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Urban Heat Island in barrios de Arboledas neighborhoods of Puebla, Mexico: an analysis of its causes

La Isla de Calor Urbana en barrios de Arboledas, Puebla, México, un análisis de sus causas

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ABSTRACT Currently, humanity is facing complicated environmental challenges due to Climate Change and Urban Heat Island (UHI) effects. This research is conducted in the Barrios de Arboledas neighborhood in Puebla, Mexico. The aim is identifying the causes of UHI at the neighborhood level and developing mitigation strategies based on building sustainability competencies among residents. The study began with a site analysis to identify the causes and factors associated with UHI through residents' surveys and photographic and geospatial information. Results indicate that the presence of air pollution, the use of low-albedo materials, the reduction of green areas, and anthropogenic heat are causing UHI. As mitigation strategies, government programs for waste management were implemented, along with workshops and sociocultural activities to raise environmental awareness.

RESUMEN Actualmente, la humanidad está viviendo momentos complicados en materia ambiental debido al cambio climático y a la Isla de Calor Urbana (ICU). Esta investigación se realiza en el fraccionamiento Barrios de Arboledas, Puebla, México, en el cual se pretende identificar las causas de la ICU a nivel barrial para el establecimiento de estrategias de mitigación basadas en el desarrollo de competencias para la sostenibilidad en los habitantes del fraccionamiento. Se partió del análisis del sitio para identificar, mediante encuestas y levantamientos fotográficos y geoespaciales, las causas y factores asociados a la ICU. Los resultados muestran que la contaminación del aire, el uso de materiales bajos en albedo, el desplazamiento de áreas verdes y el calor antropogénico, están presentes. Como estrategias de mitigación se implementaron programas gubernamentales para manejo de residuos, impartición de talleres y actividades socioculturales para la concientización ambiental.

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PALABRAS CLAVE isla de calor urbana, educación ambiental, competencias para la sostenibilidad, estrategias de mitigación, barrios sostenibles



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1. Introduction

Over the past 80 years, the city of Puebla, Mexico, has grown exponentially. Urban development in the area has displaced green spaces due to infrastructure construction, residential zones, subdivisions, shopping malls, and demand for electricity, sewage, and water, creating an Urban Heat Island (UHI).

In the late 1980s, a housing project comprising three subdivisions—Arboledas de San Ignacio, Vista Alegre, and Barrios de Arboledas—was established in the southern part of the city. With the arrival of these developments, infrastructure and public and private services grew, as did the construction of other subdivisions in the area.

Barrios de Arboledas was designed with a predominance of roads and buildings over green spaces; materials that absorb solar radiation are evident, as is the replacement of permeable surfaces with impermeable ones. Furthermore, it is observed that some residents' daily activities contribute to air pollution. All of this led to morphological changes at the study site, destabilizing existing biodiversity and causing health problems among residents.

This study observes and identifies the causes of the Urban Heat Island (UHI) at the neighborhood scale by fostering sustainability competencies among the residents of Barrios de Arboledas, Puebla, to help establish and adopt strategies that mitigate this phenomenon.

2. The Urban Heat Island, an environmental problem requiring attention

The UHI phenomenon is currently an environmental problem in cities worldwide and must be addressed due to its impacts on biodiversity and human health.

2.1. The origin of environmental impacts

The scientific discussion regarding the evident impact of humans on planet Earth began at Princeton University (1955) with the conference *"The Role of Man in Changing the Face of the Earth."* Since then, a shift has occurred in research on the interaction between humans and their natural environment, driven by anthropological and archaeological studies that have highlighted the impact of human activities on ecosystems. In 1987, the International Geosphere-Biosphere Program (IGBP) launched a collaborative effort in the natural sciences among several countries that contributed new comparative scientific methods and measurements on global environmental change (Arizpe, 2019).

In an article for the IGBP newsletter (2000), the term "Anthropocene" was introduced by P. Crutzen and E. Stoermer (Arizpe, 2019); it mentions the impact of

human activities on the Earth and the atmosphere at a global level, highlighting that population growth and urbanization have led to the depletion of natural resources, the extinction of species in tropical rainforests, greenhouse gas emissions, and the release of toxic substances into the environment (Crutzen and Stoermer, 2000). For his part, Segovia (2017) refers to the Anthropocene as "a geological epoch that begins when human activities start to hurt the global balance and ecosystems" (p. 56) due to the excessive use of natural resources that has led to environmental disasters.

2.2. The presence of the Urban Heat Island

Global warming is a fact; according to figures from COP26 (2021) and the IPCC (2023), the global surface temperature has increased by 1.1 °C between 2011 and 2020 compared to the 1850–1900 period. It is estimated to reach 1.5°C by 2032, with larger increases over land (1.59°C) than over the ocean (0.88°C). If we do not address the generation of greenhouse gas (GHG¹) emissions to reduce them globally by at least 50% by 2030, global net-zero emissions will not be achieved by 2050, with the risk of exceeding the critical threshold of 2 degrees Celsius (Arellano-Ramos et al., 2022).)

Heat waves are a phenomenon linked to global warming; Rosas and Pérez (2024) note that prolonged high temperatures cause stress and harm to human health and ecosystems. According to Chen et al. (2023), urban heat has become a major problem for city dwellers; the phenomenon is known as the Urban Heat Island (UHI) effect, and, due to its frequency, intensity, and extent, it negatively affects human health, ecosystems, and air quality.

The UHI is also defined as the presence of higher air temperatures in urban and suburban areas than in outlying areas. This phenomenon, observed in cities worldwide, has long been studied (Gartland, 2008) and is considered an example of unintended climate modification caused by human activity and urban growth (Oke et al., 2017).

The mechanism behind the generation of the UHI is due to changes in the surface energy balance (Oke, 1995; Oke et al., 2017); this imbalance determines the transfer and storage of energy within the urban system (streets, walls, roofs, among others) and between the system and the urban elements within its atmosphere (humans and buildings).

The first research on the UHI was conducted by the English climatologist Luck Howard in 1818; in 1855, the French climatologist E. Renou documented a rise in temperatures in central Paris. The UHI was identified in Mexico City in 1899 by climatologist Manuel Moreno y Anda (Jáuregui, 1993); in the city

¹ According to the IPCC (2023), GHG concentrations have risen rapidly since 1850. Net GHG emissions include CO₂, CH₄, and N₂O.

Causes of the Urban Heat Island							
1995	2008	2015	2016	2019	2020	2020	Case identified
Oke	Gartland	Tzoni	Lemus	Kelbaugh	Herbel	Cuesta	
Increased solar gain	Increased net radiation			Greater retention, less exposure to the sky, less natural ventilation			Increased solar heat gain
Increased long-wave radiation from the sky		Air pollution					Air pollution
Decrease in net loss of long-wave radiation		Street and building geometry		Increased absorption and delayed release of solar heat by buildings and streets	Urban geometry		Urban Heat Island
Anthropogenic heat	Increase in anthropogenic heat	Heat production	Anthropogenic heat	Residual heat from fuel combustion	Anthropogenic heat	Anthropogenic heat	Anthropogenic heat
Increased sensible heat storage	Heat storage	Materials used in construction	Low albedo of materials	Increased absorption due to dark surfaces and heat-trapping building geometries	Urban geometry		Low-albedo building materials
Decrease in evapotranspiration	Reduction in evaporation	Displacement of green areas	Impermeable materials prevent moisture from dissipating the sun's heat	Higher proportion of absorbed solar radiation converted into sensible heat	Characteristics of urban surfaces	The growing process of urbanization	Displacement of green spaces
Decrease in total turbulent heat transfer	Reduction in convection	Urban convection due to urban heating			Urban geometry		Reduction in wind speed
Increased absorption of short-wave radiation		Contribution to greenhouse gases and global warming	Greenhouse effect			Radiation reflected back by the atmospheric pollution layer	Increased absorption of shortwave radiation

Table 1: Causes of the Urban Heat Island. (2024)

of Puebla in 1970, Günther Michael Gäb of the University of Bonn recorded its presence in the Historic Center (Tzoni, 2015). Subsequently, Balderas (1998), Tzoni (2015), and Lemus (2016) confirmed its existence and identified a growing increase in outdoor temperatures south of the capital.

The growth of the city of Puebla has been rapid; it currently extends to other municipalities and another state, constituting the so-called Puebla-Tlaxcala Metropolitan Area (ZMPT), which was defined in 2000. Over the past fifty years, the population of the ZMPT has quadrupled, and the built-up area has increased 6.5-fold (Balderas and Luyando, 2021). It is estimated that the urban area currently accounts for nearly 50% of the municipal territory, implying a significant shift from permeable to impermeable surfaces (Tzoni, 2015) that contributes to this growth.

Climate alterations in urban areas result from changes in the morphology of the ZMPT's territory and from anthropogenic activities. Both contribute to the generation of environmental problems such as climate change and associated phenomena, including the Urban Heat Island effect.

As mentioned earlier, in 1970, Gäb identified UHI in the historic center of Puebla through urban transect surveys. Twenty-eight years later, Balderas (1998), using the same method, not only confirmed its existence but also identified a heat island in the Jardines San Manuel neighborhood. By 2015, Tzoni corroborated, through satellite imagery, the presence of a surface UHI in the city center and in other areas with high temperatures, which he identified as priority areas for attention, including the Barrios de Arboledas neighborhood. A year later, Lemus (2016) concluded through his study (urban transects) that the presence of the UHI is indeed clearly defined in the city of Puebla.

2.3. Causes of the Urban Heat Island

The Urban Heat Island phenomenon originates, among other causes, from changes in the thermal and reflective properties of urban infrastructure, buildings, streets, and sidewalks, which raise air temperatures. To reduce the negative impacts of the UHI on people and their environment—such as increased energy consumption, harm to human health, increased pollution, and deterioration of air quality—the causes of the UHI must be analyzed.

Some authors have conducted studies to identify and understand these causes, to propose short- and medium-term solutions. Based on a literature review, eight causes of UHI were identified (Oke, 1995; Gartland, 2008; Tzoni, 2015; Lemus, 2016; Kelbaugh, 2019; Herbel, 2020; and Cuesta, 2020): increased solar radiation retention, air pollution, the urban canyon effect, anthropogenic heat, the use of low-albedo building materials, the displacement of green spaces, reduced wind speed, and increased absorption of shortwave radiation (Table 1).

Table 1 shows that anthropogenic heat and the displacement of green spaces are two causes clearly identified in the literature. Anthropogenic heat from human activities in cities alters the energy balance through patterns of energy use and consumption. The second cause leads to a reduction in evapotranspiration because impermeable surfaces (buildings and roads) predominate over permeable surfaces, affecting the regulation of local microclimates.

Another recognized cause is the use of low-albedo materials; these materials have a higher heat capacity and thermal mass, allowing them to store heat within buildings. Some authors believe this is related to urban geometry (the urban canyon) because radiation becomes trapped within the built environment, reflected multiple times off buildings and roadways, leading to an increase in air temperature.

The urban canyon and reduced wind speed are two other linked causes, as both result from the geometry of the urban layout. In some cities, tall buildings and narrow streets prevent heat from dispersing, trapping it because airflow is obstructed.

The last three causes—increased solar retention, air pollution, and greater absorption of shortwave radiation—are associated with certain atmospheric gases that prevent radiation from being reflected, trapping it and raising ambient temperatures.

2.4. Environmental education as an agent of change

A key aspect of addressing the current environmental crisis, particularly given the concerning presence of Urban Heat Islands, is environmental education. It can be viewed as a strategy for tackling the current environmental crisis. Through environmental

education, environmental awareness is fostered as a learning process that helps people understand environmental and socio-historical degradation, raise awareness of their lifestyles and the value of natural resources, thereby increasing their knowledge and information (Matos and Flores, 2016).

UNESCO (2017) proposes Education for Sustainable Development (ESD) to enable present and future generations to make informed decisions and act responsibly regarding environmental integrity, economic viability, and social justice. This organization states that achieving a sustainable citizenry requires acquiring key competencies within the contextual framework of the Sustainable Development Goals (SDGs) of the 2030 Agenda and sustainability-oriented environmental education (Murga, 2018).

Humans are considered primarily responsible for environmental problems; therefore, efforts must be made to work more closely with society and in smaller communities, that is, at the neighborhood level. The creation of organizations that address this scale provides mechanisms for accessing sustainable development programs that act as catalysts for change toward more environmentally responsible behaviors.

3. Methodology

The methodology used in this study is a mixed-methods approach that involves collecting, analyzing, and integrating quantitative and qualitative data to support the research question (Hernández-Sampier and Mendoza, 2018). This method systematically integrates the information obtained to provide a more comprehensive picture of the situation under analysis.

The methodological process was divided into four sections. The first section highlights the perspectives of various authors who address the origins of environmental impact, the presence of the heat island effect and its causes, and environmental education as an agent of change, which served as the foundation for understanding the different interpretations of the subject of study.

The second section presents the results, beginning with the population characteristics, socioeconomic status, and housing types in the Barrios de Arboledas neighborhood, located south of the city of Puebla. It also discusses the importance of using low-albedo building materials as an alternative for absorbing solar radiation, as well as data on permeable and impermeable areas and the significance of the decline in green spaces within the neighborhood.

Subsequently, data on anthropogenic heat and its contribution to the rise in ambient temperature are presented. To determine the anthropogenic activities

4. Results

associated with the ICU, two types of surveys were administered: one with multiple-choice questions and a Likert scale. The first survey was general in nature, covering anthropogenic activities and mobility within the neighborhood; it included 56 participants. The second survey addressed anthropogenic activities related to electricity and gas, mobility to locations near Barrios de Arboledas, and the consumption of products and the generation of waste; the sample consisted of 25 households.

The third stage presents the research conclusions, highlighting the importance of identifying the causes and the factors that give rise to them. Understanding the causes and factors that drive the ICU in Barrios de Arboledas enables the identification of the most appropriate mitigation strategies. As a cross-cutting approach, outreach was conducted with neighborhood residents through participatory action research (PAR) (Fals, 2009), which involved establishing communication channels with residents, the Neighborhood Council, and the Municipal Government to share information via WhatsApp and the neighborhood's website. Additionally, the Committee for Sustainable Development was formed. Finally, the fourth section presents the conclusions, outlining the factors contributing to the ICU in the Arboledas neighborhood and helping determine the mitigation strategies.

This research was conducted in the Barrios de Arboledas neighborhood located south of the city of Puebla, Mexico, near the auxiliary council of San Francisco Teotimihuacán. It currently borders Capitán Carlos Camacho Espíritu Boulevard to the east, one of the city's most important primary thoroughfares (Figure 2).

The housing development was built between 1979 and 1981; it covers an area of 105,966.47 m² and includes 341 lots, 315 of which are already built and contain 327 single-family homes (two stories). These figures account for 92.38% of the total area. The subdivision has only three green areas totaling 6,784.60 m², equivalent to 6.40% of its total area. Based on a field survey and the 2020 Population and Housing Census, the population was estimated at approximately 889 residents. According to the Mexican Association of Market and Opinion Research Agencies (AMAI), the average socioeconomic level is "C+," as more than 69% of heads of household have at least a high school education, more than 53% have three bedrooms in their homes, 13% have at least two computers, and 98% have internet access.

Based on studies of the Tzoni surface heat island (2015), 168 neighborhoods in the city of Puebla were identified as areas with high temperatures, including the Barrios de Arboledas subdivision.

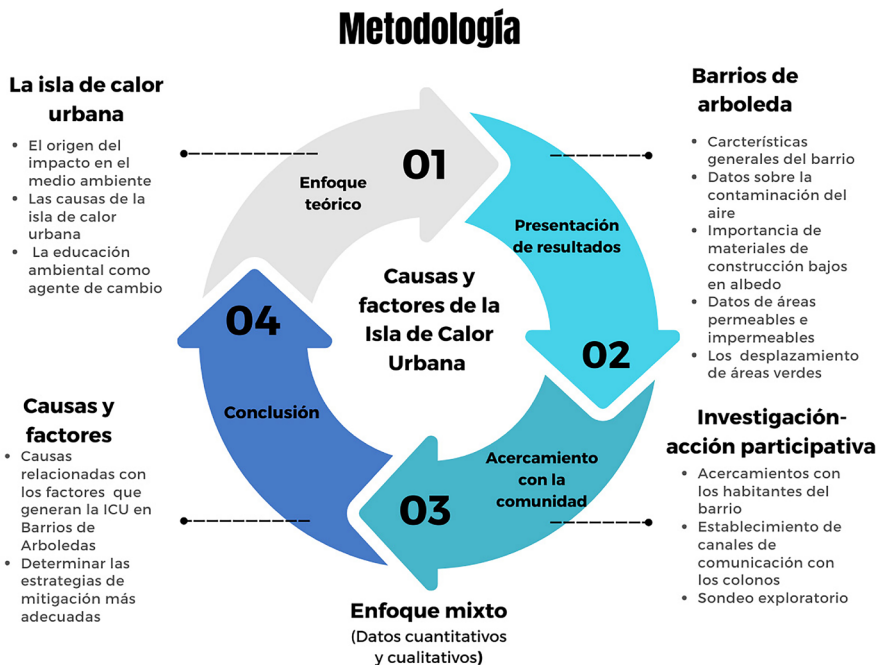


Figure 1: Methodological Process. (2024)

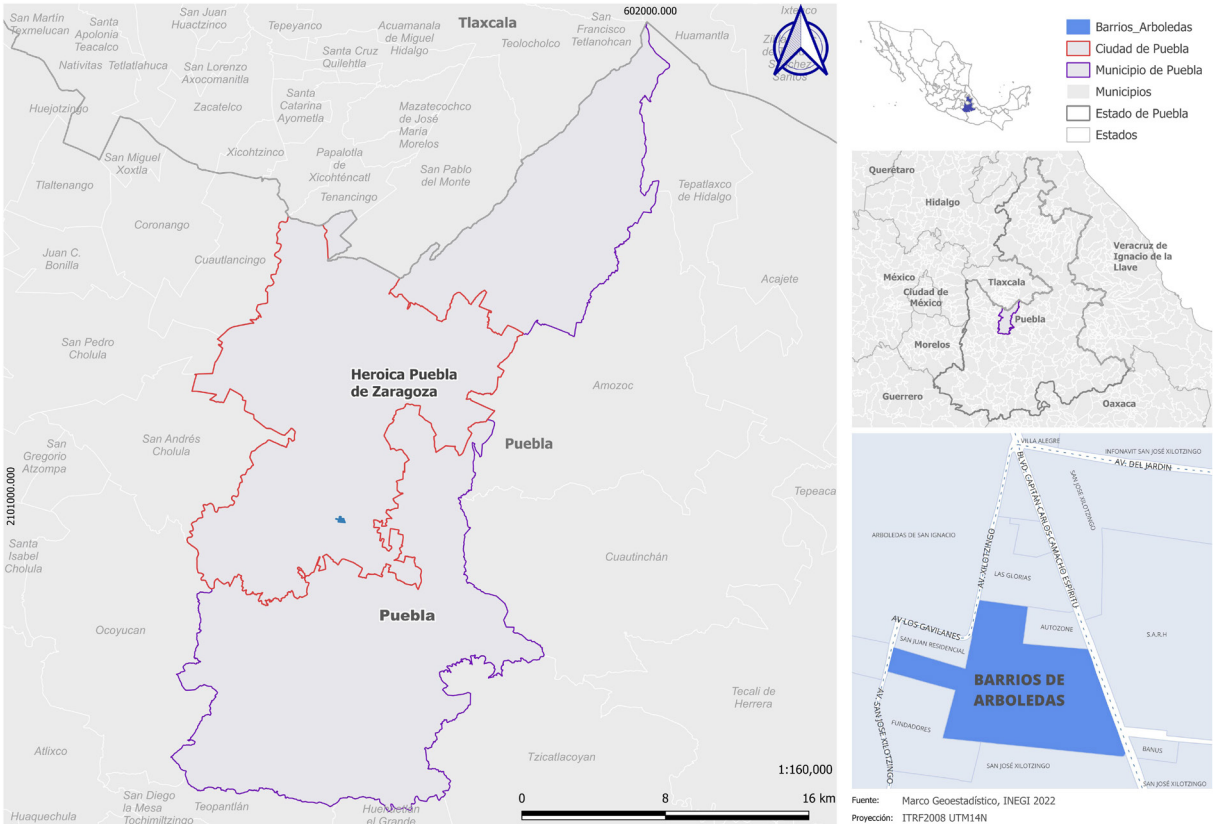


Figure 2: Location of the study area. Authors based on the Geostatistical Framework, INEGI, (2022)

Using the Landsat OIL TIRS platform and satellite imagery, priority areas were identified corresponding to the most densely populated parts of the city's urban sprawl. The study also determined that approximately 33% of the city requires intervention.

Furthermore, in his study on air temperature trends, Lemus (2016) used the transect method to establish an increase in air temperature in the city of Puebla. Furthermore, he found differences between urban and rural areas ranging from 1.8 °C in spring to 2.4 °C in winter in the southwest, and from 0.8 °C in spring to 1.1 °C in autumn in the southeast. These values correspond to the intensity of the heat island effect.

In the Barrios de Arboledas neighborhood, an analysis based on Lemus (2016) was conducted of air temperatures during two seasons: spring and winter. In April (spring), temperatures range from 18°-21°C, while in January (winter) they range from 17°-19°C, between 6:00 and 8:00 a.m. On the other hand, between 1:00 and 3:00 p.m., air temperatures in April (spring) range from 28°C to 30°C and in January (winter) from 21°C to 23°C. Based on the above, we can conclude that air temperature varies by at least 2 degrees in each season. Different temperature ranges were also identified in the area where the housing development is located, as shown in Figure 3.

In addition to the above, a study was conducted on the evolution of air temperature from 2006 to 2024; The data were provided by the Automatic Meteorological Monitoring Network (RAMM) of the Department of Architectural and Urban Research (DIAU) at the Benemérita Universidad Autónoma de Puebla (BUAP), comprising 24 stations located at various points within the ZMPT, which record meteorological conditions.

Specifically, information from the RAMM BUAP CU San Manuel station, located near the study site and still in operation today, was analyzed. The results show normalized data on temperature trends from January 2006 to June 2024, excluding two years (2008 and 2021) due to missing data.

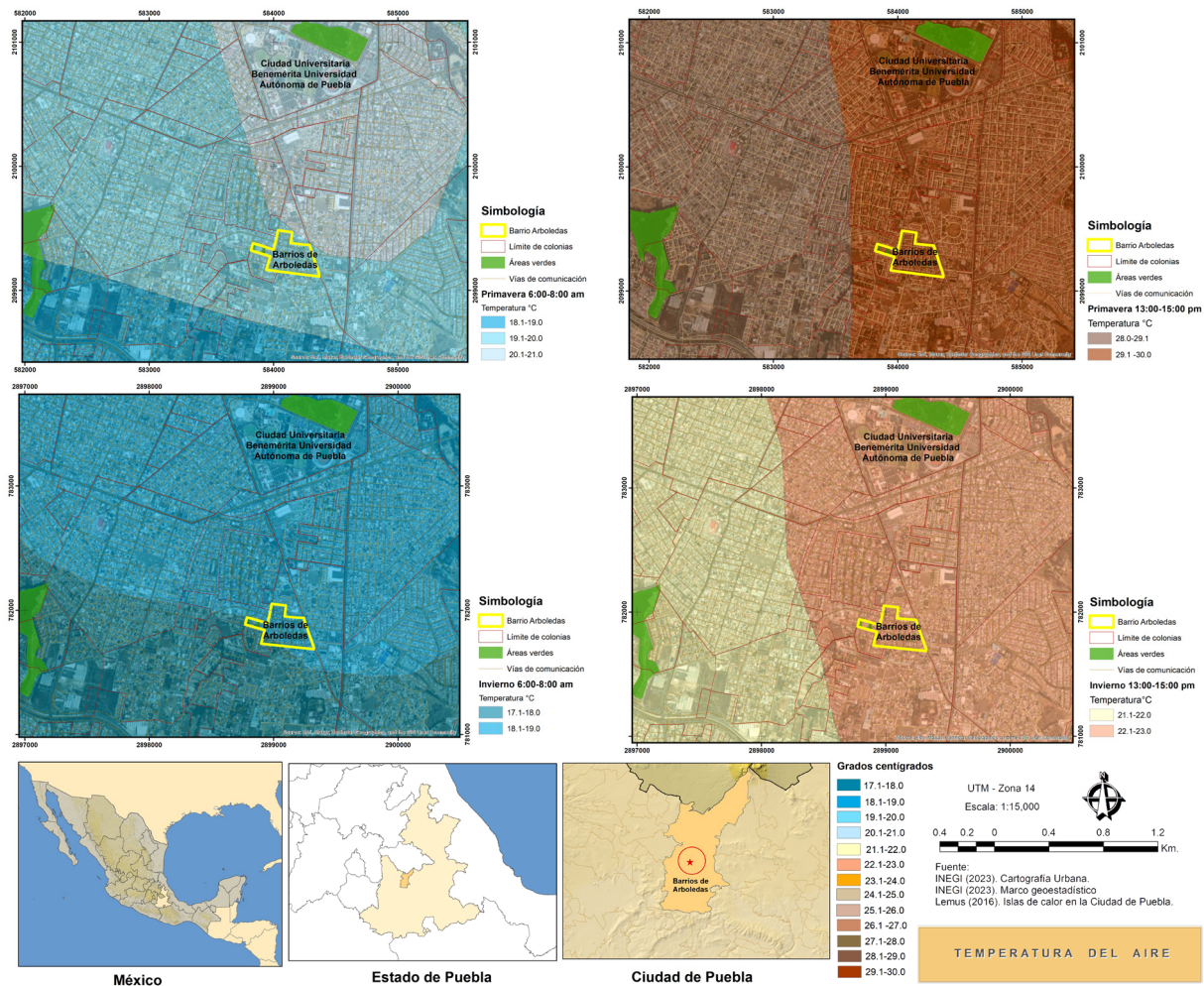


Figure 3: Air Temperature. (2024)

It is important to note that, due to the COVID-19 pandemic, the BUAP closed its facilities in 2020, and access to this station was not available until November 2021. Figure 4 shows increases in minimum, average, and maximum temperatures over 19 years. During this period, the minimum temperature increased by 4.61°C, the average by 1.89°C, and the maximum by 1.94°C. These data confirm that minimum temperatures have increased significantly, a characteristic of ICU presence.

The following shows the results of the analysis of each of the four causes identified at the study site.

4.1. Air pollution

According to SEMARNAT (2019), human activities have negatively impacted biodiversity and human health. To control air pollution and prevent these problems, state and federal authorities have established regulations and programs that regulate

emissions and concentrations of air pollutants through an air quality monitoring system that collects data for impact assessment and decision-making (INECC, 2020). Air quality assessment and identification of health risks to the population are carried out using the Air Quality Index (AQI), which uses a color-coded scale and numbers (SEDEMA, 2018).

The state of Puebla has the State Atmospheric Monitoring Network (REMA), managed by the Secretariat of Environment, Sustainable Development, and Land Use Planning of the Government of Puebla. It consists of eight stations: four in Puebla, one in Coronango, one in Atlixco, one in San Martín Texmelucan, and one in Tehuacán.

Near the study area are the Agua Santa (STA) and NINFAS (NIN) stations; due to the scope of the air quality measurements, information from these two stations was extracted from the National Air Quality

4.2. Low-albedo building materials

Report for 2014–2020. The data indicate that carbon monoxide (CO), sulfur dioxide (SO₂), and nitrogen dioxide (NO₂) do not show high levels, so air quality is considered “good.” In the case of ozone (O₃) and, primarily, particulate matter, air quality levels have increased.

PM10 particulate matter at both stations (NINFAS and Agua Santa) showed an average air quality index of “fair” between 2015 and 2018. It is important to note that, in 2020, due to the pandemic, data collection at the Agua Santa station may have been difficult or even showed an improvement in air quality during the lockdown. At the NINFAS station, data indicate an improvement in air quality from “poor” to “moderate.”

Due to their size, PM2.5 particulate matter can penetrate deeply into the respiratory system and increase cardiovascular or pulmonary health issues (SEMARNAT, 2019). As with PM10, it is difficult to determine whether air quality has improved during the observation period. PM2.5 levels do not show a significant improvement in air quality; for the most part, days with “good” air quality are recorded.

Ozone is a naturally occurring gas in the atmosphere that, through a chemical reaction between sunlight and other gases, can increase significantly and become an environmental pollutant (SEMARNAT, 2019). According to the WHO (2021), this gas can also cause serious cardiovascular and respiratory problems by triggering heart attacks or asthma.

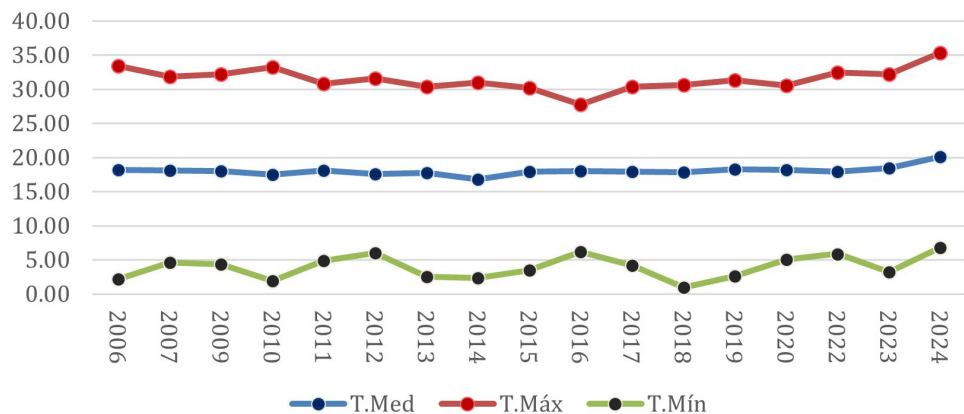
According to records, its presence has increased since 2015, affecting air quality from “good” to “fair,” and further decreasing it to “poor” starting in 2017.

The Arboledas neighborhood is characterized by the predominance of impervious surfaces on roads and buildings (streets, sidewalks, roofs, and walls), as well as the use of low-albedo materials that absorb solar radiation. This alters outdoor temperatures by increasing the heat released into the air at night, leading to higher energy consumption, particularly during the hot season.

The construction materials in the neighborhood have lower reflectance than plant materials; therefore, they absorb more heat. Site visits confirm the use of low-albedo materials (steel, concrete, brick, dark-colored paints, among others) for the construction, remodeling, and maintenance of homes. Some of these materials, used primarily in building envelopes, can increase air temperature and have higher thermal conductivity and heat capacity due to their thermal emissivity and solar reflectance, which tend to absorb rather than reflect solar radiation.

To identify the materials used on horizontal surfaces (rooftops, roads, sidewalks, and patios) in Barrios de Arboledas, a geospatial survey was conducted using QGIS with the Urban and Rural Geostatistical Cartography of Threatened Areas (INEGI, 2016) and supported by satellite imagery from Google Satellite (QGIS 3.32) and the World Map satellite imagery (OpenStreetMap, n.d.). Figure 5 shows that the predominant materials on horizontal surfaces are: concrete (28.61%), found on unwaterproofed rooftops, sidewalks, and driveways; asphalt pavement on streets (20.02%); and terracotta waterproofing on rooftops (16.19%). Other identified but less commonly used materials include glazed fired clay tiles (3.42%) and ceramic tiles, among others. White waterproofing, the material most recommended for its high reflectance, is used on only 4.88% of the total rooftop area.

Figure 4: Evolution of maximum, average, and minimum temperatures. Authors based on data from RAMM BUAP CU San Manuel (2006–2024)



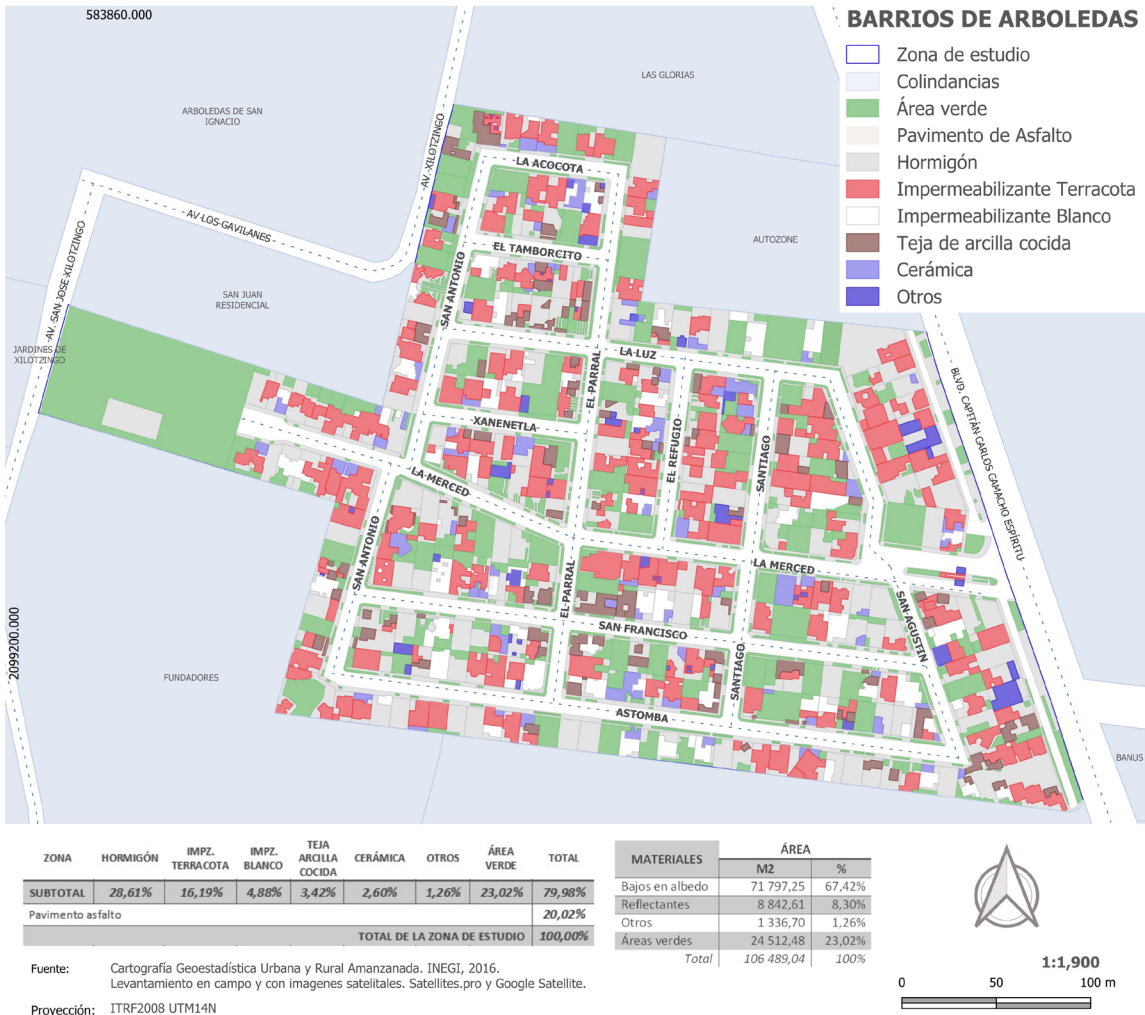
4.3. Displacement of green areas

Over the past 40 years, the Barrios de Arboledas neighborhood has undergone modifications to existing homes and public spaces, roads, sidewalks, green areas, and access points. The predominance of impervious areas over permeable ones is evident; through walking tours, the replacement of green strips on some sidewalks with concrete was documented. These alterations occur due to the lack of internal regulations; some residents of the neighborhood consider the sidewalks an extension of their property, leading them to make decisions outside the Board of Directors' purview that reduce the already scarce permeable areas.

It has not only been the residents of Barrios de Arboledas who have caused the displacement of green areas; during the construction of Line 3 of the RUTA (Urban Articulated Transport Network) system, the green strip of the sidewalk corresponding to the neighborhood was used to widen Capitán Carlos Camacho Espíritu Boulevard from two to three lanes.

To determine the percentage of permeable and impermeable surfaces and demonstrate that green spaces are being displaced, a geospatial survey was conducted using QGIS and the "Geostatistical Mapping of Threatened Urban and Rural Areas" (INEGI, 2016),

Figure 5: Characterization of materials on horizontal surfaces. (2023)



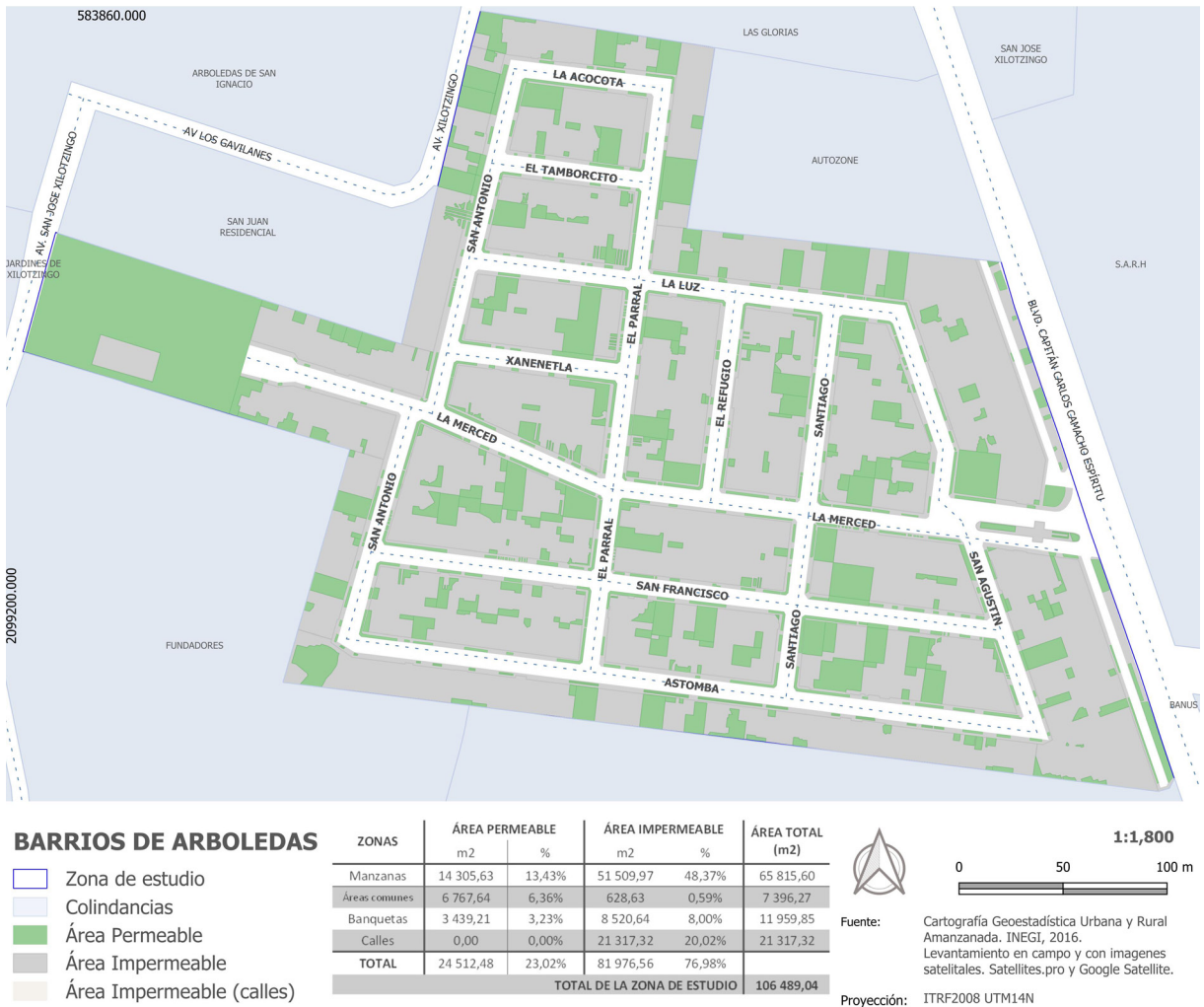


Figure 6: Permeable and impermeable areas. (2023)

supported by satellite imagery from Google Satellite (QGIS 3.32) and World Map Satellite (OpenStreetMap, n.d.). Figure 6 shows a predominance of impervious surfaces, accounting for 76.98% of the total area, compared to permeable surfaces, which account for only 23.02%. More than half, 56.37%, of the total area of the subdivision consists of sidewalks and blocks; a quarter consists of roadways (20.02%), and the remainder consists of permeable areas (23.02%).

It is also evident that in some blocks, impermeable surfaces predominate over permeable ones, accounting for nearly 80%. These include blocks M01, M02, M03, M05, M15, M18, and M20; the latter four are 100% built-up, and only two blocks, M10 and M13, have more than 50% permeable surface area. It is important to note that there are still three undeveloped lots.

4.4. Anthropogenic heat

Anthropogenic heat in Barrios de Arboledas is derived from analyses of patterns of gas use and consumption, product consumption, household municipal solid waste generation, and mobility within the neighborhood and surrounding areas. The results of the survey conducted among 25 households show that 70% of respondents in Barrios de Arboledas use natural gas, and 30% use LP gas (liquefied petroleum gas).

Gas use in households is as follows: 52% use lids to reduce cooking time, and 40% use them sometimes; this is a good practice that reduces energy consumption, but 33% leave the water heater on during the day, and the majority use warm water for washing dishes (68%), hands (84%), and teeth (92%).

The last four practices are not recommended, as they involve higher consumption of fossil fuels. Regarding the generation and use of domestic hot water (DHW), only 16% have a solar water heater, while the remaining 84% use conventional, electric, or instantaneous water heaters. The time spent using DHW in the shower varies: 10 minutes (44%), 20 minutes (40%), and 30 minutes (16%). For cooking, 92% of respondents use gas for up to 2 hours.

Regarding mobility within the neighborhood, among the 56 residents, results showed heavy car use, with most walking and a small percentage using bicycles. To go to stores located within the neighborhood, 30% always use a car and 44% walk; to visit family or neighbors, 10% always use a car and 57% walk. It is noted that it takes 10 minutes to walk from one end of the neighborhood to the other.

According to the mobility map for nearby locations, residents of Barrios de Arboledas use cars despite a RUTA public transportation stop very close to the neighborhood's entrance; the average travel time on this mode is 16 minutes. Short-distance trips are made on foot.

The consumption habits of residents in Barrios de Arboledas are largely due to industrialization, which, through the manufacturing process, generates internal combustion emissions that negatively impact the environment. In this case, residents contribute to local greenhouse gas emissions (in the city of Puebla). Product consumption is varied; some purchase items out of necessity, while others do so for pleasure.

Water and perishable foods (legumes, sugar, meat, chicken, fish, fruits, and vegetables) are reported as necessary items. To a lesser extent, but still considered necessary, are soft drinks, sweets, flour, coffee, milk, yogurt, tea, salt, and cooking herbs. This category also includes computers, cell phones, and tablets. Products consumed for pleasure include magazines/newspapers, paintings, makeup, television, and books.

It is important to note that the packaging of many of these products eventually becomes waste and ends up in the trash. The 4 R's strategy aims to educate the public on proper waste management; its guiding principles are Recycle, Reduce, Reuse, and Recover (Albina, 2004). The results obtained from the 25 households surveyed show that most residents of Barrios de Arboledas habitually recycle and reuse the waste they generate; recovery and reuse are the least practiced. A small percentage ends up in the landfill.

The integrated analysis of both qualitative and quantitative results confirms that four of the eight causes of UIS are present in Barrios de Arboledas. In the study area, air quality has deteriorated due to elevated levels of PM10, PM2.5, and ozone (O3). There is a high percentage (67.42%) of low-albedo construction materials; the percentage of displaced green space is 76.98%; and anthropogenic heat generation is evidenced by patterns of gas use, general consumer products, mobility, and the final destination of waste.

A summary of the results is shown in Table 2, which indicates that the factor explaining the occurrence of the four identified causes is the alteration of the energy balance in cities, followed by heat generated by the burning of fossil fuels (gasoline, natural gas) and the emissions of gases resulting from such combustion. The reflectance of the materials used, the different types of radiation, and suspended particles are also evident.

Causes and factors present in Barrios de Arboledas				
Factors/Causes	Air pollution	Anthropogenic heat	Low-albedo building materials	Displacement of green spaces
Lower reflectance of materials				
Emissions from internal combustion (motor vehicles, stoves)				
Particulate matter				
Increased absorption and re-emission of infrared radiation				
Reflected radiation				
Trapped radiation				
Increase in air temperature				
Change in the urban energy balance				
Heat generated by the burning of fossil fuels (gasoline, natural gas)				
Increased heat capacity and thermal conductivity of building materials (thermal mass effect)				
Reduction in evapotranspiration				

Table 2: Causes and factors present in Barrios de Arboledas. (2024)

Considering the causes of UHI identified in Barrios de Arboledas, the type of environmental education (non-formal and informal), and the competencies for sustainability in the neighborhood, the following strategies are proposed: conducting activities, sociocultural events, informational campaigns on sustainable programs, and workshops as short-term actions that will enable the development of the four competencies mentioned (Table 3).

5. Conclusion

Understanding the causes and factors that generate the ICU in Barrios de Arboledas allows us to determine the most appropriate mitigation strategies for each study area and foster a sustainable citizenry. It is assumed that humans are the primary cause of environmental problems; therefore, it is proposed that key competencies for sustainability be developed among the neighborhood's residents. Of the competencies established by UNESCO, four were identified as priorities: complex thinking, collaborative competence, integrated problem-solving competence, and a sense of responsibility toward present and future generations.

Indirectly, waste generation is one of the factors contributing to GHG emissions at the local level. In Barrios de Arboledas, an annual awareness campaign is conducted on Municipal Solid Waste (MSW) generation and the Recycling Collection Program, promoted by the City of Puebla through the Cleaning Service Operating Agency. This program has received a positive response from residents. Since its launch in August 2021, it has grown from 39 participating households in the May 2022 census to 70 by September 2023.

The workshops on crafts using recycled materials and family gardens promote sustainable citizenship and development by creating equitable and viable social, economic, and environmental environments.

The workshops have sparked some interest, but there is still work to be done on their planning and promotion, so they are being restructured into a sustainable coursework.

The City Council of Puebla attempted to integrate the "Adopt a Tree" Program. However, because it considers the green strip along the building's facade to be its property, this has complicated residents' participation, and the initiative remains pending.

The actions currently underway are: a sustainability course-workshop addressing air quality, anthropogenic heat, and the displacement of green spaces. Additionally, this includes implementing three informational campaigns on energy efficiency, the efficient use and maintenance of vehicles, and the impact of indiscriminate product consumption.

To promote the use of low-albedo building materials, we have been working with the incoming Board of Directors to draft internal regulations that can include a section on Climate Change and Urban Heat Islands.

To strengthen neighborhood coexistence and collaboration and foster active participation that promotes ecologically responsible citizenship, various sociocultural activities were launched in 2021, including the Day of the Dead offering, a costume contest for children and pets, the Christmas Bazaar, the Kermés, and a treasure hunt.

Although there is no strong neighborhood organization, there is interest in sociocultural activities, which have helped foster collaborative skills. This has led to active economic participation through a WhatsApp sales group among residents, established since December 2022, as well as a vegetable oil collection initiative launched in December 2023.

In the Arboledas neighborhood, mitigation strategies have been established for each cause identified at the neighborhood level through environmental education.

Strategies for Mitigating the ICU in Barrios de Arboledas			
Identified Causes	Actions	Status	Result
Air pollution	Course – workshop, module II. Energy and Carbon Footprint	In progress	
	Information campaign on the efficient use of energy and vehicles	In progress	
	Information campaign on consumerism	In progress	
Anthropogenic heat	Recycling Collection Program	Implemented	Good
	Recycled Crafts Workshop	Applied	Fair
Low-albedo building materials	Create the Subdivision Bylaws (conduct an informational campaign)	In progress	
Displacement of green areas	Build Your Own Family Garden Workshop	Implemented	Regular
	Adopt a Tree	Pending	Poor

Table 3: Environmental education as an ICU mitigation strategy. (2024)

Finally, the development of basic sustainability skills is being adopted by residents. It is worth noting that there has been significant progress in collaborative skills, as well as early progress in complex thinking, integrated problem-solving, and a sense of responsibility toward present and future generations.

Conflict of interest. The author declares no conflicts of interest.

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