Environmental Impact of Corn Tortilla Production: A Case Study

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Featured Application: This work helps to realise improvements in the cultivation of corn and corn–nixtamalisation–dough–tortillas production, which could mean more environmentally friendly food production.

Abstract: The research on the environmental impacts of corn-derived products has been mainly on cultivation techniques and the production of biofuels, so there is limited information on the impacts produced by the transformation of corn for human consumption. The tortilla is a millennial product derived from corn of which consumption is increasing in North America. The aim of this study is to identify the environmental hotspots of the tortilla using a life cycle assessment (LCA) approach. The process studied included only the corn–nixtamalisation–dough–tortillas production. The functional unit is one kg of tortillas packed in kraft paper. The impacts of the tortilla production process were evaluated using SimaPro 8.5.0 software, considering ReCiPe Midpoint. The production has the greatest impact in 15 of the 18 impact categories. The normalisation reveals that the most significant impacts concentrate in the categories terrestrial acidification (TA), particulate matter formation (PMF), marine ecotoxicity (MET) and fossil fuel depletion (FD). Improvements in the cultivation could mean more environmentally friendly tortilla production.

Keywords: corn; climate change; life cycle assessment; environmental impact; CO \(_2\) emission

1. Introduction

Soil conservation is one of the main sustainability goals in ensuring food security and environmental protection [1]. For this reason, the production of food with the minimum impact on the environment is a major challenge for agricultural production. Nitrogen (N) is a critical input for optimum crop production because it promotes rapid growth of corn plants, increases leaf size and quality, and promotes fruit and seed development [2]. Many grain legumes require limited doses of N fertilisers, but others, such as maize, are big consumers of N, and consequently of energy [3]. This is important because maize is the second largest crop worldwide, with a production of 615,533,645 Mton (millions of tons) [4]. Moreover, in corn production the use of herbicides for the chemical control of weeds is intensive [5]; its high water requirements and the associated nutrient runoff contribute to several
impacts on the environment such as eutrophication, algal growth and hypoxia in downstream water bodies [6]. Other corn production-associated environmental impacts are the unsustainable use of water for irrigation, the expansion of genetically modified corn, soil erosion and biodiversity loss [4]. This situation is unsustainable in the long term.

Research on the environmental impacts of corn has been mainly on cultivation techniques [3,5,7,8] and the production of biofuels [6,9,10], so there is limited information on the impacts produced by the transformation of corn for human consumption using life cycle analysis. The study by Grant and Beer [11] was conducted using life cycle assessment (LCA) for the determination of greenhouse gas (GHG) emissions from pre-agricultural activities on farms and post-farms in the manufacture of corn chips, taking as an indicator the CO$_2$ equivalent (CO$_2$ eq) and as a functional unit a box of ten 400 g packages of corn chips. They found that GHG emissions from obtaining raw materials comprises approximately 5% of the total throughout their life cycle; corn cultivation produces around 27%, and the manufacturing stage of corn fritters around 68%. The study showed that the most important source of GHG emission is the emission of nitrous oxide on the farm as a result of the application of fertilisers (0.12 kg of CO$_2$ eq per box). Sánchez Femat [12] took as a basis the ISO 14067:2013 standard to perform an analysis of the carbon footprint produced by ten nixtamal mills distributed in the Metropolitan Zone of the Valley of Mexico. His door-to-door study produced a result of 43.38 kg CO$_2$ eq t$^{-1}$ of processed nixtamal mass.

Corn has many food uses, among which is its use for making tortillas. This is a millennial product which is part of the culinary tradition that continues to lift generations and cultures. Historically it was considered as the “bread of life” and there is a connection between Mesoamericans of around 2500 years ago and today’s international tortilla marketplace [13]. Nowadays there is a great demand in North America and some countries in Central America; in the United States, the tortilla market is projected to reach USD 29.39 billion at a Compound Annual Growth Rate (CAGR) of 5.50% over the forecast period. North America alone captures 59.06% of the global market share in the year 2017 [14]. The tortilla is a food in circular and flattened form, with diameters ranging from 160 to 300 mm and is 2 to 6 mm thick. It is made with the mass of cooked corn that is obtained through the process of nixtamalisation [15]. In Mexico, half of the corn produced goes to the production of nixtamalised corn tortillas, while 11.3% of corn production is used to make flour for tortillas [16,17]. The National Council for the Evaluation of Social Development Policy (CONEVAL) estimates that in the urban environment the annual per capita consumption of tortillas is 56.7 kg, and in rural areas, 79.5 kg [18].

Despite the economic and cultural importance of the tortilla, a study describing the environmental impact derived from the production of nixtamalised corn tortillas using an LCA approach has not been carried out. For this reason, the environmental impacts associated with each of the stages of its production are unknown. The LCA is a useful method that has been used in numerous agri-food studies in order to identify environmental hotspots and pinpoint solutions to mitigate environmental burdens [19]. The aim of this study is to identify the environmental hotspots of the tortilla as a support tool for food sovereignty, the generation of GHG emission reduction strategies, and the identification of opportunities for the technological improvement of the process.

**Tortilla Description**

There are two ways to produce the dough for making tortillas: the traditional method (corn–nixtamal–dough–tortilla) and that based on nixtamalised corn flour (corn flour–dough–tortilla) [20]. Tortillas in Mexico are created mainly with nixtamalised corn dough, which represents 65% of the national production, compared to 35% produced with the nixtamalised corn flour [21]. In Mexico, white corn is traditionally used to make tortillas and oils, while yellow corn is mostly used for livestock pigments and starches.

The process of cooking the tortilla is very varied, from the use of “comales” (a flat iron griddle) to automatic machines known as “tortilladoras” (see Figure 1). Currently, the most used manufacturing
process in the United States and Mexico is the semi-industrial automatic tortilla machine, which, in addition to the moulding, bakes the dough in a continuous process [20].

![Automatic machine or “tortilladora”](image)

**Figure 1.** Automatic machine or “tortilladora”. Source: TAPSA [22].

## 2. Materials and Methods

Life cycle assessment (LCA) is one of the most established environmental assessment methods for modelling the environmental effects of goods and services throughout their life cycle [23]. An LCA identifies the environmental impacts of all stages in the production cycle and enables the evaluation of environmental impacts for comparative and improvement purposes [24]. To achieve this, the LCA requires that the process be checked in order to identify all resources used (materials, energy) and all emissions of environmental pollutants (wastes, effluents, and emissions) [25].

### 2.1. LCA Approach and Assumptions

The process studied included only the corn–nixtamalisation–dough–tortillas production. The functional unit is one kilogram of tortillas packed in kraft paper. In the limits of the system (Figure 2), it was considered from the obtaining of raw materials for the production of corn, to the elaboration of the already packaged product, with a focus on the cradle to the door, i.e., “cradle to gate”. The stages of obtaining the rest of the raw materials, the use of the product, and the disposition of the residues at the end of life were excluded. In this study no comparisons were made between systems. A producer in Quiroga, Michoacán was surveyed in the year of 2017 to understand the process of corn production. A tortilla shop, equipped with a nixtamal mill and an automatic tortilla maker was studied, which is representative of the business class in Mexico that complies with the official standard for dough, tortillas and prepared flours [26].

![Diagram of the life cycle of tortilla production](image)

**Figure 2.** Limits of the system in the life cycle of the tortilla.
The stages considered in the LCA are:

- **Production of raw material.** The production of white corn is considered because it is the raw material for the production of tortillas. It includes the preparation of the earth up to the drying of the seed. The preparation of the land uses the conservation tillage technique with the use of an agricultural tractor, which includes a ploughing phase, two harrowing phases and sowing. Mechanised planters are used to plant the seed and the first fertilisation of the soil is carried out, adding the total amount of the required phosphorus and 40% of the total nitrogen. The second fertilisation consists of adding the remaining nitrogen to the corn. Pest control is carried out by sprinklers coupled to the tractor. Harvesting is done with agricultural harvesters to later go through a grain drying process. Once dry, the grain is packed in sacks and distributed to the tortilla shops.

- **Transport of raw material.** This includes the distribution of the pesticides, fertilisers and supplies necessary to produce corn, as well as those needed for the production of tortillas, such as corn and calcium hydroxide in the nixtamalisation stage.

- **Nixtamalisation.** The technique is based on the cooking of the corn grains in a calcium hydroxide solution ($\text{Ca(OH)}_2$) or lime. For each kg of corn, 15 g of lime are used in 3 L of boiling water ($85–100\ ^\circ\text{C}$) for at least 45 min, depending on the hardness of the grain [27]. The mixture is left to rest for 8–24 h in the cooking solution (knowing as nejayote), then washed two or three times with clean water to remove the nejayote, the pericarp of the grain and any impurities. The result of alkaline cooking is the nixtamalised or nixtamal corn. Subsequently, it is passed to a wet milling process to obtain the dough (with 48–55% humidity).

- **The cooking of the dough.** The dough is baked in an automatic tortilla machine which moulds, cuts and bakes. The machines are fuelled by natural gas or propane as a fuel source and the mechanical system is powered by electricity. The dough is fed through a hopper where there are two rollers (kneading) that rotate in opposite directions, directing the dough to the extruders which, in turn, feed the moulders, where it is shaped flat and then cut out by some blades. The discs of dough move along a hot iron caterpillar to be cooked at temperatures of 280–300 °C with a residence time of 20 to 40 s. Each side is cooked twice, at the end the tortilla is obtained [28]. Approximately 30 g of dough is needed for each tortilla. The complete process of the production system is shown in Figure 3.

2.2. **Life Cycle Inventory of Corn Tortilla**

The data and sources to execute the life cycle inventory (LCI) of tortilla production are described in Table 1. These data are referenced to the functional unit according to the ISO methodology [29]. The data were validated according to the quality criteria referred to by the ISO international standard [30].
Figure 3. Process scheme for making the tortillas.
Table 1. Types and data sources.

| Stage                        | Data                               | Kind           | Source                                                                 |
|------------------------------|------------------------------------|----------------|------------------------------------------------------------------------|
| Transport of raw material    | Producers of materials             | Primary        | Survey of corn producers and tortilla owners; Google-Maps              |
|                              | Transported materials              | Primary        |                                                                         |
|                              | Transport vehicle                  | Primary, Secondary |                                                        |
|                              | Distance travelled                 | Primary, Secondary |                                                        |
| Corn production              | Water consumption                  | Primary, Secondary | Datasheet catalogues [31]                                               |
|                              | Use of fertilisers                 | Primary        |                                                                         |
|                              | Use of pesticides                  | Primary        |                                                                         |
|                              | Use of seeds                       | Primary        |                                                                         |
|                              | Production yield                   | Primary, Secondary | FIRA [32]                                                              |
|                              | Land use                           | Secondary      | Material balance                                                       |
| Nixtamalisation, grinding    | Water consumption per unit process | Secondary      | Calculated by mass balance                                             |
| and cooking                  | Electric consumption               | Primary        | Light bill                                                              |
|                              | Electricity requirements per unit  | Secondary      | Calculated and based on technical of equipment data sheets             |
|                              | process                            |                |                                                                         |
|                              | Requirement of materials per unit  | Primary, Secondary | Material balance of each process                                      |
|                              | process                            |                |                                                                         |
|                              | Solid waste generation             | Secondary      | Calculated by material balance and scientific articles                 |
|                              | Discharge of residual water        | Primary, Secondary | Balance of material in the field                                       |

The life cycle analysis was performed using SimaPro software version 8.5.0. The environmental impact assessment of tortilla production considered the 18 midpoint impact categories of the ReCiPe method (2008): climate change (CC), ozone depletion (OD), terrestrial acidification (TA), freshwater eutrophication (FE), marine eutrophication (ME), human toxicity (HT), photochemical oxidant formation (POF), particulate matter formation (PMF), terrestrial ecotoxicity (TET), freshwater ecotoxicity (FET), marine ecotoxicity (MET), ionising radiation (IR), agricultural land occupation (ALO), urban land occupation (ULO), natural land transformation (NLT), water depletion (WD), mineral resource depletion (MRD) and fossil fuel depletion (FD).

2.3. Transport of Materials

The materials needed for the production of tortillas are purchased from various suppliers. Through an interview, the location of each one of them was identified and then the distance travelled in the transport of the inputs was calculated using the web application “Google-Maps” (Table 2).
Table 2. Life cycle inventory of the transport of materials for corn production.

| Raw Material          | Mass (kg) | Distance (km) | Quantity (kg·km) |
|-----------------------|-----------|---------------|------------------|
| Corn seeds            | $7.83 \times 10^{-3}$ | 0             | 0                |
| Fertiliser 1          | $3.13 \times 10^{-2}$ | $8.68 \times 10^{0}$ | $2.71 \times 10^{0}$ |
| DAP (diammonium phosphate) | $1.13 \times 10^{2}$ | $4.85 \times 10^{1}$ | $1.52 \times 10^{0}$ |
| Fertiliser 2          | $1.10 \times 10^{-1}$ | $8.68 \times 10^{0}$ | $9.55 \times 10^{0}$ |
| Urea                  | $1.13 \times 10^{2}$ | $4.85 \times 10^{1}$ | $5.34 \times 10^{0}$ |
| Herbicide 1           | $6.91 \times 10^{-4}$ | $3.17 \times 10^{2}$ | $2.19 \times 10^{-1}$ |
| Desyerbal-500         | $4.64 \times 10^{-4}$ | $3.17 \times 10^{2}$ | $1.47 \times 10^{-1}$ |
| Herbicide 2           | $1.88 \times 10^{-5}$ | $3.17 \times 10^{2}$ | $5.94 \times 10^{-3}$ |
| Machetazo 2000        | $1.04 \times 10^{-4}$ | $3.17 \times 10^{2}$ | $3.31 \times 10^{-2}$ |
| Pesticide 1           | $1.06 \times 10^{-2}$ | $2.54 \times 10^{2}$ | $2.70 \times 10^{0}$ |
| Quicklime             | $7.10 \times 10^{-1}$ | $9.38 \times 10^{2}$ | $6.66 \times 10^{2}$ |

2.4. Corn Production

In order to carry out the LCI of corn production, a producer from the city of Quíroga, Michoacán, Mexico, was interviewed. The resulting information is detailed below.

- Preparation of the land. There are two annual sowing seasons. The producer performs rotary sowing by conservation mode with a plough or fallow stage, two harrowing steps, and then sowing. For these activities, he uses a New Holland 6610 tractor which, according to Gaytán Ruelas et al. [33], has a power of 88 hp, 77 hp to the power take-off (PTO) and a fuel consumption of 7.5 L for each hour of work.
- Sowing. A two-row planter with a cultivator is used to sow the seed and perform the first fertilisation. The farmer requires 30 kg of seeds for each hectare planted and it takes approximately 2 h to carry out the activity.
- Fertilisation. The amount of fertiliser was calculated by considering the doses shown in Table 3. The production is carried out by means of seeding by storm, in common with the majority of the country [32], adding 40% of the nitrogen in the first fertilisation at the time of sowing and the remaining 60% in the second. The producer mentioned that the fertilisers he uses are diammonium phosphate (DAP) and urea with NPK contents of 18-46-0 and 46-0-0, respectively. Water consumption is assigned according to the green water footprint reported by Mekonnen and Hoekstra [34] for Mexico in corn crops.

Table 3. Dose of corn fertiliser sown at various humidity conditions.

| Humidity Condition                                      | NPK Fertilisation Dose (kg ha$^{-1}$) |
|--------------------------------------------------------|---------------------------------------|
| Irrigation                                             | 250-46-0                              |
| Watering tip                                           | 230-46-0                              |
| Efficient temporary (greater than 650 mm of annual precipitation) | 184-46-0                              |
| Poor temporary (less than 650 mm of annual precipitation) | 138-46-0                              |

Source: Vallejo et al. [35].
• Pest control. The soil is fumigated twice for the control of herbs and twice for insect control. The herbicides used are atrazine at 44% for pre-emergent control and glyphosate at 36% for post-emergent weed control at the doses indicated on the package. The most common insects are the armyworm which is treated with 24% cypermethrin and grasshoppers, treated with 50% malathion. Equation (1) was used to calculate the quantity of pesticides to be used.

\[ m_p = \text{dose} \times A \times C, \]  

where \( m_p \) is the pesticide mass to be used (kg or L); pesticide dose is in kg ha\(^{-1}\) or L ha\(^{-1}\); \( C \) denotes the concentration of an active ingredient in the presentation of the pesticide; and \( A \) denotes the area that will be treated (ha).

• Harvest and shelling. The corn is harvested manually when it has high moisture content, and drying is done in the sun. The corn is shelled with a sheller attached to the shaft of the PTO of the tractor, with a capacity of 1.5 t h\(^{-1}\). The LCI for the corn production process is shown in Table 4.

### Table 4. Life cycle inventory of corn production.

| Product Outputs | Quantity | Unit |
|-----------------|---------|------|
| Corn            | 1.00 \times 10^0 | kg   |

| Avoided products | Quantity | Unit |
|------------------|---------|------|
| Olote            | 1.70 \times 10^{-1} | kg   |
| Straw            | 2.35 \times 10^0 | kg   |

| Material inputs | Quantity | Unit |
|-----------------|---------|------|
| Water           | 1.85 \times 10^3 | L    |
| Ground          | 3.13 \times 10^{-4} | Ha   |
| Seeds           | 7.83 \times 10^{-3} | kg   |
| Fertiliser 1    | 3.13 \times 10^{-2} | kg   |
| Fertiliser 2    | 1.10 \times 10^{-1} | kg   |
| Herbicide 1     | 6.91 \times 10^{-4} | kg   |
| Herbicide 2     | 4.64 \times 10^{-4} | kg   |
| Pesticide 1     | 1.88 \times 10^{-5} | kg   |
| Pesticide 2     | 1.04 \times 10^{-4} | kg   |
| Water           | 6.25 \times 10^{-1} | L    |

| Energy and heat inputs | Quantity | Unit |
|------------------------|---------|------|
| Diesel                 | 9.94 \times 10^{-1} | MJ   |

| Emissions to the air | Units | Unit |
|---------------------|------|------|
| N\(_2\)O            | 7.253 \times 10^{-4} | kg   |
| Ammonia             | 9.235 \times 10^{-3} | kg   |

| Waste | Units | Unit |
|-------|------|------|
| Sacks | 2.83 \times 10^{-4} | kg   |
| HDP boats | 2.79 \times 10^{-4} | kg   |
| Cardboard box | 1.52 \times 10^{-4} | kg   |

#### 2.5. Nixtamalisation

For this process, the materials and supplies necessary for the production of 1 kg of nixtamalised corn were considered. The materials required are corn grains, calcium hydroxide Ca(OH)\(_2\) and water. The water consumption was calculated considering the 2:1 formulation of water and corn, in addition to the water used for washing the nixtamal. The energy and/or heat inputs for this process are propane and electricity. The consumption of electrical energy was determined according to the technical
specifications of the equipment available in the tortilla shop. The losses of corn dough after washing were assigned according to the Mexican norm [27]. The results of this analysis are shown in Table 5.

| Table 5. Life cycle inventory for nixtamalisation. |
|-----------------------------------------------|
| **Outputs of Material** | **Quantity** | **Unit** |
| Nixtamal | $1.00 \times 10^0$ | kg |
| **Material inputs** | | |
| Corn | $7.10 \times 10^{-1}$ | kg |
| Ca(OH)$_2$ | $1.06 \times 10^{-2}$ | kg |
| Water for maceration | $1.42 \times 10^0$ | L |
| Water for washing | $7.10 \times 10^{-1}$ | L |
| **Energy and heat inputs** | | |
| Propane | $1.62 \times 10^{-2}$ | kg |
| **Emissions to the atmosphere** | | |
| Water | $5.25 \times 10^{-1}$ | kg |
| **Waste** | | |
| Nejayote | $1.32 \times 10^0$ | L |
| Sacks | $8.52 \times 10^{-5}$ | kg |
| Raffia sacks | $1.42 \times 10^{-3}$ | kg |

2.6. Grinding

The materials and supplies necessary to produce 1 kg of dough were considered. The required material is nixtamalised corn from the nixtamalisation process. The consumption of electrical energy in this process was determined according to the technical specifications of the equipment used. A nixtamal mill of the brand Arisa ML100, 1/3 HP at 110 V, with a capacity of 80 kg h$^{-1}$ and a mixer of the brand Tortimex Inox-430, 1 HP at 110 V with a capacity of 50 kg of dough per load were used. The water consumption of this process was estimated by a material balance in which nixtamalised corn enters with 42% humidity and leaves as a dough product with a humidity of 55%. The results of this process are shown in Table 6.

| Table 6. Life cycle inventory for grinding nixtamal. |
|-----------------------------------------------|
| **Outputs of material** | **Quantity** | **Unit** |
| Corn dough | $1.00 \times 10^0$ | kg |
| **Material inputs** | | |
| Nixtamal | $7.76 \times 10^{-1}$ | kg |
| Water for the grinding | $2.24 \times 10^{-1}$ | L |
| **Energy and heat inputs** | | |
| Electricity | $2.73 \times 10^{-2}$ | kWh |

2.7. Baking the Dough and Packing

The inputs for the production of 1 kg of tortilla from nixtamal were identified. The consumption of electrical energy for this process was determined according to the nameplate data of the Verduzco brand tortilla machine model TV-40. Its production capacity is 70 kg h$^{-1}$, with electricity consumption of 1.32 kWh and 3.8 L h$^{-1}$ of propane. The tortillas are delivered to the consumer wrapped in food-grade paper, with a grammage of 17 g m$^{-2}$. The LCI analysis for this stage is shown in Table 7.
Table 7. Life cycle inventory of baking the dough and packaging.

| Outputs of material | Quantity | Unit |
|---------------------|----------|------|
| Tortilla            | 1000 kg  |      |

| Material inputs     | Quantity  | Unit  |
|---------------------|-----------|-------|
| Dough               | 1.29 × 10³ | kg    |
| Food grade paper    | 2.534 × 10⁻³ | kg    |

| Energy and heat inputs | Quantity  | Unit |
|------------------------|-----------|------|
| Electricity            | 1.76 × 10² | Wh   |
| Propane                | 7.70 × 10⁻² | L    |

| Emissions to the atmosphere | Quantity  | Unit |
|-----------------------------|-----------|------|
| Water                       | 2.88 × 10⁻¹ | kg   |

2.8. Energy Flows and Greenhouse Gases for Tortilla Production

The total cumulative energy demand (CED) of a product is a parameter that represents the total of all energy inputs, concerning the consumption of primary energy. With respect to LCA phases [36] the tortilla CED can be expressed as Equation (2):

\[
CED_{\text{Tortilla}} = CED_{\text{Raw m}} + CED_{\text{Distr}} + CED_{\text{Nixt}} + CED_{\text{Gr Knd}} + CED_{\text{Cook Pack}}.
\]  

Global warming potential indicators, derived respectively from the calculation of the energy flows and the calculation of the GHG emissions, were also taken into account. These results were calculated for a mass based on functional unit (FU), for a nutritional energy value FU (100 kcal) and for a price-based FU. The FU is a reference unit, to which the inputs and outputs must be connected [37].

Mexico is divided into eight economic regions (Table 8), which each represent separate activities and economical characteristics, Figure 4 is a schematic representation of the various purchasing powers of the Mexican regions.

Table 8. Eight economic regions in Mexico.

| Zone                        | Contribution to GDP * (%) |
|-----------------------------|---------------------------|
| Northwest (Pacific)         | 27.4                      |
| Northern Centre (Central)   | 21.3                      |
| West (Lowlands)             | 18.4                      |
| Southern Centre (Central)   | 12.3                      |
| East (South Central)        | 9.5                       |
| Northeast (North)           | 2.4                       |
| Southwest                   | 1.0                       |
| Southeast                   | 0.1                       |

* GDP: gross domestic product. Source: adapted from INEGI [38,39].
The obtained results showed that to process the FU of tortilla (1 kg of packed tortilla), the CED\textsubscript{tortilla} = 1.03 MJ of primary energy is required; this represents 0.419 kg CO\textsubscript{2} eq/FU. The Mexican government uses the “basic basket” as the set of essential goods and services so that a family can satisfy their basic consumption needs from their income. The tortilla is a staple food for Mexicans, nutritionally and for cultural identity, and as such, it is one of the 83 items that comprises the basket. In fact, according to the National Consumer Price Index [41], the tortilla represents 6.78% of food expenses. Regardless of this importance, prices vary nationwide, as shown in Figure 5a. Prices do not match geographic purchasing powers, as the Pacific area—which has the highest purchasing power—has the lowest national price for tortillas. The explanation for this might be associated to the higher degree of mechanisation and availability of newer tortilla equipment. Northern zones are known for their higher industrialisation levels in Mexico, with probably more energy-efficient processes for tortilla production. This represents an opportunity for further study.

The Mexican electric power generation mix, or electricity mix, in the distinct economic zones is described in Table 9. Figure 5b represents the cost per energy unit, calculated from the tortilla price. These prices were calculated from the average price for tortilla in year 2017 in each zone. However, the electricity mix varies in each zone. The northern part relies heavily in fossil fuels, whereas the southern part generates electricity mainly by hydroelectric technology. Figure 5c shows the kg CO\textsubscript{2} eq as related to the tortilla price. As a result, zones with the highest prices have the lowest global warming indicators, such as the Northeast and the Southeast zones.
Figure 4. Schema of Mexico’s purchasing power variations depending on economic regions. Source: Nielsen-Consulting [40].

The obtained results showed that to process the FU of tortilla (1 kg of packed tortilla), the CED_tortilla = 1.03 MJ of primary energy is required; this represents 0.419 kg CO₂eq/FU. The Mexican government uses the “basic basket” as the set of essential goods and services so that a family can satisfy their basic consumption needs from their income. The tortilla is a staple food for Mexicans, nutritionally and for cultural identity, and as such, it is one of the 83 items that comprises the basket. In fact, according to the National Consumer Price Index [41], the tortilla represents 6.78% of food expenses. Regardless of this importance, prices vary nationwide, as shown in Figure 5a. Prices do not match geographic purchasing powers, as the Pacific area—which has the highest purchasing power—has the lowest national price for tortillas. The explanation for this might be associated to the higher degree of mechanisation and availability of newer tortilla equipment. Northern zones are known for their higher industrialisation levels in Mexico, with probably more energy-efficient processes for tortilla production. This represents an opportunity for further study.

Figure 5. Comparison of environmental impacts of tortilla production in Mexico based on energy consumed, greenhouse gas emissions and cost. (a) Price (USD)/functional unit (FU); (b) MJ demanded by cost (USD); (c) global warming potential indicator related to tortilla cost (kg CO₂eq/USD); (d) national averages for FU of tortilla production process, estimated in this work. This information was obtained from a representative survey conducted in 53 Mexican cities located in all the states of the republic, based on a sample of 384 tortilla shops and 120 self-service stores, with a confidence level of 95% and a 5% margin of error. Source: tortilla price is the yearly average (2017), SNIIM [42].

Table 9. Mexican electricity installed capacity in the economic zones and their respective technologies for electric power generation.

| Economic Zone     | Installed Capacity (MW, 2014) | Percentage Installed | Conventional (Thermal) | Coal-Fired | Nuclear-Electric | Combined Cycle | Others | Hydro-Electric | Alternative Sources |
|-------------------|-------------------------------|----------------------|------------------------|------------|------------------|----------------|--------|----------------|---------------------|
| Northwest         | 7198.7                        |                      | 34.5                   | -          | -                | 27.7           | 16.5   | 13.0           | 8.1                 |
| Northeast         | 13,814.2                      |                      | 12.5                   | 18.8       | -                | 64.4           | 3.2    | 0.9            | -                   |
| South-Southeast   | 18,742.4                      |                      | 13.7                   | 14.8       | 7.5              | 20.8           | 2.2    | 37.8           | 3.2                 |
| Centre northwest  | 9853.5                        |                      | 25.9                   | -          | -                | 37.3           | 1.9    | 34.9           | -                   |
| Centre            | 4754.9                        |                      | 43.2                   | 29.9       | -                | 11.7           | 14.4   | 0.9            | -                   |

Source: adapted from SENER [43].

Finally, Table 10 shows a comparison of environmental impacts for selected food products, particularly bread. Despite the difference in grain (wheat versus corn), the global warming indicator is comparable among bread types and tortillas, with the main hotspot being identified as the corn production phase.

Finally, Table 10 shows a comparison of environmental impacts for selected food products, particularly bread. Despite the difference in grain (wheat versus corn), the global warming indicator is comparable among bread types and tortillas, with the main hotspot being identified as the corn production phase.
Table 10. Comparison of environmental impacts of selected food products based on the energy consumed, emissions and greenhouse gas costs.

| Food                  | Functional Unit                                           | kg CO2 eq kg⁻¹ | MJ kg⁻¹ | kg CO2 eq 100 kcal⁻¹ | MJ 100 kcal⁻¹ | MJ US$⁻¹ | kg CO2 eq US$⁻¹ | Environmental Hotspots       | System Boundaries                      | Reference               |
|-----------------------|----------------------------------------------------------|----------------|---------|----------------------|--------------|---------|----------------|-------------------------------|---------------------------------------|------------------------|
| Mexican Tortilla      | 1 kg of tortillas wrapped in paper sheet                  | 0.419          | 24.1    | -                    | 1.03         | -       | 0.52           | Corn production               | cradle to gate (business to business) | This work               |
| Corn chips            | 1 box with 10 packages of 0.4 kg                          | 3.2            | -       | -                    | -            | -       | 0.30           | Electricity used during the manufacture | cradle to gate                     | Grant and Beer [11]         |
| Romanian pasca        | 1 kg of bread                                            | 4.8            | 33.0    | 0.140                | 0.92         | 1.8     | 0.26           | Agriculture/farming           | cradle to bakery gate               | Notarnicola et al. [44]        |
| Italian focaccia      | 1 kg of bread                                            | 0.7            | 9.5     | 0.030                | 0.36         | 3.3     | 0.25           | Agriculture/farming           | cradle to bakery gate               |                                     |
| French baguette       | 1 kg of bread                                            | 0.4            | 8.0     | 0.020                | 0.38         | 4.3     | 0.22           | Bread production              | cradle to bakery gate               |                                     |
| Hungarian pogasza     | 1 kg of bread                                            | 3.4            | 24.0    | 0.080                | 0.58         | 1.4     | 0.19           | Agriculture/farming           | cradle to bakery gate               |                                     |
| Greek pita            | 1 kg of bread                                            | 0.7            | 9.0     | 0.035                | 0.37         | 2.4     | 0.18           | Trade, distribution and retail | cradle to bakery gate               |                                     |
| White bread, plastic bag | Standard 800 g loaf of sliced brad                      | 1.37           | 0.4     | -                    | -            | -       | -              | Wheat production              | cradle to grave                     | Espinoza-Orias et al. [45]      |
| Wholemeal bread, plastic bag | Standard 800 g loaf of sliced brad                   | 1.28           | -       | -                    | -            | -       | -              | Wheat production              | cradle to grave                     |                                     |
| Chicken               | 1 kg of chicken (carcass)                                | 0.7            | 9.2     | -                    | -            | -       | -              | Food production               | production in chicken farms, does not consider management of excreta and commercialisation | Baltierra-Trejo et al. [46]     |
| Bread                 | 1 kg packed sliced bread loaves                          | 0.496          | 23.0    | 0.89                 | -            | -       | -              | Cultivation of durum wheat    | cradle to gate                     | Ingrao et al. [47]             |
| White asparagus       | 1 kg of white asparagus                                  | 0.05           | -       | -                    | -            | -       | -              | Fertiliser                    | cradle to gate                     | Stoessel et al. [48]            |
3. Results and Discussion

3.1. Life Cycle Impact Assessment (LCIA) of Corn Production

According to Zampori et al. [49], the hotspot analysis is important in identifying the life cycle stages, processes and elementary flows that are hotspots (>50% contribution) and that are relevant (>80% contribution). The environmental performance of a product and its hot areas might “warn” an organisation where to focus the attention. The agricultural stage of corn production, here defined as the operations related to the FU occurring from the cradle to the gate of the farm, as often reported for other grains (Table 10), was identified as a critical life cycle phase. This result is similar to that found by Jensen and Arlbjørn [50] in their study about rye bread. It was found that the primary hotspot was the raw material stage, especially agricultural production (cultivation), with processing and distribution stages as secondary hotspots.

The impact categories as hotspots and relevant (>80% contribution), due to the use of pesticides, fertilisers and land use for all life cycle phases are shown in Table 11. In fact, the use of diammonium phosphate represents four relevant impact categories (MET, ULO, NLT, MRD) and land use/rainwater (flows from nature) comprises three relevant impact categories (TA, PMF, WD) (Figure 6). According to Rezaei Rashti et al. [51], due to heavy fertiliser N applications to maintain productivity in vegetable cropping systems, agricultural land is a major source of anthropogenic N\(_2\)O, which has a significant role in global warming and destruction of the ozone layer. Masuda [52] points out that the intensification of agriculture by various means, including irrigation, fertilisers, pesticides and mechanisation, has caused harmful impacts such as global warming and eutrophication of terrestrial and aquatic environments.

| Life Cycle Phase      | Impact Category Hotspot (>50% Contribution) | Relevant Impact Category (>80% Contribution) |
|-----------------------|--------------------------------------------|---------------------------------------------|
| Corn production       | CC, FE, TET, FET, ALO, WD                  | TA, MET, PMF, ULO, MRD                       |
| Cooking               |                                            |                                             |
| Nixtamalisation       |                                            |                                             |
| Grinding              |                                            |                                             |
| Cooking and packing    |                                            |                                             |
| Transport             |                                            |                                             |

The hotspots in the tortilla manufacturing process involve, for masa preparation (grinding and nixtamalisation), the use of propane, electricity and the nejayote production. For tortilla cooking and packaging, the use of propane is representative in 13 impact categories. The aforementioned list points out areas where the tortilla shops have opportunity to improve. For instance, nejayote or lime wastewater has been reported (laboratory scale) as a potential source of a fraction enriched in carbohydrates, a fraction with high content of calcium components and a clear fraction enriched in phenolic compounds [53] or as biohydrogen substrate [54]. The Mexican standard NOM-019-ENER-2009 indicates that a horizontal tortilla machine should provide a minimum cooking time of 34 s. Table 12 describes the maximum energy use for tortilla machine equipment. It is evident that the lowest energy demands (MJ kg\(^{-1}\) h\(^{-1}\)) correspond to type 1 and type 11, as propane comprises 97% of the mentioned energy demand. The energy efficiency of this equipment, as required by Mexican standard (NOM-019-ENER, 2009), that points to NOM-014-ENER or NOM-016-ENER, corresponds only to the electrical part; thus, there is room for technical solutions for the thermal part of the machine.
Figure 6. Characterisation of impacts of the tortilla production process.

| Horizontal Tortilla Machine Type | Maximum Propane Usage ($\text{m}^3$) | Maximum Electricity Usage (kWh) |
|---------------------------------|-------------------------------------|---------------------------------|
| Tortilla (units $\text{h}^{-1}$, ± 5.0%) | 0.13 | 69 |
| Tortilla (kg $\text{h}^{-1}$, ± 5.0%) | 0.12 | 780 |
|                                    | 0.66 | 950 |
|                                    | 2.02 | 2100 |
|                                    | 3.25 | 3000 |
|                                    | 3.45 | 4000 |

Figure 6. Characterisation of impacts of the tortilla production process.
Table 12. Energy demand for horizontal tortilla machine.

| Horizontal Tortilla Machine Type | Maximum Propane Usage (m³) | Maximum Electricity Usage (kWh) | Tortilla (Units h⁻¹, ±5.0%) | Tortilla (kg h⁻¹, ±5.0%) | a MJ kg⁻¹ h⁻¹ |
|---------------------------------|---------------------------|---------------------------------|-----------------------------|--------------------------|---------------|
| 1                               | 0.13                      | 0.12                            | 780                         | 20                       | 0.69          |
| 2                               | 0.66                      | 0.64                            | 950                         | 25                       | 2.80          |
| 3                               | 2.02                      | 1.4                             | 2100                        | 55                       | 3.86          |
| 4                               | 3.25                      | 2.3                             | 3000                        | 80                       | 4.27          |
| 5                               | 3.45                      | 3                               | 4000                        | 104                      | 3.50          |
| 6                               | 4.5                       | 4.7                             | 6000                        | 156                      | 3.06          |
| 7                               | 4.06                      | 3.92                            | 6600                        | 172                      | 2.50          |
| 8                               | 4.56                      | 4.44                            | 9000                        | 234                      | 2.07          |
| 9                               | 6.21                      | 6.05                            | 10,000                      | 260                      | 2.53          |
| 10                              | 6.9                       | 6.73                            | 12,000                      | 312                      | 2.34          |
| 11                              | 8.28                      | 8.07                            | 22,000                      | 572                      | 1.53          |

a Obtained after the conversion of propane (m³) and kWh to MJ, divided by kg h. Source: adapted from Mexican Standard [55].

3.2. Analysis of Contribution to Environmental Impact

The main emissions that contribute to each of the environmental impacts of the mid-point categories of the ReCiPe method were evaluated. In the contribution analysis to the category of CC, the GHGs with the greatest impact are CO₂ and N₂O, which are emitted by the use of fossil fuels (propane, diesel, gasoline), while N₂O is the result of the volatilisation of nitrogen fertilisers (Figure 7a). In the category of TA, the emission of NH₃ has the greatest contribution. This is emitted by the volatilisation of nitrogen fertilisers (Figure 7b). The contribution analysis of WD shows that the impact is mainly due to water consumption for irrigation of maize and water use in hydroelectric turbines for the generation of electricity (Figure 7d). In the category of MRD, the exploitation of Cu and Fe had the greatest impact. The depletion of these metals is linked to use in vehicles (Figure 7e). The production of corn is the process with the greatest contributions.

![Figure 7. Cont.](image-url)
Figure 7. Analysis of contribution to environmental impact. (a) CC; (b) TA; (c) PMF; (d) WD; (e) MRD; (f) ULO.

3.3. Impact Dimensioning (Normalisation)

The normalisation of the results of the LCIA is based on an analysis of the relative importance of each impact category. It consists in the calculation of the relative contribution of the total environmental loads of the product/process under study. The obtained values during the characterisation are expressed in differing units, and normalisation makes it possible to transfer them to units that allow comparison [56]. Figure 8 reveals the normalisation of the results, where the greatest impacts are concentrated in TA, PMF, MET and FD.

Figure 8. Normalisation of impact categories.

3.4. LCIA: National Dimensioning

Table 13 shows the summary of the results of the LCIA, i.e., the total impact on each of the 18 categories and the process that involves the greatest impact. The environmental impact of tortilla production in Mexico was obtained by multiplying the impacts obtained in the LCIA by the annual production of tortillas (6.94 million tonnes, 2017). The national impact on CC was 3090 Gg CO$_2$ eq year$^{-1}$, which represents 0.4% of GHG emission in Mexico [57]. Corn production has the greatest impact on 15 of the 18 impact categories, as has already been explained.
## Table 13. Impacts of tortilla production in Mexico.

| Impact Category | Units | Process with the Greatest Impact | Emissions/Inputs with the Greatest Impact | Functional Unit | Coefficient of Variation * | National Environmental Impact |
|-----------------|-------|----------------------------------|------------------------------------------|-----------------|--------------------------|-------------------------------|
| CC              | kg CO₂ eq | Corn Production | CO₂, N₂O | 4.19 × 10⁻¹ kg CO₂ eq | 10% | 3.09 × 10⁶ t CO₂ eq |
| OD              | kg CFC-11 eq | Cooking | Halon 1301 | 7.25 × 10⁻⁹ kg CFC-11 eq | 50% | 5.36 × 10⁻⁵ t CFC-11 eq |
| TA              | kg SO₂ eq | Corn Production | NH₃ | 1.83 × 10⁻² kg SO₂ eq | 23% | 1.35 × 10³ t SO₂ eq |
| FE              | kg P eq | Corn Production | PO₄³⁻ | 1.04 × 10⁻⁵ kg P eq | 53% | 7.71 × 10³ t P eq |
| ME              | kg N eq | Corn Production | NH₃ | 7.78 × 10⁻⁴ kg N eq | 20% | 5.75 × 10⁻¹ t N eq |
| HT              | kg 1,4-DB eq | Corn Production | Sb | 1.98 × 10⁻² kg 1,4-DB eq | 60% | 1.47 × 10⁵ t 1,4-DB eq |
| POF             | kg NMVOC | Raw material transport | N₂O₅ | 9.95 × 10⁻⁴ kg NMVOC | 10% | 7.36 × 10⁵ t NMVOC |
| PMF             | kg PM10 | Corn Production | NH₃ | 2.78 × 10⁻³ kg PM10 eq | 20% | 2.06 × 10⁴ t PM10 eq |
| TET             | kg 1,4-DB eq | Corn Production | Chlorpyrifos, Cypermethrin | 9.00 × 10⁻⁵ kg 1,4-DB eq | 12% | 6.65 × 10² t 1,4-DB eq |
| FET             | kg 1,4-DB eq | Corn Production | Br, Chlorpyrifos | 4.50 × 10⁻⁴ kg 1,4-DB eq | 28% | 3.33 × 10³ t 1,4-DB eq |
| MET             | kg 1,4-DB eq | Corn Production | Cu, Ni | 3.91 × 10⁻⁴ kg 1,4-DB eq | 28% | 2.89 × 10³ t 1,4-DB eq |
| IR              | kBq U235 | Cooking | U²³⁵ | 2.73 × 10⁻² kBq U235 eq | 51% | 2.02 × 10⁵ MBq U235 eq |
| ALO             | m² year | Corn Production | Arable land | 4.02 × 10⁻² m² year | 14% | 2.97 × 10⁶ m² year |
| ULO             | m² year | Corn Production | - | 1.05 × 10⁻¹ m² year | 24% | 7.74 × 10⁶ m² year |
| NLT             | m² | Corn Production | - | 5.19 × 10⁻⁸ m² | 1698% | 3.83 × 10⁻² m² |
| WD              | m³ | Corn Production | Irrigation water | 1.87 × 10⁰ m³ | 15% | 1.39 × 10⁵ m³ |
| MRD             | kg Fe eq | Corn Production | Cu | 1.91 × 10⁻³ kg Fe eq | 23% | 1.41 × 10⁴ t Fe eq |
| FD              | kg oil eq | Corn Production | Raw oil | 1.97 × 10⁻¹ kg raw oil eq | 16% | 1.46 × 10⁵ t raw oil eq |

* Values less than 30% of the coefficient of variation are considered reliable for the analysis.
Another indicator of environmental impact widely used is the water footprint. In this study it was considered as the category of WD. Table 14 shows the water footprint of some of the foods consumed by Mexicans.

| Product                | Functional Unit | Water Footprint (L) |
|------------------------|-----------------|---------------------|
| Tortilla (This work)   | 1 kg            | 1870 *              |
| Cup of coffee          | 0.125 L         | 140                 |
| Glass of orange juice  | 0.200 L         | 170                 |
| Glass of milk          | 0.200 L         | 200                 |
| Glass of wine          | 0.125 L         | 120                 |
| Glass of beer          | 0.250 L         | 75                  |
| Egg                    | 0.040 kg        | 135                 |
| Tomato                 | 0.070 kg        | 13                  |
| Slice of bread         | 0.030 kg        | 40                  |

* Irrigation regime. Source: Chapagain and Hoekstra [58]; Hoekstra and Chapagain [59].

4. Conclusions

This investigation allowed estimating the potential environmental impacts of the production of tortillas by the life cycle analysis method included in ISO 14040 and ISO 14044. The corn production stage was the unitary process with the most significant impact on 15 of the 18 categories evaluated; this was due to the use of fertilisers and pesticides during the development of the crop.

Due to the lack of specific literature on the environmental impacts of tortilla production, the comparisons with other studies were limited to general considerations about the life cycle of cereal products. Based on the results obtained, improvements could be made in the production processes to reduce their environmental impacts, especially the cultivation phase. Possibilities include the search for environmentally friendly fertilisers that do not affect the yield of crops, or changing to organic soil fertilisation. Although this project was only evaluated for a tortilla shop, the analysis is scalable at each production level.

For future research, the following recommendations are made: (a) compare the environmental impacts of tortilla production of nixtamalised corn flour with dough; (b) compare the environmental impacts of tortilla production in various geographical conditions; (c) evaluate the water footprint of corn production by irrigation and by storm; and d) carry out an LCA that covers the final disposal of the waste generated in the process.

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