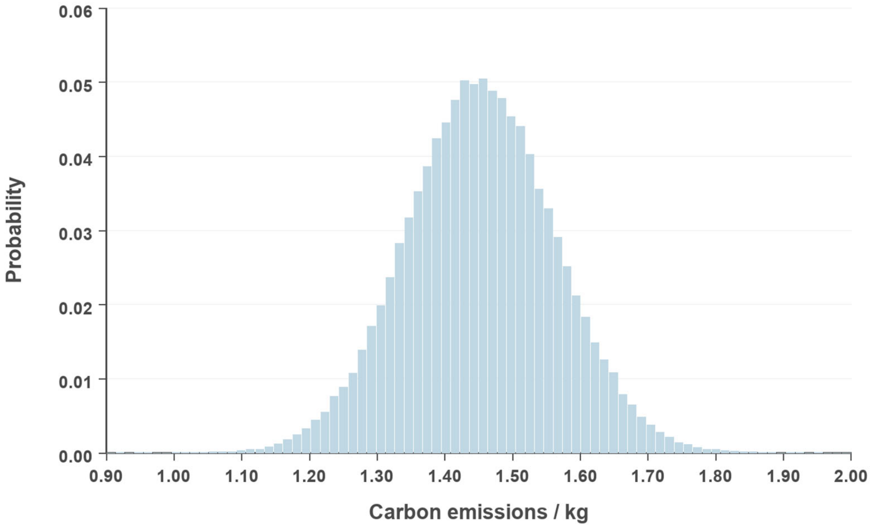

Figure 6. Histogram of carbon emissions based on Monte Carlo simulation.

3.4. Future Research Directions

Existing literature [12]-[14], together with the findings of this study, suggests that the environmental impact assessment of sanitary ware still faces several challenges. To improve assessment accuracy, future research should focus on the following two aspects.

First, a regional raw material database should be established to improve the accuracy of emission factors. The raw materials used in sanitary ware are mainly non-metallic mineral resources, whose extraction and processing are closely tied to local resource characteristics and production technologies. Consequently, environmental emission factors for non-metallic minerals vary by region. Existing international databases may therefore not fully capture the environmental characteristics of non-metallic mineral extraction in China, nor do they cover all types of raw materials. Accordingly, a database of raw material emission factors that reflects China's extraction and processing technologies is necessary. A regular updating mechanism should also be developed, and leading supply-chain enterprises should be encouraged to participate in data collection and sharing. These measures will help ensure the timeliness and representativeness of emission factors and further improve the accuracy of product environmental impact assessments.

Second, data quality standards for activity data should be established to improve the reliability of statistical results. The production process of sanitary ware is lengthy, the level of refinement in production practices remains limited, and different products may share the same production line. Therefore, specific life cycle data collection requirements for sanitary ware should be developed, including guidance on the collection, aggregation, analysis, review, and recording of data such as raw material transport distances, transport vehicle types, raw material formulations, and energy consumption during production. Data quality control and validation should be conducted to ensure the consistency and validity of activity data. Furthermore, the analysis in this study shows that energy consumption during production is the dominant source of environmental impact, accounting for nearly 80% of the total. Thus, the accuracy of energy data is critical to ensuring the reliability of the assessment results. Manufacturers are advised to install metering and monitoring equipment on production lines and adopt digital, intelligent, and big-data-enabled technologies to substantially improve the capacity for collecting and statistically processing activity data during production.

4. Conclusion

In this study, life cycle assessment and Monte Carlo uncertainty analysis were applied to quantify the environmental impacts and associated uncertainty of sanitary ware production in China. The product manufacturing stage is the dominant contributor to the overall environmental impact, accounting for 79.90%. At this stage, human carcinogenic toxicity, freshwater ecotoxicity, marine ecotoxicity, freshwater eutrophication, ozone formation impacts on terrestrial ecosystems, and ozone formation impacts on human health are mainly attributable to electricity consumption. In contrast, fossil resource scarcity, terrestrial ecotoxicity, and global warming are primarily associated with the combined consumption of electricity and natural gas. The 95% confidence interval for global warming potential is 1.2381 - 1.6695 kg CO_2 eq, with a coefficient of variation of 7.56%, indicating a relatively low level of uncertainty in the results. The main sources of uncertainty include discrepancies between background database assumptions and actual production conditions in China, as well as the limited precision of raw material transport distance data. To improve the reliability of environmental impact assessment results for sanitary ware, future research should focus on two priority areas: establishing a regional raw material background database and developing quality standards for activity data.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

References

[1] Vargas, F., La Fé-Perdomo, I., Ramos-Grez, J.A. and Navarrete, I. (2025) Machine Learning-Based Estimation of CO_2 Footprint and Environmental-Mechanical Performance of Blended Cement Concrete. *Case Studies in Construction Materials*, **22**, e04741. https://doi.org/10.1016/j.cscm.2025.e04741

[2] Krishnan, N., Lucero, C., Daut, L., Bay, B.K., Isgor, O.B. and Weiss, W.J. (2026) Binder Optimization, Mechanical Properties, and Carbon Footprint Assessment of Cellulose Cement Composites. *Construction and Building Materials*, **528**, Article 146483. https://doi.org/10.1016/j.conbuildmat.2026.146483

[3] Wang, D., Bui, T.T.P., Reinke, B., *et al.* (2026) Life Cycle Assessment of Both Cement and Sand-Replaced Biochar Concrete. *Resources, Conservation & Recycling Advances*, **30**, Article 200337. https://doi.org/10.1016/j.rcradv.2026.200337

[4] Haverkamp, P., Schmidt, L., Backes, J.G. and Traverso, M. (2025) Product Environmental Footprint in the Construction Sector—Proposal and Assessment of a Representative Product for Carbon-Reinforced Concrete. *Journal of CO_2 Utilization*, **95**, Article 103078. https://doi.org/10.1016/j.jcou.2025.103078

[5] Mao, Y., Wang, X., Drissi, S., *et al.* (2026) Life Cycle Assessment of Carbonated Recycled Concrete Fine Products. *Journal of Cleaner Production*, **556**, Article 148215. https://doi.org/10.1016/j.jclepro.2026.148215

[6] Da, B., Lan, Z., Fan, H., *et al.* (2025) Carbon Emissions Assessment and Analysis of Marine Aggregate Concrete Based on the Theory of Life Cycle Assessment. *Journal of Building Engineering*, **114**, Article 114160. https://doi.org/10.1016/j.jobe.2025.114160

[7] Desole, M.P., Fedele, L., Gisario, A. and Barletta, M. (2024) Life Cycle Assessment (LCA) of Ceramic Sanitaryware: Focus on the Production Process and Analysis of Scenario. *International Journal of Environmental Science and Technology*, **21**, 1649-1670. https://doi.org/10.1007/s13762-023-05074-6

[8] Buonomo, B., Manca, O., Nardini, S., Plomitallo, R.E., Gobio-Thomas, L. and Stojceska, V. (2025) Life Cycle Assessment of Implementation of an Innovative Solar Thermal Technology in Italian Ceramic Industry. *Thermal Science and Engineering Progress*, **61**, Article 103517. https://doi.org/10.1016/j.tsep.2025.103517

[9] Xian, Y., Li, N. and Wang, K. (2024) Carbon Emissions Marginal Abatement Cost and Its Influencing Factors from the Construction and Hygienic Ceramics Manufacturing Industries in China. *Environmental Impact Assessment Review*, **104**, Article 107352. https://doi.org/10.1016/j.eiar.2023.107352

[10] Martini, E., Pavese, A., Tabacchi, D., Fortuna, D.M. and Fortuna, A. (2021) Effects of Sintering Temperature on Microstructure and Properties of Sanitaryware Ceramic

Produced with Waste Material. *Cerâmica*, **67**, 39-47. https://doi.org/10.1590/0366-69132021673813022

[11] Zeng, J., Li, H.J. and Li, F.Z. (2025) A Carbon Footprint Assessment for Building Ceramics from the Life Cycle Perspective: A Case Study in Eastern China. *Engineering*, **17**, 625-634. https://doi.org/10.4236/eng.2025.1712035

[12] Bachawati, M.E., Belarbi, Y.E., Zakhem, H.E. and Belarbi, R. (2026) Life Cycle Assessment of Sustainable Materials: A Comprehensive Analysis of Methodological Asymmetries and Environmental Trade-Offs. *Buildings*, **16**, Article 1385. https://doi.org/10.3390/buildings16071385

[13] Jerome, A. and Ljunggren, M. (2025) Product Lifetime in Life Cycle Assessments of Circular Economy Strategies—A Review and Consolidation of Methodology. *The International Journal of Life Cycle Assessment*, **30**, 2162-2189. https://doi.org/10.1007/s11367-025-02470-7

[14] Ding, N., Pan, J.J., Cui, H., *et al.* (2025) Research Status and Trends of LCA Data Quality Evaluation. *China Environmental Science*, **45**, 7097-7104.