Household carbon footprint integrating extension and teaching in an undergraduate course in environmental engineering

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Abstract

The curricularization of university extension within the pedagogical projects of Engineering programs is a recent and still consolidating approach in Brazil. This study aimed to evaluate household carbon footprint management as an extension-based educational strategy in undergraduate Environmental Engineering. The extension project was conducted in 2024 and 2025 within the Environmental Management course of the Environmental Engineering program at São Paulo State University (Unesp), in Sorocaba, São Paulo, Brazil. Students assessed environmental management practices in household settings that could reduce carbon emissions. 15 residences located in 8 municipalities within approximately 100 km of São Paulo were evaluated. The project included: (a) raising residents' awareness of climate change impacts; (b) inventorying logistics (Scope 1), energy consumption (Scope 2), and solid waste generation and management (Scope 3); (c) conducting dialogic activities with residents to discuss alternatives for reducing the carbon footprint; and (d) estimating the projected carbon footprint based on management options selected by the residents. The results indicated that logistics was the main source of household carbon dioxide emissions (69%), followed by household waste management (20%) and energy consumption (11%). Although all residents demonstrated awareness of climate change and willingness to reduce their carbon footprint, resistance to change was observed, particularly regarding logistics-related practices. Consequently, the projected reductions based on feasible actions reached 12% for logistics, 23% for waste management, and 19% for energy consumption. The integration of extension activities into the Environmental Engineering curriculum contextualized course content and provided students with practical experience in understanding the social, economic, and cultural factors that influence environmental management decision-making at the household level.

Keywords: environmental impact, solid waste, energy management, logistics, climate change.

Pegada de carbono residencial integrando extensão e ensino em um curso de graduação de Engenharia Ambiental.

Resumo

A curricularização da extensão universitária nos projetos pedagógicos dos cursos de Engenharia é uma abordagem recente e ainda em consolidação no Brasil. Este estudo teve como objetivo avaliar a gestão da pegada de carbono domiciliar como uma estratégia educacional baseada em extensão no curso de graduação em Engenharia Ambiental. O projeto de extensão foi desenvolvido em 2024 e 2025, no âmbito da disciplina Gestão Ambiental do curso de Engenharia Ambiental da Universidade Estadual Paulista (Unesp), campus de Sorocaba, São Paulo, Brasil. Os estudantes avaliaram práticas de gestão ambiental em ambientes domiciliares com potencial para reduzir as emissões de carbono. Foram analisadas 15 residências localizadas em 8 municípios, situados em um raio aproximado de 100 km da cidade de São Paulo. O projeto contemplou: (a) a sensibilização dos moradores quanto aos impactos das mudanças climáticas; (b) o inventário da logística (Escopo 1), do consumo de energia (Escopo 2) e da geração e gestão de resíduos sólidos (Escopo 3); (c) a realização de atividades dialógicas com os moradores para discutir alternativas de redução da pegada de carbono; e (d) a estimativa da pegada de carbono projetada com base nas opções de gestão selecionadas pelos moradores. Os resultados indicaram que a logística foi a principal fonte de emissões de dióxido de carbono nos domicílios (69%), seguida pela gestão de resíduos sólidos (20%) e pelo consumo de energia (11%). Embora todos os moradores tenham demonstrado conscientização sobre as mudanças climáticas e disposição para reduzir sua pegada de carbono, observou-se resistência à mudança, especialmente em relação às práticas associadas à logística. Consequentemente, as reduções projetadas com base em ações consideradas viáveis alcançaram 12% para a logística, 23% para a gestão de resíduos e 19% para o consumo de energia. A integração das atividades de extensão ao currículo do curso de Engenharia Ambiental permitiu a contextualização dos conteúdos da disciplina e proporcionou aos estudantes experiências práticas na compreensão dos fatores sociais, econômicos e culturais que influenciam a tomada de decisão em gestão ambiental no nível domiciliar.

Palavras-chave: impacto ambiental, resíduos sólidos, gestão de energia, logística, mudanças climáticas.

1. Introduction

Greenhouse gas (GHG) emissions from anthropogenic sources have been identified as the main driver of global warming, posing a threat to biodiversity, agricultural production, the tourism industry, and public health (Abbass et al., 2022). Global efforts to limit and adapt human society to the effects of climate change are reflected in Sustainable Development Goals (SDGs) 11 (Sustainable Cities and Communities), 12 (Responsible Consumption and Production), and 13 (Climate Action) (Huang et al., 2023a). However, effectively reducing the impacts of this climatic phenomenon requires the engagement of societal stakeholders (Sri; Banerjee, 2023).

The carbon footprint is an indicator used to assess the potential impact of anthropogenic activities on the climate, expressed in carbon dioxide equivalents (CO_2eq). Environmental management employs the carbon footprint to evaluate the effectiveness of policies and actions aimed at reducing climate change impacts, as observed in sectors such as education (Medeiros; Daniel, 2009; Dutra et al., 2019), industry (Barbosa et al., 2025; Lenort et al., 2023), agriculture (Araujo et al., 2025; Abbass et al., 2022; Costa et al., 2018), urban planning (Liang et al., 2024), and solid waste management (Menichelli et al., 2023; Oliveira et al., 2022), among others.

Household consumption represents a substantial contributor to global GHG emissions and therefore plays a critical role in climate change mitigation efforts. In highly urbanized economies such as the United States, China, and Japan, household activities are estimated to account for 70–80% of total final GHG emissions (Long et al., 2021). Similarly, in the United Kingdom, domestic actions associated with food and goods consumption and transportation contribute approximately 60% of national emissions (West et al., 2015). In northeastern China, households were responsible for about 40% of GHG emissions between 2015 and 2017 (Liao et al., 2023). Despite the clear relevance of the household sector as a major source of emissions, the formulation and implementation of effective climate policies targeting household carbon footprints remain challenging. This complexity arises from behavioral, socioeconomic, and cultural factors that influence household decision-making and adoption of low-carbon alternatives.

A wide range of factors influences residential GHG emissions, including the location of the household (urban or rural) (Fu et al., 2024; Liang et al., 2024; Ottelin et al., 2019), household income (Feng et al., 2021; Zen et al., 2022), lifestyle (Huang et al., 2024; Huang et al., 2023b; Jiang et al., 2023), education level (Zen et al., 2022), family size (Feng et al., 2021; Fu et al., 2024; Miehe et al., 2016), climate (Shigetomi et al., 2021; Long et al., 2021), and access to technologies (Liao et al., 2023; Sri; Banerjee, 2023; Shigetomi et al., 2021). Furthermore, household emissions are highly diverse, ranging from those associated with the direct use of fuels for heating, cooking, and personal transportation (direct emissions) to those embedded in food, durable goods, and services (indirect emissions) (Long et al., 2021). These multidimensional aspects pose significant challenges to the development of effective strategies aimed at reducing household carbon footprints.

Several initiatives have been developed to promote changes in population habits, including the use of carbon footprint calculators (West et al., 2015; Enlund et al., 2023). However, sustained public engagement with these tools remains a challenge, particularly when they are intended to support policies aimed at guiding household consumption patterns (Salo et al., 2019).

Universities have also assumed an increasingly active role in addressing climate change by assessing their own carbon footprints to guide the development of institutional policies aimed at reducing environmental impacts, as reported in Portugal (Deda et al., 2025) and Finland (Kiehle et al., 2023). At the interface of teaching and research, technological tools have been created to disseminate concepts related to carbon neutrality and sustainability, such as immersive virtual reality platforms that facilitate engagement with complex sustainability strategies in an interactive and accessible manner (Hu et al., 2025).

These approaches indicate a growing tendency to integrate the Sustainable Development Goals (SDGs) and climate change themes into higher education institutions, fostering the involvement of students, faculty, and administrators in climate-related issues (Hoffman; Dicks, 2023). In this context, university extension represents an additional dimension through which SDGs can be incorporated into the academic environment, complementing and strengthening the integration between teaching and research.

In Brazil, Resolution CNE/CES No. 7/2018 of the Ministry of Education established that undergraduate programs must allocate at least 10% of their total curricular credits to extension activities (Brasil, 2018). In Engineering programs, this requirement corresponds to approximately 360 to 400 hours, equivalent to nearly one academic semester over the duration of the degree (Oliveira-Melo et al., 2025). The resolution aims to strengthen the connection between universities and society, integrating teaching, research, and extension while promoting social engagement and inclusion (Hogemann, 2025).

Following this resolution, several initiatives have been implemented to incorporate extension activities into undergraduate curricula across various fields in Brazil, including Public Administration (Lucas et al., 2023), Business Administration and Accounting (Silva et al., 2024), and Law (Hogemann, 2023). Reports published in peer-reviewed journals also document experiences related to the curricularization of extension in Engineering programs, such as Civil Engineering (Silveira et al., 2022), Food Engineering (Klein et al., 2024), Forest Engineering (Folli-Pereira et al., 2025), and Chemical Engineering (Cruz et al., 2024).

Despite a growing body of literature addressing curricularization strategies in Brazilian undergraduate programs since 2018, there remains a noticeable gap in studies presenting quantifiable indicators of extension experiences, particularly in technological fields such as Engineering (Oliveira-Melo et al., 2025). In this context, the household carbon footprint emerges as a promising theme for extension curricularization due to its interdisciplinary nature and its environmental, social, cultural, economic, and political implications.

Therefore, the objective of this study was to evaluate household carbon footprint management as an extension-based approach within the Environmental Management course of an undergraduate Environmental Engineering program.

2. Materials and Methods

2.1 Selection of households

The research was performed within the Environmental Management course of the Environmental Engineering program at the Institute of Science and Technology, São Paulo State University (Unesp), Sorocaba city, São Paulo state, Brazil, during 2024 and 2025. Although designed for Environmental Engineering, the course also serves students in Forest Engineering, Business Management, and Information Technology (Medeiros; Daniel, 2009).

Students were assigned an active role by selecting the households to be evaluated. Working in groups of three, they contacted families to request consent, gather information, and schedule discussions on the results.

A total of 15 residences were evaluated (nine in 2024 and six in 2025), distributed in Sorocaba (6 residences), São Paulo (3), and in Boituva, Carapicuíba, Itatiba, Mairinque, Santana do Parnaíba, and Vargem Grande Paulista (1 each). All municipalities are situated within approximately 100 km of the city of São Paulo (23° 33' 01" S and 46° 38' 02" W).

2.2 Enhancing families' awareness of the environmental impacts associated with global warming

The Climate Change impact category was selected because it is part of everyday public discourse, frequently addressed in television news, documentaries, social media, and digital platforms (Sun et al., 2024). This visibility facilitates the sensitization of the social actors involved. In this stage, students first presented the objectives of the project and discussed the impacts of global warming to enhance residents' environmental awareness regarding GHG emissions (Fengler et al., 2015). They then introduced the diagnostic schedule and outlined the information to be collected.

2.3 Enhancing families' awareness of the environmental impacts associated with global warming

With the participation of residents, primary and secondary data related to the socioeconomic and environmental aspects of each household were collected. Primary socioeconomic information included household type (house or apartment), location (urban or rural), household size (number of residents), age, education level, total monthly income, and tenure status (Zen et al., 2022). Secondary data encompassed environmental aspects associated with residential logistics, energy consumption, and estimated solid waste generation, following the classification proposed by Gershon and Patricia (2019).

The procedures for surveying environmental aspects for GHG estimation were as follows:

a) Residential logistics:

Information was collected through interviews, including vehicle type and model, distance traveled by transportation mode (motorcycle, car, public transport), and whether trips were shared with other passengers.

b) Energy consumption:

Secondary data were obtained from household electricity bills. The electrical power of major appliances and devices (e.g., shower, refrigerator, lighting, air conditioning, television) was also recorded. A dialogic activity on electricity use was conducted to expand residents' understanding of seasonal variations in energy demand.

c) Solid waste generation:

Household solid waste generation was estimated based on municipal per capita values reported in the literature. Per capita generation was assumed to be 1.10 $kg \cdot inhabitant^{-1} \cdot day^{-1}$ for São Paulo and 0.87 $kg \cdot inhabitant^{-1} \cdot day^{-1}$ for Sorocaba, which together accounted for nine households (60% of the sample) (Paes et al., 2021). For Boituva, Mairinque, and Vargem Grande Paulista, a value of 0.80 $kg \cdot inhabitant^{-1} \cdot day^{-1}$ was adopted, consistent with municipalities of 25,000-100,000 inhabitants in São Paulo State (São Paulo, 2020). For Carapicuíba, Itatiba, and Santana do Parnaíba, the assumed value was 0.90 $kg \cdot inhabitant^{-1} \cdot day^{-1}$, corresponding to cities with 100,000-500,000 inhabitants (São Paulo, 2020). For households that separated recyclable dry waste, a reduced per capita generation equivalent to 60% of the literature value was applied, producing a positive effect on the household carbon footprint.

2.4 Carbon footprint calculation

Based on the inventory of environmental aspects, the carbon footprint of the households was estimated by considering direct emissions associated with mobility and residential logistics (Scope 1), indirect emissions related to electricity consumption (Scope 2), and other indirect emissions arising from household solid waste generation (Scope 3), according to the ISO 14064-1 classification (ISO, 2018). The carbon footprint was calculated using the following equation 1 (Kiehle et al., 2023):

$$E = C.F \qquad \text{Eq. (1)}$$

where E is the total emission of carbon dioxide equivalent (CO_2 eq); C is the consumption of a natural resource or waste generated; and F is the emission factor.

For Scope 1, the emission factor adopted for gasoline vehicles with ethanol blend was 1.75×10^{-3} tCO_2 eq L^{-1}, whereas for vehicles fueled with ethanol, the factor was 5.6×10^{-4} tCO_2 L^{-1} (IPEA, 2011). For Scope 2 emissions, the average emission factor was 0.0523 tCO_2 eq MWh^{-1} for the year 2024, based on the electricity mix of Brazil's National Interconnected System (MCTI, 2024). In Scope 3, the emission factors for municipal solid waste (MSW) management were 1.48 tCO_2 eq $tMSW^{-1}$ in Sorocaba and 1.22 tCO_2 eq $tMSW^{-1}$ in São Paulo, while for the remaining municipalities, the adopted factor was 1.27 tCO_2 eq $tMSW^{-1}$. These factors were derived from the MSW management systems of Sorocaba, São Paulo, and Piedade, and include gravimetry, collection, transportation, and final disposal in sanitary landfills (Paes et al., 2021).

2.5 Guidelines for carbon footprint mitigation, economic evaluation, and resident engagement

Alternatives for reducing the carbon footprint were presented to residents and are summarized in Table 1. Based on these options, guidelines were developed collaboratively through dialogic activities. During these discussions, residents selected mitigation measures considering the social, cultural, economic, environmental, and infrastructural characteristics of their respective regions, including the availability of public transportation, bicycle lanes, and selective solid-waste collection systems.

Table 1. Household management alternatives to reduce the carbon footprint, presented to residents as a basis for dialogic engagement.

Scope	*Dimension*	*Alternative Description*
Scope 1	Logistics	Increase the use of bicycles
		Increase the use of public transport
		Vehicle exchange (car for motorcycle)
		Vehicle exchange (gasoline/flex car for electric car)
		Car fuel change (gasoline for ethanol)
Scope 2	Energy	Changing light bulbs
		Refrigerator change
		Reduced shower time
		Photovoltaic System
Scope 3	Waste	Sorting waste and sending dry recyclables for processing, while directing organic waste to the municipal collection system and its subsequent disposal in a sanitary landfill
		Sorting waste and sending recyclables for processing, along with home composting of a portion of organic waste

Source: Author, 2025.

3. Results

3.1 Socioeconomic diagnosis

All dwellings were in urban areas, with a predominance of single-family houses (12 units; 80%), followed by apartments (3 units; 20%). Household size most frequently comprises four residents (40%), followed by three (27%) and two residents (20%) (Figure 1). Only one dwelling accommodated five residents (7%), while the maximum observed was eight residents (7%). The mean household size was 3.7 residents, exceeding the national average for Brazil (2.80) (IBGE, 2022) and that of several European countries, such as Germany (2.1) (Miehe et al., 2016) and Greece (2.6) (Markaki et al., 2017). All residents were between 12 and 64 years of age; notably, in Europe, children and older adults exhibit a lower per-capita residential carbon footprint compared with individuals of working age (Ottelin et al., 2019).

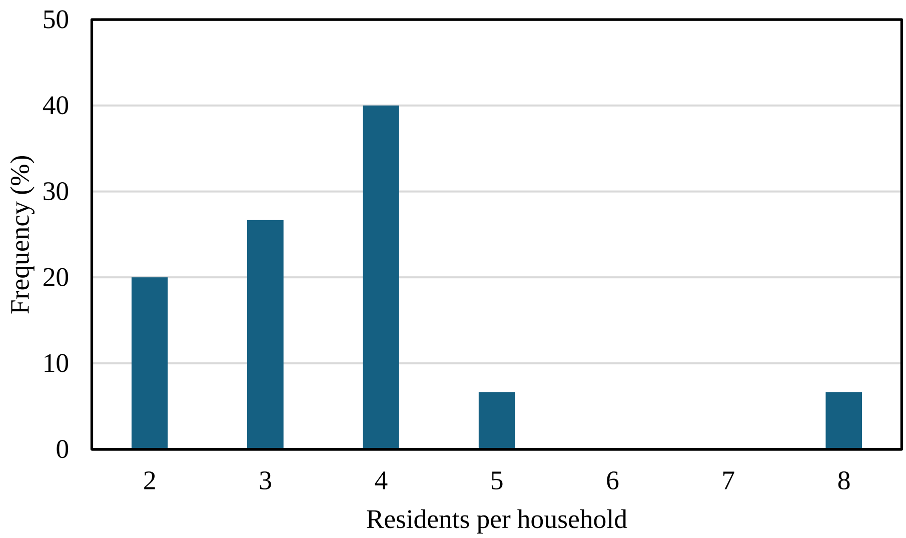

Figure 1. Distribution of the number of residents per household. Source: Author, 2025.

Figure 2 presents the monthly income range of each household, using a minimum wage of US$ 288.00 (R$ 1,518.00 in 2024) as reference. The most prevalent income class comprised households earning above US$ 3,000 per month (40%), which corresponds to the medium-high (US$ 2,400-5,000) and high-income categories (above US$ 5,000) according to the Brazilian Association of Research Companies (ABEP, 2024). This was followed by income brackets of US$ 1,500-2,000 (27%), US$ 900-1,500 (20%), and US$ 2,000-3,000 (13%).

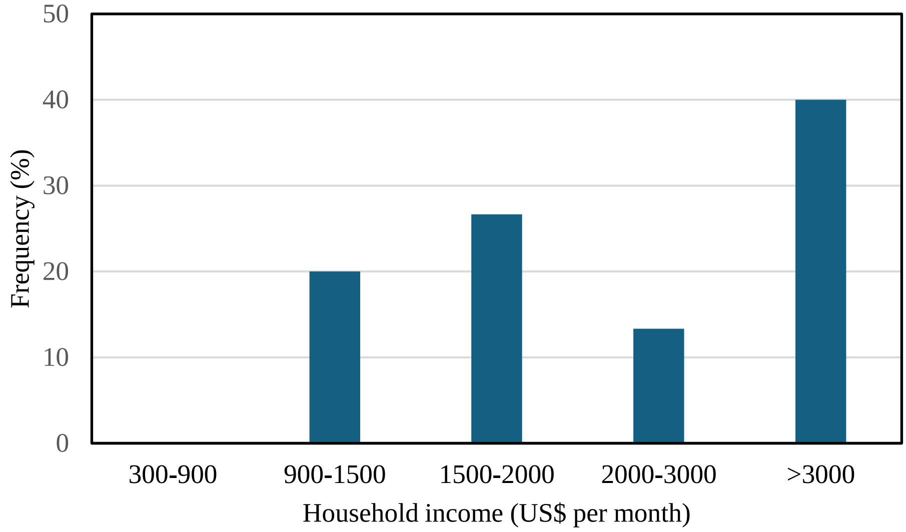

Figure 2. Distribution of the monthly income range of housing. Source: Author, 2025.

In Brazil, the nominal per-capita monthly household income reached US$ 390.00 (R$ 2,069.00) in 2024, while the state of São Paulo reported a higher average of US$ 502.00 (R$ 2,662.00) (IBGE, 2025). Compared with this state-level benchmark, nine households in the sample (60%) achieved or exceeded São Paulo's per-capita income, and only one household fell below the national mean, despite all dwellings including at least one resident with higher education.

3.2 Household carbon footprint survey

Figure 3 displays the household carbon footprint derived from the GHG emissions inventory across the evaluated dimensions: energy use (CF Energy), solid waste generation (CF Waste), and mobility/logistics (CF Logistics). The average household carbon footprint was 3.95 tCO_2 eq $(housing\cdot year)^{-1}$, ranging from 1.20 to 8.91 tCO_2 eq $(housing\cdot year)^{-1}$. On a per-capita basis, the mean carbon footprint reached 1.08 tCO_2 eq $(inhabitant\cdot year)^{-1}$, with values spanning from 0.42 to 2.93 tCO_2 eq $(inhabitant\cdot year)^{-1}$.

Comparisons with other countries are inherently constrained by methodological differences among carbon footprint inventories, which may incorporate additional consumption components such as food (Fu et al., 2024; Huang et al., 2024), clothing (Liu et al., 2024; Long et al., 2021), personal care products (Long et al., 2021), and recreational activities (Zen et al., 2019). Nonetheless, the per-capita carbon footprint observed in this study is substantially lower than values reported for industrialized nations, including the United States (18.1 tCO_2 eq $(inhabitant\cdot year)^{-1}$) (Feng et al., 2021), Germany (14.3 tCO_2 eq $(inhabitant\cdot year)^{-1}$) (Miehe et al., 2016), Sweden (8.8 tCO_2 eq $(inhabitant\cdot year)^{-1}$) (West, 2015), and Japan (3.0-4.4 tCO_2 eq $(inhabitant\cdot year)^{-1}$) (Long et al., 2021).

The logistics dimension (Scope 1) was the most prominent, accounting for 57% of the household carbon footprint, equivalent to 2.27 tCO_2 eq $(household\cdot year^{-1})$. It was followed by waste generation (Scope 3), which accounted for 33% or 1.31 tCO_2eq (household·year-1), and energy consumption (Scope 2), which accounted for 9% or 0.37 tCO_2eq $(household\cdot year^{-1})$. Figure 3 shows that logistics (Scope 1) exhibited the largest interquartile range and the greatest discrepancy between the mean and median, indicating higher variability in this dataset.

Energy consumption (Scope 2) displayed the highest degree of symmetry, with the arithmetic mean closely approximating the median, as well as the smallest interquartile range, features typically associated with a normal distribution.

An outlier was observed only in the household carbon footprint associated with solid waste generation (Scope 3). This phenomenon is likely related to a household with the maximum number of residents (n = 8), which increases waste production.

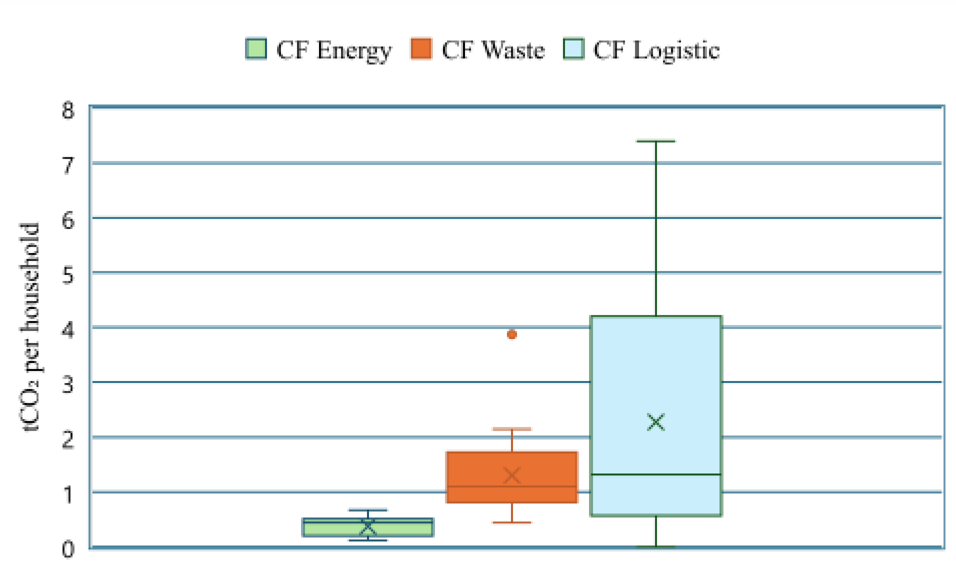

Figure 3. Household carbon footprint boxplot for each dimension evaluated: energy (CF Energy), waste generation (CF Waste), and logistics (CF Logistics). Source: Author, 2025.

3.3 Result of the dialogical activities with the residents

The first question posed to residents concerned their awareness of the impacts of global warming. All households expressed concern about climate change and associated its effects with intense rainfall and prolonged droughts in their regions, consistent with findings reported by Zen et al. (2019) in a study conducted in Malaysian households. This awareness was reflected in unanimous positive responses to the second question, which addressed residents' willingness to reduce the carbon footprint of their homes. The third question surveyed residents regarding residential environmental management alternatives aimed at reducing GHG emissions for each evaluated Scope, as summarized in Table 1.

For Scope 1 (logistics-related emissions), the most accepted alternative was switching vehicle fuel from gasoline to ethanol, reported by 5 households (33%). Between 2003 and 2024, Brazil sold 1.7 million flex-fuel vehicles, representing approximately 85% of total sales, followed by electric vehicles (174,000 units, or 9%). This context supports the feasibility of adopting fuel substitution at the household level (ANFAVEA, 2025). The second most accepted alternative was reducing car use or the number of cars (3 households, 20%). Replacing a flex-fuel vehicle with an electric vehicle was accepted by 2 households (13%), although about 20% of households considered the cost prohibitively high. Conversely, 4 households (27%) were resistant to changing their mobility practices due to convenience, inadequate public transport, limited cycling infrastructure, and safety concerns.

For Scope 2 (emissions from energy consumption), 14 households (93%) rejected the installation of photovoltaic panels due to the high upfront investment. In contrast, 12 households (80%) accepted, or had already implemented, the replacement of conventional light bulbs. Alternatives related to bathing practices (e.g., reducing shower time or replacing showerheads) were accepted by 6 households (40%), while appliance replacement (microwave, washing machine, or refrigerator) was considered by 4 households (27%). However, 5 households (33%) showed no interest in the proposed alternatives because of cost.

For Scope 3 (solid waste generation), 7 households (47%) already separate dry waste for recycling, and 5 households (33%) expressed willingness to adopt this practice. Three households (20%) were unwilling to separate waste due to the absence of selective collection services and limited storage space. Regarding organic waste, 4 households (27%) reported willingness to implement home composting.

Following the assessment of residents' willingness to adopt these management alternatives, the potential impact of the proposed actions on the projected household carbon footprint was evaluated (Figure 4).

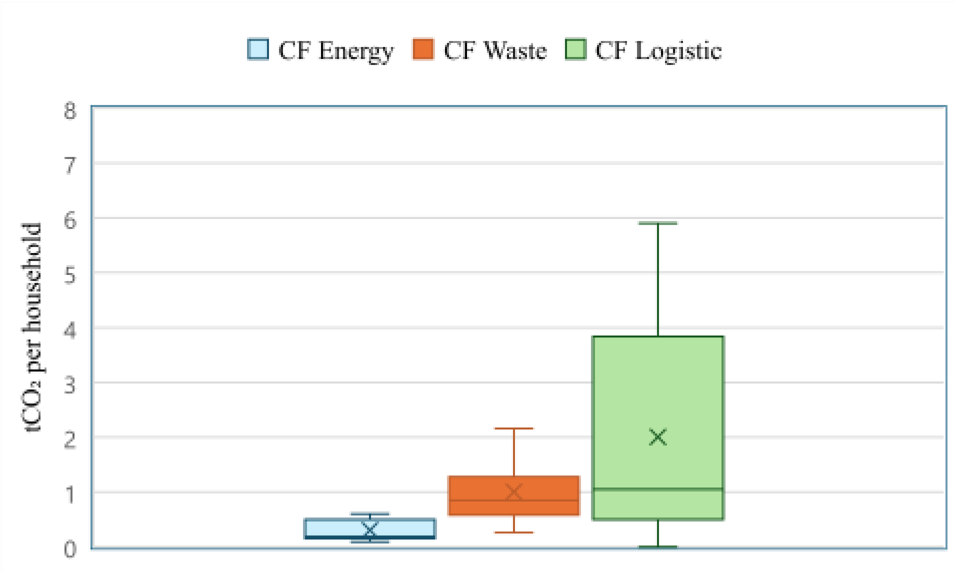

Figure 4. Boxplot of the projected household carbon footprint for each dimension evaluated: energy (CF Energy), waste generation (CF Waste), and logistics (CF Logistic), after the implementation of household management alternatives. Source: Author, 2025.

The mean household carbon footprint was reduced by 16%, reaching 3.31 tCO_2 eq (household·year^{-1}), with a range of 0.52 to 6.60 tCO_2 eq (household·year^{-1}). This reduction corresponded to a mean per capita carbon footprint of 0.90 tCO_2 eq (capita·year^{-1}), with minimum and maximum values of 0.26 and 2.70 tCO_2 eq (capita·year^{-1}), respectively.

In this new scenario, the logistics dimension (Scope 1) increased its relative importance, accounting for 61% of the household carbon footprint (2.00 tCO_2 eq household·year^{-1}), as it showed the smallest reduction (12%). Emissions from Scope 3 (waste generation) were the second largest contributor, representing 30% of total GHG emissions (1.00 tCO_2 eq household·year^{-1}), and showed the greatest reduction following the adoption of management actions (23%). Scope 2 emissions (energy consumption) reached 0.30 tCO_2 eq household·year^{-1}, corresponding to a 9% reduction.

Figure 4 shows a reduction in the interquartile range for the carbon footprint across all three Scopes. In this scenario, the carbon footprint associated with energy consumption continued to display the highest symmetry, the lowest interquartile range, and a mean value closest to the median, indicating a trend toward a normal distribution. Conversely, the carbon footprint associated with Scope 1 (logistics) exhibited the largest interquartile range and the greatest difference between the mean and median, reflecting high variability in the data. After households agreed to adopt solid waste management alternatives, the previously observed outlier was eliminated.

4. Discussion

The households evaluated shared characteristics known to influence carbon footprints, including location in urban areas (Liang et al., 2024; Ottelin et al., 2019), climate (Huang et al., 2023a; Shigetomi et al., 2021), the household head's educational level (Zen et al., 2019), and the presence of working-age residents (Ottelin et al., 2019). Therefore, the demographic factors with the greatest influence on household carbon footprints were family size and income, corroborating previous studies (Feng et al., 2021; Fu et al., 2024; Miehe et al., 2016).

Larger households tended to exhibit higher total emissions; however, their per capita carbon footprint was lower due to shared use of appliances and other consumption items. This trend has also been reported in the United States (Feng et al., 2021), China (Fu et al., 2024), Japan (Long et al., 2021), Greece (Markaki et al., 2017), Germany (Miehe et al., 2016), and the Netherlands (Patel et al., 2022). Notably, the household with the largest number of residents (eight) had the fourth-highest total carbon footprint (5.7 tCO_2 eq household·year^{-1}), as all residents were university students. This condition intensified resource sharing, including transportation, since commuting destinations were similar and located near the residence.

The household with the highest carbon footprint consisted of five residents and belonged to the highest income group (above US$ 3,000). Income also acted as a strong driver of emissions, as observed in India (Lee et al., 2021), China (Fu et al., 2024), and Japan (Huang et al., 2024). The second- and third-highest carbon footprints were also associated with households with incomes above US$ 3,000.

Per capita carbon footprint analysis further reinforced the relationship between household size and income. The maximum value (2.93 tCO_2 eq capita·year^{-1}) occurred in a two-person household with per capita income above US$ 2,000, while the minimum (0.42 tCO_2 eq capita·year^{-1}) was observed in a three-person household with the lowest per capita income (US$ 300), a sevenfold difference. Similar patterns are observed internationally: high-income households emit 4.3 times more GHG than low-income households in Germany (Miehe et al., 2016) and 2.6 times more in China (Fu et al., 2024).

Direct emissions from transportation (Scope 1) were the largest contributor to total household emissions (54%), consistent with Patel et al. (2022), who reported 45%. However, in many countries, indirect emissions (Scope 2, energy use) dominate residential footprints, as observed across Europe (Ottelin et al., 2019), including Greece (Markaki et al., 2017), Germany (Miehe et al., 2016), and the United Kingdom (West et al., 2015); in the United States (Feng et al., 2021); and in Asian nations such as Japan (Huang et al., 2023b; Huang et al., 2024; Long et al., 2021) and China (Fu et al., 2024; Liang et al., 2024). These regions experience colder climates, increasing demand for heating and, in some cases, cooling (Long et al., 2021; Feng et al., 2021; Markaki et al., 2017).

In the municipalities analyzed, the average annual temperature ranges from 20°C to 21°C, with minimums of 12-13°C and maximums of 27-29°C (AGRITEMPO, 2025), contributing to lower residential energy consumption. Additionally, Brazil's energy mix includes 45% renewable sources, with 86% renewables in the electricity matrix (Saccardo et al., 2023).

Transportation-related emissions exhibited the greatest inequality among households, consistent with findings from Japan (Huang et al., 2023b). The lowest values occurred in the only car-free household, whereas the highest footprint was recorded in a household with five private vehicles, corresponding to 83% of its total GHG emissions. Similar dependence on private vehicles has been documented in the United States (Feng et al., 2021), Germany (Miehe et al., 2016), China (Liang et al., 2024), and Greece (Markaki et al., 2017), often correlated with improvements in income levels.

Despite broad awareness of the impacts of climate change among all participating families, there was resistance to adopting the alternatives discussed during the dialogic activities aimed at reducing the household carbon footprint. Fuel switching from gasoline to ethanol emerged as the most feasible alternative for reducing Scope 1 emissions (direct emissions from logistics). In Brazil, this is economically viable: in 2024, 1.7 million new flex-fuel vehicles (capable of running on gasoline or ethanol) were registered, representing approximately 85% of all licensed private vehicles (ANFAVEA, 2025). In the same year, 175,000 electric vehicles were registered, accounting for 9% of new vehicles, demonstrating a growing adoption of electric mobility (ANFAVEA, 2025).

The expansion of electric vehicle sales in Brazil is relatively recent and intensified after 2018, with annual registrations increasing from 4,000 to 175,000 from 2018 to 2024 (ANFAVEA, 2025). This trend is likely linked to policy incentives and legislative proposals promoting electromobility (Schvartz et al., 2024). Nevertheless, the Brazilian electric vehicle market still faces significant barriers, including high purchase prices, limited driving range, and insufficient charging infrastructure (Schvartz et al., 2024). These conditions help explain the low household adherence to purchasing electric vehicles (2 households; 13%), even though about 40% of the sample belonged to Brazil's higher-income group.

The results for Scope 1 emissions suggest resistance to habit changes, such as adopting electric vehicles or giving up at least one private car. Reducing car ownership or use is an alternative recommended by Shigetomi et al. (2021) and Liang et al. (2024) to mitigate household carbon footprints in Japan. However, in the present study, only 20% of households were willing to adopt this alternative. Resistance to public transportation and cycling was also reported, except in households located in São Paulo, where public transit and metro infrastructure are better developed. In the student residence in Sorocaba, public transport was rejected due to poor service quality; walking was considered the most viable alternative, consistent with the residents' age group (20-25 years).

Among households with residents over 50 years of age (60% of the sample), there was resistance to giving up private vehicles, with a stronger preference for switching fuels or purchasing an electric vehicle. Working age in Brazil ranges from 15 to 64 years (Souza et al., 2022), contributing to high reliance on private vehicles and higher mobility-related emissions. Moreover, the study area is in Brazil's most industrialized and urbanized region, where private transportation use is similar to trends observed in industrialized countries in Europe (Ottelin et al., 2019) and the United States (Feng et al., 2021).

Decisions regarding alternatives for reducing indirect emissions (Scope 2) were primarily guided by economic considerations, despite the predominantly high-income profile of the sample by Brazilian standards. Although simulations presented to residents indicated a 5-10 year payback period, more than 90% declined the installation of photovoltaic panels due to investment costs (approximately US$ 2,000), housing type (apartment), or rental status. The expansion of solar energy in Brazil still faces obstacles such as insufficient technological and economic incentives and the absence of specific national policies for sectoral promotion (Saccardo et al., 2023).

Replacing light bulbs was the most accepted and practical alternative. Changes related to shower duration or equipment upgrades can substantially reduce the carbon footprint, since these activities are associated with high emission intensity over time, like cooking and mobility (Jiang et al., 2023). Although income levels would support investments in more energy-efficient appliances, as recommended by Fu et al. (2024) and Feng et al. (2021), only 27% of households accepted this alternative. Overall, the results for Scope 2 also indicate resistance to lifestyle changes, as one-third of households expressed no interest in any proposed option.

Scope 3 emissions (solid waste) reflected the waste generation patterns of the municipalities evaluated, where the predominant management approach is linear: collection, transport, and disposal in landfills. Both municipalities provide collection services for recyclable dry waste, facilitating adherence to separation practices. Consequently, half of the households already separate recyclables, and an additional third expressed willingness to adopt this practice, totaling roughly 80%. In contrast, significant resistance was observed regarding the management of organic waste: only one-quarter of households were willing to implement home composting.

Wet waste represents 51% and 48% of total municipal waste in São Paulo and Sorocaba, respectively (Paes et al., 2021). According to these authors, this trend reflects national patterns, with 51.4% of Brazilian municipal waste consisting of organic matter. In the present study, barriers to home composting included cultural factors, concerns about insects and odors, lack of perceived usefulness for the compost, absence of gardens, limited time, and reduced storage space. Few successful cases of home composting exist in Brazil; one example is the municipality of Harmonia, in Rio Grande do Sul, where environmental education and local traditions in home horticulture enabled significant diversion of organic waste from landfills (Paes et al., 2025). Thus, adopting household organic waste management alternatives faces considerable cultural and social challenges. Nevertheless, Scope 3 was the dimension with the greatest reduction in the household carbon footprint, largely due to high acceptance of dry waste separation.

Based on the GHG emission results and the influence of the dialogic activities implemented during the extension process, several guidelines were proposed to support the reduction of the residential carbon footprint. At the household scale, the most critical aspect is community engagement in bottom-up initiatives aligned with university extension and environmental education programs (West, 2015; Miehe et al., 2026). These initiatives include investing in more energy-efficient technologies (Shigetomi et al., 2021), promoting the rational use of energy (Long et al., 2021), encouraging the use of public transportation and car reduction (Patel et al., 2022; Shigetomi et al., 2021), and minimizing food waste, which contributes to reducing the generation of wet waste (Liu et al., 2024; Liu et al., 2023).

From a top-down perspective, policymakers could establish more ambitious carbon footprint reduction targets for higher-income households, given their greater capacity to adopt efficient technologies (Fu et al., 2024). According to these authors, financial incentives and technical support should be directed toward low-income families to promote equitable policies and leverage the specific characteristics of each household type.

The curricularization of university extension at São Paulo State University (Unesp) was established by Resolution No. 41 of August 31, 2021, to integrate teaching, research, and extension to promote a more comprehensive academic education and strengthen dialogue between the university and society (Klein et al., 2024). This resolution required the restructuring of the political-pedagogical projects of all undergraduate programs at the institution, mandating that at least 10% of the total credit load be dedicated to activities directly linked to university extension and aligned with the Sustainable Development Goals (SDGs) of the United Nations 2030 Agenda (Klein et al., 2024).

Within Engineering programs in Brazil, Environmental Engineering, Forestry Engineering, and Food Engineering are among the fields most engaged in extension activities, given their emphasis on sustainability, natural resource conservation, and community awareness (Oliveira-Melo et al., 2025). In this context, the Residential Carbon Footprint project was developed and incorporated into the teaching plan of the Environmental Management course in the Environmental Engineering program at the Sorocaba Campus. The project sought to disseminate and co-develop, with external communities, actions and initiatives aimed at residential environmental management, with emphasis on SDGs 11 (Sustainable Cities and Communities) and 13 (Climate Action) through the assessment and mitigation of the carbon footprint.

The data collected and analyzed by the students were discussed during in-class presentations, while maintaining the confidentiality of the participating families. This experience enabled a wide range of reflections on the professional practice of engineers, the ethical principles and responsibilities inherent to university extension, and the barriers and gaps that hinder the engagement of social groups and their specificities. These reflections emerged despite a shared societal awareness of the consequences of a widely publicized problem across various communication channels and media outlets.

Therefore, from a teaching standpoint, the carbon footprint assessment provided an opportunity to develop, contextualize, and socially apply the concepts of environmental aspects and impacts within the scope of carbon accounting. Within the integration of teaching and extension, the project fostered a mutually reinforcing relationship between the university and society, contributing to a new paradigm of professional training, as highlighted by Hogemann (2025).

The outcomes of the project generated several benefits for students, the University, and the community:

(i) experience in managing a project that requires communication with external stakeholders (Cruz et al., 2024);

(ii) understanding of social, economic, and environmental aspects across diverse local contexts (Klein et al., 2024);

(iii) development of social and environmental competencies essential for sustainability (Folli-Pereira et al., 2025);

(iv) promotion of student protagonism, shifting from passive knowledge acquisition to an active, critical, and socially responsible practice (Hogemann, 2025; Lucas et al., 2023; Bressane et al., 2017);

(v) establishment of a dialogical relationship and knowledge exchange between the University and the community (Klein et al., 2024).

Similar results have also been reported in technological programs such as Business Management and Informatics (Medeiros; Daniel, 2009).

The curricularization of extension in Engineering programs in Brazil is still evolving, particularly within traditional engineering disciplines (Oliveira-Melo et al., 2025). These authors emphasize the need for sustained institutional support, including coordinated policies, financial and cultural incentives, and approaches that consider local and regional specificities. The present study offers relevant guidelines for consolidating extension-oriented curricula in the Environmental Management course and related fields within the Environmental Sciences, including student and community engagement, reciprocal exchange of experiences between the University and the community, and the understanding of social, economic, cultural, and environmental aspects involved in decision-making alongside the recognition of barriers associated with changes in consumption habits.

5. Conclusions

The findings of this study highlight the social, economic, and cultural factors that influence decision-making in residential environmental management aimed at reducing the carbon footprint. These results underscore the relevance of university extension as a pedagogical tool for contextualizing the content of the Environmental Management course within the Environmental Engineering curriculum.

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7. Authors' Contributions

Gerson Araujo de Medeiros: All stages of the article were carried out by the lead author.

8. Conflicts of Interest

No conflicts of interest.

9. Ethics Approval

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