Article

Sweet sustainability: Comparative study of solar and electric cooking in the production of crystallized orange peel candy

Dulce sostenibilidad: Estudio comparativo de la cocción solar y eléctrica en la elaboración de dulce cristalizado de cáscara de naranja

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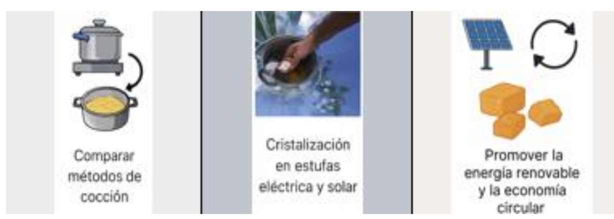
Abstract

Food waste represents one of the most pressing global challenges for sustainability. Among the most abundant by-products of the food industry is orange peel, whose potential applications remain underexploited. This study explores the elaboration of crystallized orange peel candy using two different cooking methods: an electric stove and a parabolic solar stove. The objective was to compare their efficiency, preparation times, and the sensory quality of the final product through attributes such as color, aroma, flavor, and texture. Experimental results revealed that the solar stove achieved competitive cooking performance, reaching adequate temperatures to ensure food safety and acceptable sensory characteristics, while reducing energy consumption and greenhouse gas emissions. In comparison with the electric stove, the solar method demonstrated longer preparation times but offered a cleaner and more sustainable alternative. Overall, the findings highlight solar cooking as a viable strategy that contributes to renewable energy use, circular economy, and sustainable food practices.

Orange peel, solar stove, crystallized candy, renewable energy, sustainability

Resumen

El desperdicio de alimentos constituye uno de los mayores retos globales para la sostenibilidad. Entre los subproductos más abundantes de la industria alimentaria se encuentra la cáscara de naranja, cuyo aprovechamiento sigue siendo limitado. Este estudio presenta la elaboración de dulce cristalizado de cáscara de naranja utilizando dos métodos de cocción: una parrilla eléctrica y una estufa solar parabólica. El objetivo fue comparar su eficiencia, los tiempos de preparación y la calidad sensorial del producto final en atributos como color, aroma, sabor y textura. Los resultados experimentales mostraron que la estufa solar alcanzó temperaturas suficientes para garantizar inocuidad y características sensoriales aceptables, reduciendo al mismo tiempo el consumo energético y las emisiones asociadas. En comparación con la parrilla eléctrica, el método solar requirió mayor tiempo de cocción, pero demostró ser una alternativa más limpia y sostenible. En conjunto, los hallazgos confirman a la cocción solar como estrategia viable que impulsa la economía circular y el uso de energías renovables.



Cáscara de naranja, estufa solar, dulce cristalizado, energía renovable, sostenibilidad

Area: Development of strategic leading-edge technologies and open innovation for social transformation

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Introduction

The citrus agroindustry is a strategic sector in Mexico and Latin America, but nearly 40% of an orange is peel, which is usually discarded, generating negative environmental impacts. Several studies highlight its nutraceutical value due to the presence of flavonoids, essential oils and vitamin C, with applications in the food, cosmetics and pharmaceutical industries (Rolffy & Araujo, 2023; Dongre et al., 2023). Its use in bioenergy to produce biogas and bioethanol has also been demonstrated (Gonzabay & Suárez, 2016).

In food, Basurto, Limongi and Muñoz (2025) confirmed that orange peel flour can improve the nutritional properties of biscuits, while Barrero et al. (2024) proposed its use in the sustainable extraction of essential oils with social and economic impact. At the same time, the Mexican tradition of crystallised sweets (Vázquez, 2020; Del Carmen, 2020; Balboa, 2024) constitutes a cultural heritage that can be linked to clean technologies such as solar cooking, documented in bread making and fruit drying (Ceviz et al., 2024; Basurto, 2021; Cogollo, 2022). Ramírez, Jaramillo and Dorantes (2015) validated the viability of parabolic solar cookers, reaching over 100 °C under direct irradiation, which supports their application in new processes. In this context, the present study aimed to produce crystallised orange peel sweet using a parabolic solar cooker and compare it with the electric method, evaluating its technical, sensory and environmental viability.

2. Theoretical basis

The performance analysis of a parabolic solar cooker is based on the principles of optical concentration and heat transfer.

2.1 Concentrator aperture area

where D is the diameter of the parabolic (m). This expression is the classic formulation for circular concentration collectors

2.2 Incident solar power

The theoretical solar power available in the concentrator is given by:

where:
G is the incident solar irradiance (W/m^2)
Aap=Aap is the aperture area (m^2)
η is the optical efficiency, product of the reflectance of the material, transmittance of the covering and absorptance of the receiver.

2.3 Energy and useful power absorbed by the food

The energy absorbed by the food product is estimated using the calorimetric equation:

where:
m is the mass of the food (kg),
c is the specific heat (J/kg·°C),
ΔT is the temperature increase of the food (°C).

The useful power (Pútil) is determined as:

where t is the cooking time (s).

2.4 Comparison with electric cooking

The power of the electric grill was determined from its energy consumption, calculated as:

where E corresponds to the electricity consumption (kWh) in a given cooking period.

2.5 Thermal efficiency (η) measures the fraction of captured solar energy that is actually used in the food (sweet in this case). The most commonly used formula (Duffie & Beckman, 2013; Kalogirou, 2009) is:

$\eta = Q_u/Q_s$
Q_u = Useful energy absorbed by the product [J]
Q_s = Solar energy incident on the opening area of the stove [J]

Methodology

The research was carried out in San Juan del Río, Querétaro, Mexico (20°23′N, 100°00′W, 1,920 m above sea level) on 8 July this year, during a sunny day with maximum irradiance of 1123 W/m². A 1.5 m diameter parabolic solar cooker and a 1500 W electric grill were used. The instruments included a pyranometer, digital thermometer, scale, and stopwatch.

The study was conducted using a comparative experimental design, in which batches of crystallised orange peel candy were produced using two cooking methods: electric grill and parabolic solar cooker.

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The aim was to evaluate differences in cooking time, environmental parameters and sensory quality of the final product.

3.1. Raw materials and materials

Raw material: fresh oranges (Citrus sinensis) at commercial maturity.

Utensils and equipment: stainless steel knives, cutting boards, plastic containers. Four main pieces of equipment were used for the experimental development. First, an Ohaus triple-beam balance (maximum capacity 610 g, accuracy ±0.1 g) was used to accurately determine the initial mass of the orange peel in each test. Secondly, a laboratory electric grill (127 V power supply, 1,500 W nominal power, temperature control by electrical resistance), which allowed conventional cooking of the jam and served as a reference for comparing times and energy consumption. Thirdly, a compact infrared thermometer model 42510A-121 (measuring range −50 °C to 500 °C, accuracy ±2 %, resolution 0.1 °C, distance-to-spot ratio 12:1, adjustable emissivity) was used to monitor the temperature of the product during the cooking process. The instruments ensured that reliable and comparable data were obtained for the two cooking methods evaluated. Auxiliary ingredients: food-grade salt (NaCl) and refined sugar.

3.2. Initial preparation (common to both methods)

1. Washing and disinfecting the oranges with 2% sodium hypochlorite.
2. Removing the peel, taking care to remove as much of the albedo as possible.
3. Cut the peel into 2 cm wide strips.
4. Weigh 70 g of fresh peel per batch.
5. Initial soaking in salt water (5 g/L) for 15 minutes.

3.3. Blanching and reduction of bitterness

- **Electric grill:**
- First cycle: boil in water with 1 g of salt for 30 minutes.
- Second cycle: boil in unsalted water for 15 minutes.
- Repeat the process in clean water three more times.

- **Parabolic solar cooker:**
- First cycle: boil in water with 1 g of salt for 15 minutes.
- Second cycle: boil in unsalted water for 15 minutes.

Repeat the process in clean water three more times.

The cooker was manually adjusted to ensure maximum solar radiation capture.

3.4. Syrup preparation and cooking

The same formulation was used in both methods: 200 g of sugar dissolved in 500 mL of water.

- **Electric grill**:

The syrup was heated over low heat until completely dissolved; then the peels were added and cooked for 60 minutes at an average temperature of 90 to 95°C.

- **Parabolic solar cooker**:

The syrup was prepared directly with solar radiation. Once boiling point was reached, the peels were added and cooked for 60 minutes under irradiance of 820–1120 W/m². During the process, irradiance, relative humidity, ambient temperature and syrup temperature were recorded every 45 minutes.

3.5. Crystallisation and drying (common to both methods)

1. The peels were left to rest in the syrup for 24 hours.
2. They were then removed, drained and sprinkled with 3 g of sugar per batch.
3. Finally, they were dried at room temperature (25 ± 2 °C) until they obtained a firm, crystallised texture.

3.6. Sensory evaluation

A hedonic test was conducted with a panel of 20 untrained judges, who evaluated the attributes of colour, aroma, flavour and texture on a scale of 1 (very unpleasant) to 9 (very pleasant).

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4. Results

The results of the experiment were divided into three main blocks: environmental measurements, comparison of cooking methods, and sensory evaluation.

4.1. Measurements

The climatic variables corresponding to irradiance, relative humidity, and ambient temperature were recorded during solar cooking using data from https://www.wunderground.com/dashboard/pws/IQUERETA29. This provided real, verified data on local weather conditions.

Box 1

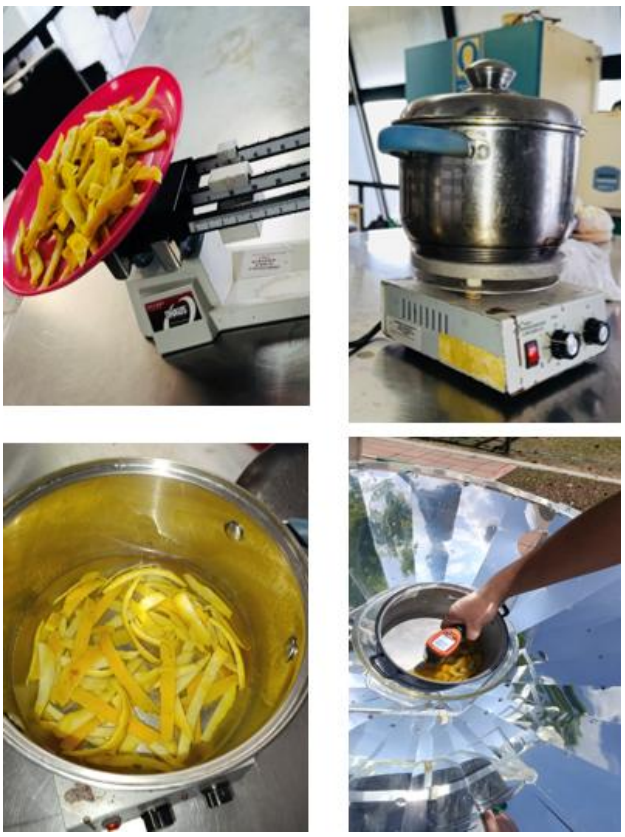

Figure 1
Preparation of orange peel sweet

Box 2

Table 1
Climate and process variables recorded during the preparation of crystallised sweets in a solar oven.

Time	Irradiance (W/m²)	Ambient temperature (°C)	Wind speed (km/h)	Sweet temperature (°C)	Relative humidity (%)
11:30	860	22.0	0.0	17.9	57
11:45	932	22.6	0.0	35.3	56
12:00	916	22.8	0.0	56.8	54
12:15	976	22.7	0.0	69.4	56
12:30	274	23.2	0.0	40.9	55
12:45	1116	23.1	0.0	48.5	57
13:00	1065	23.7	0.0	80.0	53
13:15	1085	23.9	0.0	21.8	52
13:30	1123	24.2	0.0	47.6	51
13:45	1083	24.3	0.0	56.7	50
14:00	1041	24.1	0.0	62.4	52
14:15	1079	24.0	0.0	70.0	51
14:30	323	24.0	0.0	69.8	49
14:45	346	24.4	0.0	68.8	46
15:00	1060	24.4	0.0	73.0	44
15:15	921	25.0	0.0	72.9	44

It was observed that irradiance peaked around 1:00–1:30 pm, with values exceeding 1100 W/m², which favours intense solar cooking. Relative humidity gradually decreased during the day, favouring transpiration and evaporation, which helped the jam to dry and crystallise. The ambient temperature remained between 22–25 °C °C, which helps prevent the jam from cooling too quickly while crystallising.

Figure 2. Temperature evolution of the jam in a solar oven vs. an electric grill.

4.2. Comparison between electric cooking and solar cooking

Here, the two methods were compared in terms of time, energy consumption, temperatures reached, and final product texture.

Box 3

Table 2
Comparison of technical and sensory parameters between the electric grill and the solar cooker

Method	Total time (min)	Energy consumption	Maximum temperature reached (°C))	Observed texture
Electric grill	~ 60	~ 1.5 kWh	~ 85	Firm, uniform, more golden colour
Solar greenhouse	~ 240	0 kWh	~ 80	Firm, crystallised, slightly lighter colour

Although solar cooking took approximately four times longer than electric cooking, it completely eliminated conventional energy consumption, which is a significant advantage in terms of sustainability.

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The maximum temperature in the solar cooker was close to 80 °C, high enough to caramelise and crystallise without burning, indicating that this method can achieve results comparable to electric cooking if the irradiance is optimised.

4.3. Sensory evaluation

A hedonic test was conducted with a panel of 20 untrained judges, evaluating the attributes: colour, aroma, flavour and texture. The average results indicate high acceptability for both methods, with slight differences favouring the solar method in some attributes:

Box 4

Table 3

Sensory evaluation of crystallised sweets made in an electric grill and a parabolic solar cooker

Attribute	Electric grill	Parabolic solar greenhouse
Colour	8.2 ± 0.5	8.5 ± 0.4
Aroma	7.8 ± 0.6	8.4 ± 0.5
Flavour	8.0 ± 0.5	8.6 ± 0.4
Texture	8.5 ± 0.4	8.2 ± 0.6
Promedio	**8.1 ± 0.5**	**8.4 ± 0.5**

The sweet prepared in the solar cooker was perceived as having a slightly superior colour and flavour, which is attributed to the gradual distribution of solar heat, which promotes a smoother and more uniform caramelisation. In contrast, the texture was more homogeneous in the electric cooking, attributed to the continuous and stable application of temperature provided by the electric grill.

4.4. Interpretation of trends and relevance

– The data collected from https://www.wunderground.com/dashboard/pws/IQUERETA29respaldan the reliability of the climate measurements during the solar test, which gives transparency to the experimental process.

– It is evident that, under high irradiance conditions (≥ 1000 W/m²), the solar cooker can come quite close in performance to the traditional electric method.

– Although solar cooking time limits its applicability in fast-paced production environments, it could be adjusted with more efficient cooker designs or hybrid assistance (solar + electric) for times of low radiation.

– In terms of practical impact, users can plan solar cooking based on local weather forecasts, optimising production periods.

Box 5

Table 4

Sensory comparison of orange peel jam prepared in a solar cooker and on an electric grill

Attribute	Solar greenhouse	Electric grill
Colour	Slightly more intense, with a uniform golden hue due to gradual caramelisation.	Less uniform colour, with slight variations in tone.
Flavour	More aromatic with mild sweet notes, attributable to slow, natural cooking.	Distinct flavour but less aromatic, tending to be more pronounced when cooked quickly.
Texture	It exhibits slight variations in consistency due to its dependence on solar radiation.	More consistent and firm, thanks to the stable temperature of the electrical equipment.
Aroma	Better preserves the essential oils in the peel, giving it a fresh, natural aroma..	Less intense aroma, with slight loss of volatile compounds during cooking..

5. Discussion

The calculation of the thermal efficiency of the parabolic solar oven yielded a value of 1.5%, lower than the range reported in the literature (5–15%), due to the high humidity of the mixture, thermal losses, and irradiance variability. As pointed out by Kalogirou (2009) and Ramírez, Jaramillo and Dorantes (2015), efficiency depends on the geometry of the concentrator, the reflectivity of the materials and the solar orientation, so improvements such as thermal storage and automatic tracking are required. In sensory terms, the solar sweet had a more uniform colour and a more aromatic flavour, which coincides with Ortiz Ballesteros (2007) regarding gentle caramelisation and the preservation of volatile compounds, while the electric grill offered greater homogeneity in texture, in line with Gómez (2019).

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The reuse of orange peel as a raw material is in line with Balboa (2016) and Cogollo Torres (2022), who highlight the circular economy in the food industry. Furthermore, the results agree with Barrero (2024), showing the viability of solar cooking for local enterprises that promote self-employment and decentralised production. Taken together, the findings reinforce their link to SDGs 12, 8 and 3, and confirm that this model is replicable for sustainable production projects with social, economic and environmental impact.

6. Conclusions

This study demonstrated the viability of producing crystallised orange peel using solar cooking as an alternative to electric cooking, comparing both methods in technical, sensory and environmental terms. From a technical point of view, the parabolic solar cooker reached temperatures above 70 °C, sufficient to guarantee cooking, although with a longer cooking time than the electric grill, in accordance with Ortiz Ballesteros (2007). Sensory analysis showed that the solar-cooked candy had a more uniform colour and a more aromatic flavour, results that coincide with those reported by Cogollo Torres (2022) on the preservation of volatile compounds, while the electric grill offered a more homogeneous texture, in line with Gómez (2019).

In environmental terms, solar cooking eliminated electricity consumption (0 kWh versus 1.5 kWh), representing a reduction of approximately 0.8 kg of CO_2 avoided for each batch of 70 g of processed peel, reinforcing the findings of Balboa (2016) and Barrero (2024) regarding the potential of solar energy in the circular economy.

From a socio-economic perspective, the use of orange peel, considered agro-industrial waste, opens up opportunities for added value and self-employment. In a scenario of community production of 100 kg of crystallised solar sweet per month, it is estimated that 2 to 3 direct jobs will be generated, with incomes of around MXN 15,000–20,000 per month depending on the selling price in local markets. In a semi-industrial scheme, the production of 1 tonne per month could avoid more than 100 kg of CO_2 equivalents, while consolidating micro-enterprises with the capacity to access green labels or fair trade certifications.

Thus, this study not only technically validates solar cooking in a traditional pastry product, but also demonstrates its potential as a driver of community development, improving quality of life, reducing agro-industrial waste, and strengthening SDGs 8, 12, and 3. The central strength of the study lies in integrating technical, environmental, social and cultural dimensions, showing that the combination of traditional knowledge and clean technologies constitutes a replicable and sustainable model with possibilities for productive scaling.

Box 6

Table 5

Hypothetical scenarios for scaling up the production of solar-powered orange peel sweets

Setting	Estimated production	Jobs created	Approximate income*	CO_2 avoided (kg/month)**	Expected impact
Domestic	1–2 kg/mes	0 (self-consumption)	—	2–3	Food safety, reducing household waste
Community	100 kg/ month	2–3 jobs	$15,000–20,000 MXN	80–100	Self-employment, local economy, strengthening gastronomic identity
Semi-industrial	1 tonne/month	8–10 jobs	$150,000–200,000 MXN	800–1,000	Consolidation of micro-enterprises, possibility of environmental and fair trade certifications, access to differentiated markets

7. Economic outlook

The study shows that solar cooking of orange peel has high socio-economic potential. In rural communities, workshops for the production of crystallised sweets could boost self-employment and strengthen local economies. In the educational sphere, the methodology offers a teaching tool for renewable energy, agribusiness, and the circular economy, fostering technical skills and environmental awareness. At the semi-industrial level, the use of parabolic solar cookers with hybrid electrical backup would allow for the production of value-added sweets with a sustainability label, aimed at differentiated markets. In addition, it opens up opportunities for environmental or fair trade certification, increasing regional competitiveness. Overall, this initiative not only reduces waste and promotes clean energy, but also contributes to economic and social development in line with SDGs 8, 12 and 13.

Figure 3 Socio-economic perspectives of solar cooking: community, education and semi-industrial production.

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Declarations

Contribution of the authors:

Ángel Marroquín de Jesús: Review of graphs and interpretation of experimental results and preparation of the manuscript.

Luz Carmen Castillo Martínez: Analysis and interpretation of results, as well as supervision of the sweet-making process.

Juana Alonso Arroyo: Search, compilation and systematisation of the literature review.

Juan Manuel Olivares Ramírez: General review of the manuscript and identification of areas for improvement.

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Conflict of interest:

The authors declare that there is no conflict of interest that could influence the results presented or the interpretation of the data.

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