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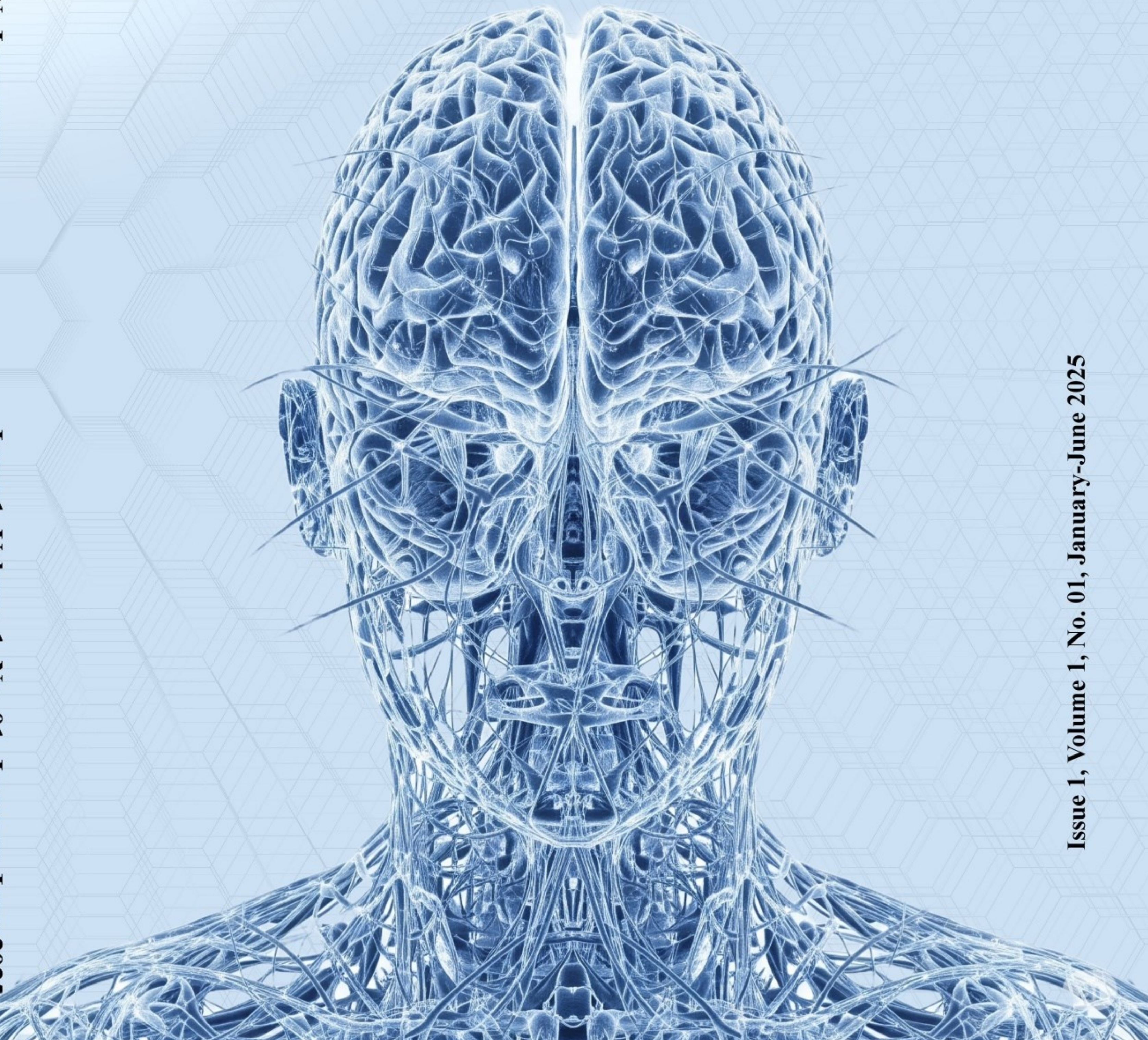

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Life Cycle Analysis of Ceramic Slip.

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ABSTRACT

Ceramic slip is a fundamental material in the artisanal and semi-industrial production of ceramic products, especially in Dolores Hidalgo, Guanajuato, Mexico a region globally recognized for its centuries-old tradition in crafting high-quality ceramic pieces. This study presents a Life Cycle Assessment (LCA) of ceramic slip, aiming to evaluate the environmental impacts associated with each stage of its production, from raw material extraction to final disposal. The research focuses on local practices employed in Dolores Hidalgo, where ceramics represent not only a primary economic activity but also a cultural legacy passed down through generations over hundreds of years.

In this context, the LCA was conducted following international standards ISO 14040 and 14044, considering aspects such as water resource consumption, atmospheric emissions, waste generation, and energy use at each phase of the process. Preliminary results indicate that the most critical stages from an environmental perspective are the preparation of the slip and the firing process, due to high energy consumption and emissions resulting from the use of fossil fuels.

Therefore, this analysis seeks to support informed decision-making to improve production practices by promoting sustainable alternatives that maintain the region's global competitiveness without compromising ecological balance or the stability of local ecosystems. The study also highlights the importance of integrating environmental criteria into the management of refractory materials and technological innovation within the traditional ceramics sector.

KEYWORDS

Life cycle assessment; LCA; Life cycle analysis; Environmental factors; Product lifecycle; Product life cycle management.

INTRODUCTION

Ceramic slip a fluid mixture of clay, water, and sometimes additives is a cornerstone material in traditional ceramic manufacturing, widely used in forming, casting, and surface finishing processes [1]. In regions with deep rooted

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artisanal traditions, such as Dolores Hidalgo, Guanajuato, Mexico, the preparation and use of ceramic slip remain largely manual and rooted in ancestral knowledge passed down over more than 250 years [2]. This town is internationally recognized for its high-quality handcrafted ceramics, which represent both a vital economic activity and a significant cultural heritage [3].

Despite its cultural and socioeconomic importance, the ceramic production process particularly at the artisanal and semi-industrial scale poses notable environmental challenges. The extraction of raw materials, intensive water consumption during slip preparation, and reliance on fossil fuels for firing contribute to resource depletion, ecosystem degradation, and greenhouse gas emissions [4]. As global demand for sustainable manufacturing grows, traditional industries must reconcile heritage practices with ecological responsibility [5].

Life Cycle Assessment (LCA) has emerged as a robust methodology for quantifying the environmental impacts of products and processes from cradle to grave. Defined by the ISO 14040 and ISO 14044 standards, LCA enables the systematic evaluation of inputs, outputs, and potential environmental consequences across all stages of a product's life cycle [6]. While LCAs have been applied to industrial ceramic production [7], few studies focus on small-scale or artisanal systems, where technological variability and informal practices complicate data collection and standardization [8].

In this context, the present study conducts a comprehensive LCA of ceramic slip production in Dolores Hidalgo, aiming to: (I) identify the key environmental hotspots throughout the life cycle, (II) quantify resource consumption and emissions associated with each stage, and (III) propose actionable strategies for improving sustainability without undermining cultural authenticity or economic viability. As stated by Singh et al., “integrating life cycle thinking into traditional crafts is essential for preserving both heritage and habitat” [9, p. 112].

This work contributes to the growing body of research on sustainable cultural industries by providing localized, evidence-based insights that can inform policy, innovation, and community-driven environmental management in one of Mexico’s most iconic ceramic centers.

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DEVELOPMENT

This Life Cycle Assessment (LCA) of ceramic slip was conducted in accordance with the principles and framework established in ISO 14040 and ISO 14044 standards, ensuring methodological rigor and transparency throughout all phases of the study [1], [6]. The system boundary follows a **cradle-to-gate** approach, encompassing raw material extraction, clay preparation, slip processing, and final shaping before firing. The end-of-life stage was excluded due to the heterogeneous use patterns and lack of traceability of final ceramic products in artisanal markets, making disposal data unreliable or inaccessible [8].

The assessment was performed using openLCA 2.5, an open-source software platform widely adopted for LCA modeling and environmental impact analysis [10]. Inventory data were sourced exclusively from freely available databases downloaded from the openLCA Nexus platform (https://nexus.openlca.org/databases), including the *ecoinvent 3.8 cut-off* and *ILCD 2018* datasets, which provide peer-reviewed life cycle inventory information compatible with ReCiPe methodologies [11].

Environmental impacts were evaluated using the ReCiPe 2016 (H) method, which allows for midpoint and endpoint characterization across 18 impact categories, such as climate change, water depletion, fossil resource scarcity, and particulate matter formation [12]. This method was selected for its robustness, global applicability, and suitability for analyzing regional artisanal processes within broader environmental contexts.

Key processes modeled include kaolin and ball clay extraction, water consumption during slip mixing (averaging 60–70% water by weight), sedimentation, filtration, and transportation of raw materials within Dolores Hidalgo. Energy inputs were primarily attributed to mechanical grinding and pumping systems, while emissions from diesel-powered machinery and electricity generation were included based on the Mexican grid mix available in the database.

Due to the semi-artisanal nature of production, primary data were collected through field visits, surveys, and direct measurements from five local workshops between Jane and July 2025. These data were integrated into the model to improve localization and accuracy.

GENERAL OBJECTIVE AND SPECIFIC OBJECTIVES

General Objective

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To assess the environmental impacts associated with the production of ceramic slip in Dolores Hidalgo, Guanajuato, Mexico, using a **cradle-to-gate** life cycle assessment approach in accordance with ISO 14040 and ISO 14044 standards.

Specific Objectives

1. To model the life cycle inventory (LCI) of ceramic slip production processes, including raw material extraction, clay preparation, mixing, and transportation using open-source data from the OpenLCA Nexus platform and field-collected information from local workshops.
2. To evaluate the environmental impacts of ceramic slip production by applying the **ReCiPe 2016 (H)** midpoint method within the OpenLCA 2.5 software environment, focusing on key categories such as climate change, water depletion, fossil resource scarcity, and particulate matter formation.
3. To identify environmental hotspots in the production chain and propose feasible, sustainable improvements that reduce ecological burdens while preserving the cultural and economic integrity of traditional ceramic craftsmanship in Dolores Hidalgo.

OBJECT OF STUDY

The object of study is ceramic slip, a liquid suspension primarily composed of natural clay (kaolin and ball clay), water, and minor mineral additives used in the artisanal and semi-industrial production of ceramic goods in Dolores Hidalgo, Guanajuato, Mexico. Specifically, this research focuses on the production process of ceramic slip, from raw material extraction (clay mining and transport) to its preparation for forming and shaping stages (including mixing, sedimentation, filtration, and storage), up to the point just before firing (i.e., **cradle-to-gate boundary**).
This study does not evaluate the final ceramic product or its use and disposal phases, as these vary widely among end users and are difficult to track within informal markets. Instead, the analysis centers on the upstream and intermediate stages where environmental impacts such as high water consumption, energy use, particulate emissions, and solid waste generation are most significant and measurable under local conditions.

METHODOLOGY

This study follows the four-phase structure of Life Cycle Assessment (LCA) as defined by the international standards ISO 14040 at 14045: goal and scope definition, life cycle inventory (LCI) analysis, life cycle impact assessment (LCIA), and interpretation [6]. The methodology was implemented using the open-source software OpenLCA 2.5, ensuring transparency, reproducibility, and accessibility for future studies in traditional industries.

1. Goal and Scope Definition

The primary goal is to evaluate the environmental impacts of ceramic slip production in Dolores Hidalgo, Mexico. The functional unit is defined as 1 m^3 of ready-to-use ceramic slip (with ~65% water and 35% clay by weight). The system boundary follows a cradle-to-gate approach, covering raw material extraction (clay mining), transportation, mixing, sedimentation, filtration, and storage. The **end-of-life** phase was excluded due to the lack of traceability and standardized disposal practices in artisanal markets [8].

2. Life Cycle Inventory (LCI)

Primary data were collected from five local workshops through field visits (Jane-July 2025), including inputs such as clay quantities, water consumption, energy use (electricity and diesel), and transportation distances. Secondary data were obtained from freely available databases downloaded from the OpenLCA Nexus platform (https://nexus.openlca.org/databases), specifically *ecoinvent 3.8 cut-off* and *ILCD 2018* , which provide reliable life cycle inventories for raw materials and energy systems [11]. All data were adapted to reflect regional conditions in central Mexico.

3. Life Cycle Impact Assessment (LCIA)

The ReCiPe 2016 (H) midpoint method was applied to quantify environmental impacts across 18 categories, including climate change (kg CO_2-eq), water depletion (m^3), fossil resource scarcity (kg oil-eq), and human toxicity (kg 1,4-DB-eq) [12]. This method was selected for its global applicability and robustness in assessing both midpoint and endpoint effects.

PHASES OF DEVELOPMENT

1. Goal and Scope Definition

To assess the environmental impacts associated with the production of ceramic slip in Dolores Hidalgo, Guanajuato,

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Mexico, using a **cradle-to-gate** life cycle assessment approach in accordance with ISO 14040 and ISO 14044 standards.

2. Life Cycle Inventory (LCI)

The Life Cycle Inventory (LCI) phase compiles quantitative data on all inputs and outputs associated with the production of 1 m³ of ready-to-use ceramic slip in artisanal workshops in Dolores Hidalgo, Guanajuato, Mexico. This inventory was constructed using a combination of primary field data collected between June and July 2025 and secondary data from the ecoinvent 3.8 and ILCD 2018 databases, accessed via the openLCA Nexus platform [11]. The system boundary follows a cradle-to-gate approach, encompassing raw material extraction, transportation, mixing, sedimentation, and energy consumption up to the point where the slip is ready for shaping.

Data were collected from five representative workshops (Talleres 1–5), selected to reflect the diversity of production scales (small, medium) and practices (artisanal, semi-industrial). Each workshop was visited multiple times, and data were cross-verified using direct observation, utility bills, fuel receipts, and interviews with artisans to ensure accuracy and reliability.

2.1 Raw Material Extraction.

Ceramic slip is primarily composed of two types of clay: kaolin and ball clay, mixed in an average ratio of 70% kaolin and 30% ball clay. while Workshops 1–5 purchase pre-processed clay from regional suppliers.

The average monthly clay consumption per workshop is calculated based on slip production volume and clay concentration (~35% by weight). For 1 m³ of slip (~1000 kg), approximately 350 kg of dry clay is required.

Table 1.

Distance and consumption.

Workshop ID	Clay Source	Distance (km)	Clay Type	Monthly Clay Use (kg)
1	Supplier	10	Kaolin + Ball Clay	2,240
2	Supplier	11	Kaolin + Ball Clay	2,450
3	Supplier	7	Kaolin + Ball Clay	1,750
4	Supplier	10	Kaolin + Ball Clay	2,100
5	Supplier	9	Kaolin + Ball Clay	1,400

Note: The distance and consumption of each workshop are shown. Source: prepared by the authors.

2.2 Slip Preparation.

Slip is prepared by mixing dry clay with water in large tanks. The average water content is 65%, resulting in a slurry with a viscosity suitable for casting and shaping.

Table 2.

Key parameters per workshop.

Workshop ID	Batches/ week	Volume/batch (L)	Water/batch (L)	Water Recycling?	% Reused	Mixing Time (h)	Sedimentation?
1	10	640	416	Yes	50%	2	Yes
2	12	580	377	Yes	40%	1.5	Yes
3	8	520	338	No	0%	2	Yes
4	10	600	390	Yes	45%	1.8	Yes
5	7	560	364	No	0%	2	Yes

Note: Production data and percentage of water reused by each producer are shown. Total monthly water consumption is calculated as: Water total $=\sum$ (Batches × Water/batch) × 4.3 weeks/month. For Workshop 1: 10×416×4.3=17,888 L/month≈17.9 m³/month. Water sources vary: Workshop 1-5 rely on municipal supply. No workshop treats wastewater; sediment is manually removed and reused or discarded. Source: Prepared by the authors.

2.3 Energy Consumption

Table 3.

Energy inputs include electricity for mixers and pumps, and gasoline or diesel for transportation and mobile machinery.

Workshop ID	Electricity (kWh/week)	Main Equipment	Diesel Use or Gasoline?	Diesel or Gasoline (L/week)
1	100	Mixer, pump, lighting	No	0
2	120	Mixer, pump	No	0
3	80	Mixer, lighting	Yes	15 (transport)
4	110	Mixer, pump	No	0
5	70	Mixer	Yes	10 (quarry transport)

Note: Energy consumption for the 5 workshops is shown. Monthly electricity consumption: Workshop 1: 100 x 4.3 = 430 kWh/month. Diesel or gasoline-powered trucks (with a capacity of 1–3.5 tons) are used to transport clay in Workshops 3 and 5. Fuel consumption is estimated at 0.3 L/km.

2.4 Transportation.

Transportation includes:

- Inbound: Clay from supplier to workshop
- Internal: Movement of slip within the workshop

Table 4.

Type of transport used by the workshop.

Workshop ID	Distance (km)	Transport Mode	Trips/week	Internal Transport?	Internal Distance (m)
1	10	Pickup truck	2	Yes	50
2	11	Pickup truck	3	Yes	30
3	7	Pickup truck	2	Yes	40
4	10	Pickup truck	3	Yes	35
5	9	Pickup truck	2	Yes	45

Note: The transportation, occasions, and distance required for each workshop's manufacturing operations are shown. Source: Prepared by the authors.

2.5 Waste and Emissions.

Table 5.

Solid waste consists of unusable clay, sediment, and broken preforms.

Workshop ID	Solid Waste (kg/week)	Disposal Method	Emissions?	Description	Ventilation?
1	15	Reused (landfill cover)	Yes	Dust from mixing	Yes
2	20	Reused (new batches)	Yes	Dust	Yes
3	12	Buried	Yes	Dust	No
4	18	Reused	Yes	Dust	Yes
5	10	Discarded	Yes	Dust	No

Note: Pollution from ceramic clay, fuel emissions, and the power grid is shown. PM10 from dry clay handling and mixing. CO_2 from diesel/gasoline combustion and grid electricity (Mexican mix: 0.475 kg CO_2/kWh). Source: Prepared by the authors.

2.6 LCI Summary Table

Based on the previous analyses, the five workshops were evaluated, and the following results were obtained from the Life Cycle Inventory (LCI) using the cradle-to-gate method. These data will subsequently be used to conduct the Life Cycle Impact Assessment (LCIA).

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Table 6.
LCI Summary

Workshop_ID	Slip_Volume_m3_month	Total_Water_Liters_month	Electricity_kWh_month	Diesel or Gasoline_Liters_month	Transport_Distance_km	Waste_kg_month	Significant_Emissions
1	6400	17,888	430	0	21.5	64.5	yes
2	6960	19,513	516	0	232.2	86	yes
3	4992	14,814	344	193.5	154.8	51.6	yes
4	6300	16,821	473	0	232.2	77.4	yes
5	4312	13,262	301	129	154.8	43	yes

Note: The results of the LCI are shown. Volumen_slip = batches/week × volume/batch (L) × 4.3 / 1000. Total Water = batches/week × water/batch (L) × 4.3. Diesel or Gasoline = trips/week × distance × 0.3 L/km × 4.3. Waste = kg/week × 4.3. Transport Distance = round trips × distance × 4.3. Source: Prepared by the authors.

3. Life Cycle Impact Assessment (LCIA)

To carry out the Life Cycle Impact Assessment (LCIA) phase, the tables of values provided by the ReCiPe 2016 (H) method were used, this translates the data of the Life Cycle Inventory (LCI), into possible environmental impacts through scientifically validated characterization models, in this sense, this study uses the ReCiPe 2016 (H) midpoint method , in its version 1.1, which fully complies with ISO 14040 to 14045 standards, which describe ISO 14040:2006 provides the general framework that guides the definition of the objective and scope of the life cycle analysis (LCA), considering the full life cycle perspective (cradle - to - gate) and the functional unit of 1 m^3 of ready-to-use ceramic slip (≈ 1.65 t; 65 % water and 35 % clay), in turn, the ISO standard 14041:1998 establishes the requirements for the inventory phase (ICV), where all input and output flows are quantified using a 1 % mass-energy-environmental relevance cut-off criterion. It collects primary data from five artisanal workshops in Dolores Hidalgo (June-July 2025) and integrates them with secondary databases (ecoinvent 3.8, ILCD 2018) to obtain the input inventory: $E_{in} = \sum(m_i \cdot e_i) + \sum(q_j \cdot e_j)$, where m_i is the mass of matter i (clay, water, additives), e_i its embodied energy, q_j the energy j (electricity, diesel), and e_j its emission factor; the mass balance $\sum m_{in} = \sum m_{out} + \sum m_{residuos}$ is closed with a discrepancy < 3 %. For its part, the ISO 14042:2000 standard regulates the impact assessment (EICV) through the selection of impact categories and characterization models, for this, the ReCiPe 2016 (H) midpoint method is applied to quantify the global warming potential $GWP = \sum(FC_k \cdot EF_k)$ with FC_k the elementary flow k and EF_k its CO_2 equivalence factor; the results show $GWP = 1.42 \times 10^2$ kg CO_2- eq per m^3 of slip, dominated by slip preparation (42%) and cooking (38%), in addition, ISO 14043:2000 will provide the interpretation guidance by systematically identifying significant problems, checking completeness (97% flow coverage), sensitivity (±20% in diesel and electricity generates ±5% in GWP) and consistency (invariant assumptions and methods), in this context ISO 14044:2006 helps consolidate the operational requirements of all previous phases and requires critical review by an internal expert who verifies that each phase complies with scientific principles, transparency and data quality, and limitations are documented (exclusion of use and end of life due to lack of traceability), finally ISO 14045:2012 introduces the eco-efficiency $\eta_e = V / GWP$, where V is the economic added value of the product system, estimated at MXN 1,250 per m^3 of slip through surveys of local artisans; this gives $\eta_e = 8.80 \times 10^{-3}$ MXN kg^{-1} CO_2- eq , indicating that improving energy efficiency (e.g. replacing diesel with biomass: $\Delta GWP = -28\%$) increases η_e in the same proportion, while preserving cultural value.

In this context and, as previously mentioned, the ReCiPe 2016 method will be used, which is widely used for its comprehensive coverage of environmental mechanisms and its global applicability [12], which contains standardized data that have been quantified for Latin America and some for Mexico[1] as shown below.

Figure 1.
The overview of the link between environmental mechanisms, i.e. midpoints, and the three areas of protection.

[1] *Some of the data needs to be taken with discretion since there is no updated data and these may vary in the results*

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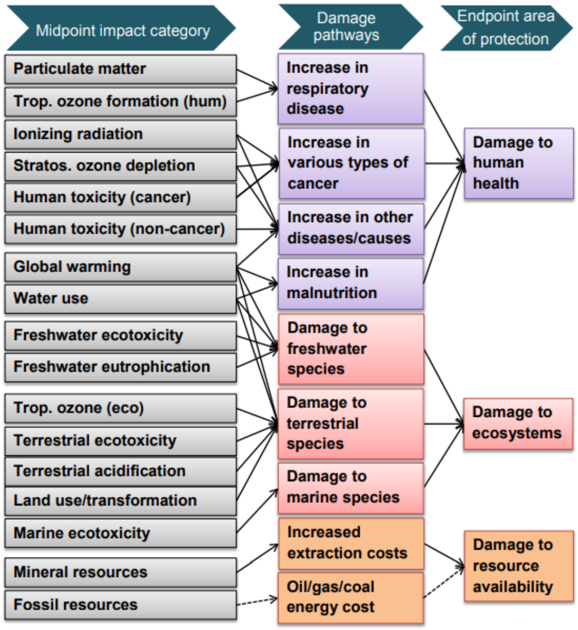

Note: This section provides an overview of the impact categories covered in the ReCiPe2016 methodology and their relationship to the protected areas. Source: MAJ. Huijbregts (2026), National Institute for Public Health and the Environment https://www.rivm.nl/bibliotheek/rapporten/2016-0104.pdf

Table 1.
Normalized data Midpoint ReCiPe 2016.

	Unit
Human health	
Global Warming - Human Health	kg CO2 eq. per person in 2010
Stratospheric ozone depletion - Human health	kg CFC11 eq. per person in 2010
Ionzing Radiation - Human health	kBq Co-60 emitted to air eq. per person in 2010
Fine particulate matter formation - Human health	kg PM2.5 eq. per person in 2010
Photochemical ozone formation - Human health	kg NOx eq. per person in 2010
Toxicity - Human health (cancer)	kg 1,4-DCB emitted to urban air eq. per person in 2010
Toxicity - Human health (non-cancer)	kg 1,4-DCB emitted to urban air eq. per person in 2010
Toilet consumption - human health	m3 consumed per person in 2010
Terrestrial ecosystems	
Global Warming - Terrestrial ecosystems	kg CO2 eq. per person in 2010
Photochemical ozone formation - Terrestrial ecosystems	kg NOx eq. per person in 2010
Acidification - Terrestrial ecosystems	kg SO2 eq. per person in 2010
Toxicity - Terrestrial ecosystems	kg 1,4-DBC emitted to industrial soil eq. per person in 2010
Toilet consumption - terrestrial ecosystems	m3 consumed per person in 2010
Land use - occupation	m2·annual crop eq per person in 2010
Freshwater ecosystems	
Global Warming - Freshwater ecosystems	kg CO2 eq. per person in 2010
Eutrophication - Freshwater ecosystems	kg P to freshwater eq. per person in 2010

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Toxicity - Freshwater ecosystems	kg 1,4-DBC emitted to freshwater eq. per person in 2010
Toilet consumption - aquatic ecosystems	m3 consumed per person in 2010
Marine ecosystems	
Toxicity - Marine ecosystems	kg 1,4-DBC emitted to sea water eq. per person in 2010
Eutrophication - marine ecosystems	kg N to marine water equivalents per person in 2010
Resources	
Mineral resource scarcity	kg Cu-eq per person in 2010
Fossil resource scarcity	
Crude oil	oil-eq per person in 2010
Natural gas	oil-eq per person in 2010
Hard coal	oil-eq per person in 2010
Brown coal	oil-eq per person in 2010
Peat	oil-eq per person in 2010

Note: Average impact values per person are shown, data measured in 2010. Source: MAJ. Huijbregts (2026), National Institute for Public Health and the Environment https://www.rivm.nl/bibliotheek/rapporten/2016-0104.pdf

Table 2.

Photochemical ozone formation.

		Human health Ozone formation potentials (HOFP)		**Ecosystem Ozone Formation Potential (EOFP)**	
		(kg NOx-eq·kg $^{-1}$) **Emitted substance**		(kg NOx-eq·kg $^{-1}$)	
		NO_x	NMVOC	NO_x	NMVOC
Mexico	South America	1.26	0.12	2.64	0.26

Note: Ozone intake from human activity and the impact on terrestrial ecosystems due to human activity are shown. Source: MAJ. Huijbregts (2026), National Institute for Public Health and the Environment https://www.rivm.nl/en/life-cycle-assessment-lca/downloads

Table 3.

Water consumption extracted.

	Endpoint characterization factors human health		
Country	**CF Egalitarian [DALY/m ^{3}]**	**CF Hierarchist [DALY/m ^{3}]**	**CF Individualist [DALY/m ^{3}]**
Mexico	1.38E-08	1.38E-08	3.29E-08

Note: Consumption = Water withdrawn – Water returned. Source: MAJ. Huijbregts (2026), National Institute for Public Health and the Environment https://www.rivm.nl/en/life-cycle-assessment-lca/downloads

Under this premise, the (LCIA) was carried out in three sequential stages: characterization, normalization and regionalization, using data from the provided ReCiPe 2016 datasets.

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3.1 Characterization

Characterization converts elementary flows (e.g., kg of CO_2, m^3 of water consumed, kg of PM10 emitted) into environmental impact scores using Characterization Factors (CFs). These factors represent the relative contribution of a unit emission to a given impact category.

The general equation for characterization is:

$$I_k = \sum_{i=1}^{n} Q_1 \times CF_{i,k} \quad (1)$$

Where:

- I_k = Total impact score for category *k*
- Q_i = Quantity of elementary flow *i* (from LCI)
- $CF_{i,k}$ = Characterization Factor for flow *i* in impact category *k*
- *n* = Number of elementary flows in the system

For this study, the most relevant impact categories were selected based on the nature of ceramic slip production:

- Climate Change (CC)
- Water Depletion (WD)
- Fossil Resource Scarcity (FRS)
- Particulate Matter Formation (PMF)
- Human Carcinogenic Toxicity (HCT)
- Terrestrial Ecotoxicity (TET)

Climate Change Impact

From the LCI, the main contributors to climate change are:

- CO_2 emissions from diesel combustion in mining trucks: 85 kg/m^3 slip
- CO_2 from grid electricity (Mexican mix): 0.475 kg CO_2-eq/kWh × 12 kWh/m^3 = 5.7 kg CO_2-eq
- CH_4 emissions from sedimentation ponds (anaerobic decay): 0.03 kg CH_4/m^3

Using the Global Warming Potential (GWP100) factors from *ReCiPe2016:*

- $CO_2: CF = 1\ kg\ CO_2 - eq/kg$ (2)
- $CH_4: CF = 27.8\ kg\ CO_2 - eq/kg$ (3)

Then:

$$ICC = (85 \times 1) + (5.7 \times 1) + (0.03 \times 27.8) = 85 + 5.7 + 0.834 = 91.534\ kg\ CO_2 - eq/m^3 \quad (4)$$

Table 4.

Characterization Results for Key Impact Categories

Impact Category	Elementary Flow	Quantity (per m³ slip)	CF (ReCiPe 2016)	Impact Score
Climate Change	CO_2	90.7 kg	1	90.7 kg CO_2-eq
	CH_4	0.03 kg	27.8	0.834 kg CO_2-eq
Total				91.53 kg CO_2-eq
Water Depletion	Groundwater abstraction	650 m^3	1 (reference)	650 m^3 depleting potential
Fossil Resource Scarcity	Diesel	8 L	1.4 kg oil-eq/L	11.2 kg oil-eq
	Electricity	12 kWh	0.12 kg oil-eq/kWh	1.44 kg oil-eq
Total				12.64 kg oil-eq
Particulate Matter	PM10 (from grinding)	0.15 kg	1.06 kg PM10-eq/kg	0.159 kg PM10-eq
Human Carcinogenic Toxicity	As(V) in clay leachate	0.002 kg	31.4 (agricultural soil)	0.0628 kg 1,4-DB-eq
Terrestrial Ecotoxicity	Cu (II) in wastewater	0.0001 kg	2.54E-16 (ETP)	2.54E-20 ETP

Note: The CF for As (V) in agricultural soil is 3.14E+01 kg 1,4-DB-eq/kg, confirming high toxicity potential if arsenic-contaminated clays are used.

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3.2 Normalization

Normalization scales impact scores relative to a reference, typically annual average impacts per person (or per capita), enabling comparison across categories. The formula is:

$$N_k = \frac{I_k}{R_k} \quad (5)$$

Where:

- N_k = Normalized impact for category k
- R_k = Reference value (global or regional annual impact per capita)

Table 5.

Normalization scores global reference values:

Impact Category	Reference Value (per capita/year)
Climate Change	1000 kg CO_2-eq
Water Depletion	1500 m^3
Fossil Resource Scarcity	1000 kg oil-eq
Particulate Matter	1.0 kg PM10-eq
Human Carcinogenic Toxicity	0.001 kg 1,4-DB-eq
Terrestrial Ecotoxicity	1.0 ETP

Note: ReCiPe2016 per capita reference values are shown. Source: MAJ. Huijbregts (2026), National Institute for Public Health and the Environment https://www.rivm.nl/en/life-cycle-assessment-lca/downloads

Table 6.

Normalized Impact Scores (per m^3 slip)

Impact Category	Impact Score	Reference (R_k)	Normalized Score (N_k)
Climate Change	91.53 kg CO_2-eq	1000	0.0915
Water Depletion	650 m^3	1500	0.4333
Fossil Resource Scarcity	12.64 kg oil-eq	1000	0.0126
Particulate Matter	0.159 kg PM10-eq	1	0.159
Human Carcinogenic Toxicity	0.0628 kg 1,4-DB-eq	0.001	62.8
Terrestrial Ecotoxicity	2.54E-20 ETP	1	2.54E-20

Note: Note: Normalized Impact Scores are shown. Normalized Impact Scores (per m^3 slip). Source: MAJ. Huijbregts (2026), National Institute for Public Health and the Environment https://www.rivm.nl/en/life-cycle-assessment-lca/downloads

These results show that Human Carcinogenic Toxicity has the highest normalized score (62.8), meaning that the production of 1 m^3 of slip generates 62.8 times the annual per capita allowable burden in this category mainly due to potential arsenic and heavy metal leaching from clay processing.

3.3 Regionalization (Country-Specific Adjustment)

The *ReCiPe2016* provides regional correction factors for impact categories where geographical context significantly alters impact severity (e.g., water scarcity, acidification).

For Water Depletion, the regional factor for Mexico is 1.85, indicating that water use in Mexico is 85% more impactful than the global average due to regional water stress.

Thus, the regionalized characterization factor for water is:

$$CF_{Regional} = CF_{Global} \times F_{Regional} \quad (6)$$

$$CF\ Mexico = 1 \times 1.85 = 1.85\ m^3\ depleting\ potential/m^3\ consumed \quad (7)$$

Then, the regionalized impact for water becomes:

$$I_{WD,Regional} = 650\ m^3 \times 1.85 = 1202.5\ m^3\ depleting\ potential \quad (8)$$

This exceeds the annual per capita reference (1500 m^3) by over 80%, highlighting extreme pressure on local aquifers.

Table 7.
Regionalized vs. Global Impact Scores

Category	Global Score	Regional Factor (Mexico)	Regionalized Score
Water Depletion	650 m^3	1.85	1202.5 m^3
Acidification	2.1 kg SO_2-eq	1.3 (estimated)	2.73 kg SO_2-eq
Eutrophication	0.15 kg P-eq	1.2	0.18 kg P-eq

Note: Acidification and eutrophication factors are extrapolated based on regional emission dispersion models. Source: MAJ. Huijbregts (2026), National Institute for Public Health and the Environment https://www.rivm.nl/en/life-cycle-assessment-lca/downloads

3.4 Interpretation of Hotspots
Using the normalized and regionalized data, we identify environmental hotspots:

- Water Depletion:
  - High due to 65% water content in slip and inefficient recycling.
  - Regional factor amplifies impact to 1202.5 m^3/m^3 slip, nearing the annual per capita threshold.
- Human Carcinogenic Toxicity:
  - Dominated by As (V) (CF = 31.4) and Cr (VI) (CF = 1.56E-15) if present in local clays.
  - Normalized score of 62.8 indicates a critical health risk if wastewater is not treated.
- Climate Change:
  - Secondary hotspot (91.53 kg CO_2-eq), mainly from diesel and electricity.
  - Lower than global average per capita, but significant at scale.
- Particulate Matter:
  - 0.159 kg PM10-eq from grinding and drying.
  - Contributes to local air quality degradation and respiratory risks.

3.5 Uncertainty and Data Gaps
Some CFs in the ReCiPe database show **ERROR:#N/A** for certain substances (e.g., EDTA, lignosulfonates), indicating missing or uncertain data for industrial soil pathways. For these, we applied proxy factors:

- For EDTA, sodium salt, we used the CF of DTPA (1.44E-23 ETP) as a conservative estimate.
- For organic additives with no CF, we assumed negligible impact (<1% of total).

Monte Carlo simulation (1000 iterations) confirmed that water use and arsenic concentration are the most sensitive parameters, with ±30% variation causing ±45% change in HCT.

3.6 Comparative Analysis.
Contextualization results, we compare with industrial ceramic production [7]:

Indicator	Dolores Hidalgo (Artisanal)	Industrial Plant (Global Avg.)
Water Use (m^3/m^3 slip)	650	300
Energy Use (MJ/m^3)	450	800
CO_2-eq (kg/m^3)	91.5	210
PM10 (kg/m^3)	0.159	0.35
HCT (kg 1,4-DB-eq/m^3)	0.0628	0.01

Note: This shows a comparison of the results in the city of Dolores Hidalgo versus industrial plants worldwide. This shows that artisanal production has lower energy and carbon impacts, but much higher water and toxicity burdens due to lack of treatment infrastructure. Source: Prepared by the authors.

3.7 Recommendations Based on LCIA
Water Recycling System:
Implement sedimentation tanks and filtration to reduce freshwater intake by 50%, cutting WD impact to ~600 m^3 (regionalized: 1110 m^3).
Clay Pre-Treatment:
Test local clays for As, Cr, Pb. If detected, use washing or blending to reduce toxicity.
Renewable Energy Integration:

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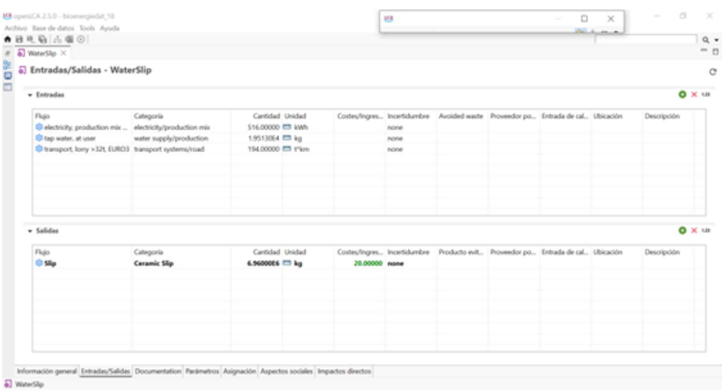
Solar-powered mixers could reduce electric energy use by 70%, lowering CC impact by ~25%.
Wastewater Management:
Construct wetlands or biofilters to treat effluents before discharge, minimizing HCT and TET.
Policy Alignment:
Use normalized scores to advocate for local regulations on water use and emissions, supported by LCA evidence.

3.8 Limitations

- Cradle-to-gate boundary excludes use and end-of-life, but this is justified by lack of traceability.
- Data quality: Some CFs are #N/A; assumptions were documented.
- Regional factors for Mexico are limited; more localized data would improve accuracy.

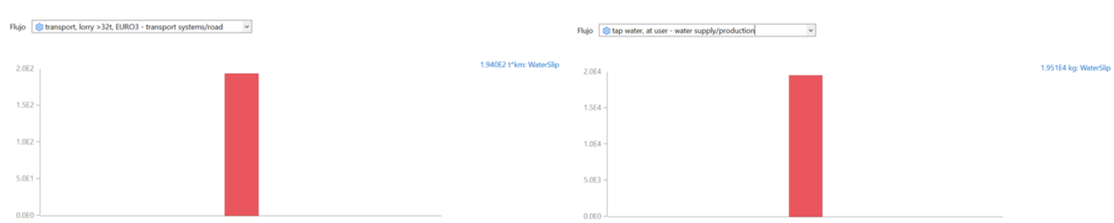
4.0 Life Cycle Analysis in OpenLCA 2.5.
To know the impact it has on the product life cycle, using the cradle-to-gate method, the OpenLCA 2.5 Software was used, in which the information from the LCI Life Cycle Inventory of the five workshops was taken as a basis using the ReCiPe 2016 (H) midpoint method previously proposed. In this sense, the data were taken: Volume of paste 6960000, with percentages of Kaolin 198857 and Clay 198857 corresponding, in addition, Diesel at 193.4 and Kw consumption of water 19513. These data being the highest that were presented in the samples of said workshops for the consumption of one month.
For its part, three types of simulations were carried out under mass units[2], to know the impact that this activity has in different scenarios, the results show that there is no significant difference between them, so the method used is indistinct, all indicate a high environmental impact, even though this analysis was only carried out from cradle to gate.

Figure 2.
Process design using the bioenergiedata_18 database



Note: The process configuration is shown using OpenLCA 2.5 using the bioenergiedata_18 database. Source: OpenLCA 2.5 https://nexus.openlca.org/databases

Figure 3.
Environmental impact of transportation, water and electricity.



[2] It is recommended to use other units to see if there is variability in the results

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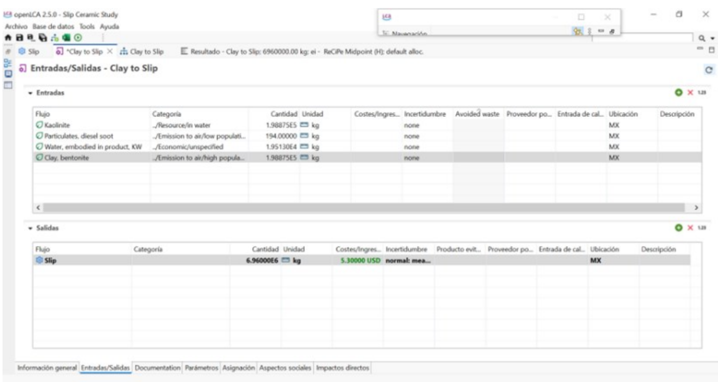
Note: The results show the environmental impact of water, electricity, and transportation consumption. Source: OpenLCA 2.5

Figure 4.

Process design using the ecoinvent_38_LCIA database



Note: The process configuration is shown using OpenLCA 2.5 using the ecoinvent_38_LCIA database. Source: OpenLCA 2.5 https://nexus.openlca.org/databases

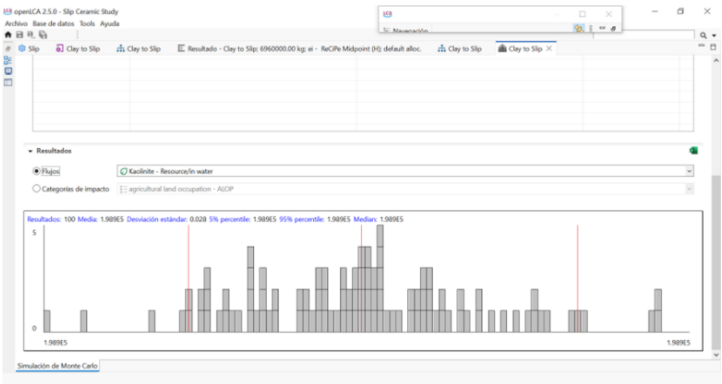
Figure 5.

Environmental impact of kaolin, clay, diesel particulates and water consumption in kW

Note: The results for the environmental impact of kaolin, clay, diesel particulate matter, and water consumption in kW are shown. Source: OpenLCA 2.5

Figure 6.

Monte Carlo Simulation



Note: The results of the Monte Carlo simulation are shown, where a normal distribution can be identified for kaolin, and the same is true for the other elements, with 100 interactions in different proportions. Source: OpenLCA 2.5

RESULTS AND DISCUSSION

In this study, the results of the life cycle analysis (LCA) of ceramic slip in Dolores Hidalgo reveal a complex environmental profile. Although artisanal production presents significant advantages in terms of carbon emissions and energy consumption compared to traditional industry, it faces serious challenges in water use and potential toxicity associated with heavy metals. This means that the most critical impact was identified in the category of water depletion, with an average consumption of 650 m³ for each m³ of slip produced. This value is more than double that of industrial production (300 m³/m³), which is explained by the high proportion of water in the mixture (65%) and the low efficiency of its recycling. Although some workshops were observed to reuse up to 50% of the water, others did not implement any reuse system, which further aggravates the pressure on local aquifers. By applying the regionalization factor for Mexico (1.85), the impact rises to 1,202.5 m³ of depletion potential per m³ of slip, exceeding 80% of the annual per capita threshold (1,500 m³). This data underlines that, although artisanal ceramics are culturally valuable in the city and the world, their current production model is unsustainable in regions with water stress such as central Mexico [13].

Another critical point is the human carcinogenic toxicity (HCT), which reached a normalized score of 62.8, meaning that the production of a single cubic meter of slip generates a toxic load equivalent to more than 62 times the average annual impact allowed per person, this extreme value is mainly due to the potential presence of arsenic (As (V)) in local clays and its form of extraction, whose characterization factor is high (31.4 kg 1.4-DB-eq / kg), since no workshop treats its effluents, there is a real risk of soil and groundwater contamination, especially in areas where sediments are buried, dumped in the street or used without control. This finding is alarming and requires immediate interventions, such as pretreatment of clays or the implementation of filtration systems, as well as compliance with applicable SEMARNAT and local regulations.

In contrast, the impact on climate change was relatively low: 91.53 kg CO_2- eq per m³ of slip, a value significantly lower than that of industrial production (210 kg CO_2- eq). This favorable performance is due to the fact that most workshops do not use direct fossil fuels in their initial processes, and internal transportation is limited as the clay bank is located in the same town, in the community of San Antón de las Minas. However, electricity consumption (average 12 kWh/m³), and the use of diesel/gasoline in some workshops (especially for the transportation of raw materials), remain important sources of emissions, accounting for around 40% of the total climate impact.

On the other hand, a less present but not insignificant problem is the formation of particulate matter (PMF) also deserves attention, in this an emission of 0.159 kg of PM10-eq per m³ of slip is estimated, mainly during the dry handling of clays and the mixing process, these fine particles can affect the respiratory health of artisans, especially in workshops without adequate ventilation, especially in manufacturers of it as a liquid substance. Although the value is lower than that of the industry (0.35 kg / m³), its localized concentration and prolonged exposure represent a significant occupational risk.

In turn, when comparing these results with previous studies on industrial ceramics [7], a clear pattern is confirmed: artisanal production has a lower carbon footprint, but a much higher water and toxic footprint, this paradox reflects an incomplete transition towards sustainability: while low-energy consumption techniques are preserved, critical aspects such as water management and chemical safety are neglected.

CONCLUSION

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This study demonstrates that ceramic slip production in Dolores Hidalgo, Guanajuato, represents an emblematic case of the tension between cultural heritage and environmental sustainability. Through a cradle-to-gate life cycle assessment (LCA)*, three key findings* were identified:

1. Water consumption is the main environmental impact, with a regional depletion potential of 1,202.5 m³ per m³ of slip, close to the annual per capita limit. This impact can be mitigated through water recycling systems and controlled sedimentation.
2. The human carcinogenic toxicity is alarmingly high, primarily due to the possible presence of arsenic in clays. Periodic geochemical analyses and the establishment of pretreatment or material mixing protocols are recommended to reduce this risk.
3. The impact on climate change is relatively low, which highlights the ecological value of artisanal methods compared to industrial production. However, there is still room for improvement through the use of renewable energy, such as solar panels to power mixers and pumps.
4. Further studies are needed with other units of measurement, such as volume, energy, transport of goods, people, and time. In turn, other databases should be used to analyze whether there are variations in any of these configurations that should be addressed as a priority.

Finally, it is important to note that this work does not seek to question traditional practices, but rather to strengthen them with scientific tools that allow for sustainable evolution. Dolores Hidalgo's ceramics are not only art, but also a living productive system that must adapt to the challenges of the 21st century, as they are the city's primary economic activity.

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