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Toru Kobayakawa and Tomohiko Ihara

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JICA Ogata Sadako Research Institute for Peace and Development, Japan International Cooperation Agency (JICA)
10-5 Ichigaya Honmura-cho, Shinjuku-ku, Tokyo, 162-8433, JAPAN
TEL: +81-3-3269-3374
FAX: +81-3-3269-2054

Infrastructure Development and Carbon Footprints of Household Consumption in India

Toru Kobayakawa* and Tomohiko Ihara†

Abstract

Infrastructure development plays a critical role in enhancing quality of life by providing essential services. However, it can also promote consumption and increase environmental burdens. While infrastructure may influence the sustainability of consumption through its effects on social practices, few empirical studies have comprehensively examined these impacts. This study focuses on Uttar Pradesh, India, and analyzes how household consumption behaviors differ across regions with varying stages of infrastructure development, including electricity, water supply, sewage systems, piped natural gas, and transportation. The study further investigates how these differences affect household carbon footprints (CF). The results indicate that regions with more advanced infrastructure exhibit higher household CFs, primarily due to increased electricity usage and fossil fuel consumption for transportation. To improve quality of life while mitigating environmental impacts, it is essential to offer options that facilitate low-CF consumption behaviors during the early stages of infrastructure development, particularly in the areas of electricity, housing, and transportation. Additionally, policy interventions and public awareness initiatives are needed to shape social practices that encourage sustainable consumption.

Keywords: Sustainable Consumption, Household Carbon Footprint, Infrastructure Development, Social Practice, Time Use

* Middle East & Europe Department, Japan International Cooperation Agency (JICA), Japan
† The University of Tokyo, Japan

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1. Introduction

Infrastructure development contributes significantly to improving people's quality of life. The development of such infrastructure as power grids, water supply and sewage systems, and transportation facilities is crucial for achieving the Sustainable Development Goals (SDGs) (Thacker et al. 2019; Kobayakawa 2021). At the same time, infrastructure encompasses a network function that facilitates the supply of goods and services (Larkin 2013), stimulating consumption and potentially increasing environmental burdens (Donaldson 2018; Lee Taherzadeh, and Kanemoto 2020; Wolfram, Shelef, and Gertler. 2012). Researchers warn that both the magnitude and extent of the negative effects from these supply systems are likely to intensify in the coming decades (Chappells et al. 2000; Shove, Chappells, and Van Vliet 2012; Hult and Bradley 2017).

While adjustments in supply systems are becoming increasingly important (Solér, Koroschetz, and Salminen 2020; Mont, Lehner, and Dalhammar 2022), consumers often have limited direct influence over how infrastructure is designed and operated. Instead, their consumption behavior is part of broader "social practices" shaped by social, cultural, and material contexts. Therefore, achieving sustainable consumption is not merely about individual lifestyle choices; it also requires a transformation in the broader social systems, including infrastructure (Sanne 2002; Mont, Lehner, and Dalhammar 2022).

On the other hand, infrastructure both shapes and is shaped by the conventions of a community of practice (Star 1999). Thus, infrastructure alone cannot drive sustainable consumption practices but needs to be integrated into social practices (Spaargaren 2011; Shove, Watson, and Pantzar 2012). The literature on sustainable consumption contains few studies on the potential for infrastructure to encourage consumers to replace unsustainable consumption with sustainable alternatives. For instance, research on the environmental impact of replacing car ownership with car-sharing services indicates that the number of consumers who have reduced their car ownership by participating in car-sharing schemes is notably low (Becker, Ciari, and Axhausen 2018).

Solér et al. (2020) highlight that infrastructure can promote sustainable consumption under certain conditions where material and institutional infrastructures mutually reinforce sustainable practices, making these alternatives integral to social behavior. To meet these conditions and achieve such transitions, future research in socio-technical transitions should more explicitly focus on studying infrastructure and social practice, as well as the challenges involved in transforming them. There is also a need for studies that explore intersections between different supply systems, such as electricity supply and housing, and how interactions and synergies between different sectors can be leveraged to promote change (Mont, Lehner, and Dalhammar 2022).

Despite this, empirical cross-sectoral studies on the impact of infrastructure development on consumption behavior remain scarce. Most empirical research on consumption behavior either focuses on advanced countries with well-established infrastructure or examines changes in consumption due to the development of individual sector-specific infrastructure (Loureiro et al. 2009; Hardinghaus, Lehne, and Kreyenberg 2016; Wu, Zhang, and Xu 2021). There is a need to pay more attention to developing countries, where infrastructure is still evolving, and to adopt a more holistic approach to understanding changes in consumption behavior.

This study aims to investigate how the state of infrastructure development influences consumption behavior and the resulting environmental impacts, with a particular focus on the relationship between infrastructure and social practices that have significant effects on household carbon footprints. Specifically, the study examines the state of supply systems in areas such as electricity, water supply, sewage, cooking fuel, and transportation in Uttar Pradesh, India, where infrastructure development is currently underway. The study will assess differences in consumption behavior and associated direct and indirect CO_2 emissions—i.e., carbon footprints (CF) —according to the varying states of infrastructure. Based on these findings, the study proposes policy recommendations to improve quality of life while minimizing consumption-based CO_2 emissions. Although there are various standards regarding how CF should be calculated, this study employs the definition of CF suggested by Wiedmann and Minx (2008), which considers direct and indirect CO_2 emissions[1] due to consumption activities without including other GHGs.

The rest of the paper is organized as follows: Section 2 introduces the data and methods employed. Section 3 and Section 4 present and discuss the results of the analyses, respectively. Section 5 summarizes the findings and discusses areas for future research.

2. Data and methods

2.1 Calculation of environmental impact

The concept of the "footprint" is used to measure the environmental impact caused by consumption. It quantifies the environmental burden generated in the supply chain due to the consumption of goods and services over their lifecycle. Many studies have been conducted to calculate the CF associated with household consumption using household survey data (Druckman and Jackson 2016; Steen-Olsen, Wood, and Hertwich 2016; Long et al. 2019). These studies have revealed a strong tendency for CF to increase with higher income levels, especially in relation to consumption in three areas: transportation, housing, and food. In this study, CF is used to quantify the environmental impact.

[1] Emissions of CO_2 include all fossil CO_2 sources, such as fossil fuel combustion, non-metallic mineral processes (e.g., cement production), metal (ferrous and non-ferrous) production processes, urea production, agricultural liming and solvent use. Sources and sinks from land use, land-use change, and forestry (LULUCF) are excluded.

2.1.1 Calculation of indirect emissions

For items purchased or procured from the market through household spending, CF can be calculated using the following formula and the input-output table (IOT), based on the amount of expenditure.

$$A = Z\hat{x}^{-1} \quad (1)$$

$$x = (I - A)^{-1}y \quad (2)$$

$$d = Sx = S(I - A)^{-1}y \quad (3)$$

Where:

A: Input coefficient matrix;

Z: Matrix representing the transaction amounts between industries;

x: Total production vector;

I: Identity matrix;

y: Expenditure amount;

S: CO_2 emission coefficient matrix;

d: Consumption-based environmental impact (CF)

The following adjustments are made to the expenditure amounts, taking into account the characteristics of the input-output table (IOT):

(1) To eliminate the effects of inflation, the expenditure data are adjusted to the IOT reference year using the consumer price index.
(2) The expenditure data are converted, along with the currency conversion if necessary, from consumer prices to basic prices by deducting transport and trade margins and tax rates. The margin matrix is used for this purpose.
(3) The import ratio for each product is calculated based on India's household final consumption. It is assumed that the import ratio for input products is uniform for each sector.

2.1.2 Calculation of direct emissions

Direct emissions from households arise from activities such as fuel use for cooking and gasoline consumption for private vehicles. When these fuels are consumed, direct emissions are calculated in addition to indirect emissions. First, the average fuel price for 2023—i.e., the year the survey was conducted—is obtained, and the quantity of fuel purchased is estimated from the amount paid. Direct emissions are then calculated by multiplying the emission factor for each fuel type by the amount of fuel purchased. The average fuel price in 2023 and the emission factor for each fuel type are shown in Table 1 (PPAC 2024; GGL 2024 WRI 2017). Since the distinction between gasoline and diesel vehicles was not made during the survey, all vehicles, both four-wheelers and two-wheelers, are assumed to use gasoline as it is the predominant fuel in the region. When firewood was used as fuel, neither indirect nor direct emissions were calculated, as it is considered carbon neutral.

Table 1: Data used for calculating direct emissions of CO_2

Fuel type	Average retail price in 2023	Emission factor
Gasoline	96.72 (INR/L)	2.27 (kg-CO_2/L)
LPG (Liquified Petroleum Gas)	1048.8 (INR/cylinder)	42.3 (kg-CO_2/cylinder)
PNG (Piped Natural Gas)	57.43 (INR/m3)	1.885 (kg-CO_2/m3)

Source: PPAC, GGL, and WRI

2.2 Data

2.2.1 Multi-Region Input-Output (MRIO) model

This study's primary data source is the EXIOBASE-3 database, a set of global MRIO tables that cover 44 specific countries and five regions with 200-sector classification per country and include a continuous time series from 1995 onwards (Stadler et al. 2018). EXIOBASE-3 is adopted for this study because, compared to other MRIO models, it has a more detailed sector classification with 200 sectors, allowing for more granular analysis, and it includes India among its 44 countries. The latest version of the EXIOBASE-3 (ver. 3.8.2) table for 2022[2] is used in this study.

2.2.2 Questionnaire survey

To obtain expenditure data, a questionnaire survey was conducted in December 2023 in Lucknow, Uttar Pradesh. The survey included responses from 281 households using the following sampling procedure:

(1) The locations of the interviews were selected in urban, suburban, and rural areas to the west and south of Lucknow so that they were at least 2km apart from each other;

(2) At each location, 10–20 households were selected for interviews. During the selection process, observations were made on the appearance of their dwellings, vehicles, and farmland so that the interviews could target households with various income levels.

[2] https://zenodo.org/records/5589597

(3) The structured interviews were conducted using the pre-prepared questionnaire. The main survey items are shown in Table 2.

Lucknow, the state capital, is a radiating city located in the center of Uttar Pradesh, where grid electricity is already supplied to virtually all the households while the development of water supply and sewage systems, piped natural gas (PNG), and a metro system has been progressing rapidly from the center of the city towards its suburban areas. This allows for the efficient capture of household consumption across various stages of infrastructure development by undertaking the survey in this area.

Table 2: Main survey items

Items	Collected data
Demographic data	family size; location; income level; etc.
Infrastructure availability	grid power; water supply; sewerage; piped natural gas; metro
Expenditures	expenditures on food; housing (electricity, water and sanitation, cooking fuel, etc.); transport; and other services (education, health, clothing, etc.)
Energy use	Ownership of personal vehicles, electric appliances, etc.
Travel mode	Transportation measures for commuting, going shopping, etc.
Time use	Daily time use of male and female heads

Source: Author's interview record

3. Results

3.1 Overview of each area

It was revealed that, from the outskirts of the city towards the city center, infrastructure is developed in the order of water supply, sewage systems, piped natural gas (PNG), and metro lines (Figure 1). This pattern reflects the gradual expansion of services as the city of Lucknow, the capital of Uttar Pradesh, undergoes intensive development. The survey areas are categorized as follows: Area 1 refers to regions where only electricity is supplied, Area 2 includes regions where water supply services are available in addition to electricity, Area 3 extends to regions with sewage services, and Area 4 consists of regions where PNG is provided (Table 3).

Currently, intensive infrastructure development is ongoing in the city, making it challenging to pinpoint exact service areas. However, information on service availability was gathered through interviews with local residents. Notably, the metro system is already operational in the city center and covers parts of Areas 3 and 4.

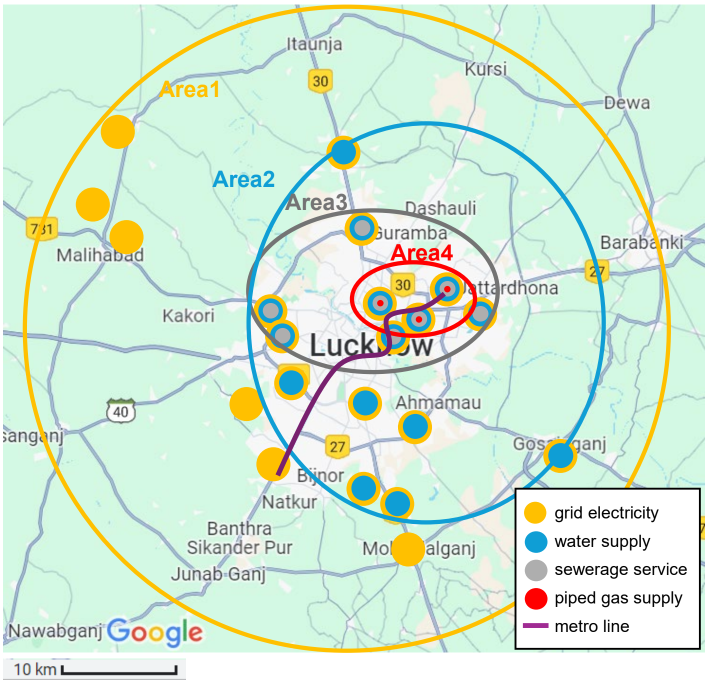

Figure 1: Distribution of Surveyed Households

Source: Google Maps (2024) and Author's interview record

Table 3: Sample sizes of each area

Area	Available infrastructure	Sample size
1	- Grid power	144
2	- Grid power - Water supply	42
3	- Grid power - Water supply - Sewer collection - Metro	67
4	- Grid power - Water supply - Sewer collection - Piped natural gas - Metro	38
	Total	281

Source: Author's interview record

3.1.1 Outline of Area1

This area is the farthest from the city center of Lucknow (Figure 2), with only electricity supply provided as infrastructure. For the interviews in this area, 144 households were selected. In Uttar Pradesh, nearly all households have access to electricity, and the use of kerosene lamps, which were commonly used before electrification, has been prohibited. With electrification, indoor air quality has improved, and the brightness and convenience have increased. Various household appliances have also become usable. In this area, the most common method of obtaining water is through hand pumps from wells, with 60% of the surveyed households having a pump installed within their property, while 40% use public water taps. Regarding sanitation, 70% of the households use pit latrines, but a certain number of households still practice open defecation (Figure 3).

Figure 2: Typical street view of Area 1

As for cooking fuel, nearly all households use LPG, but more than half of them also use fuelwood. More than 20% of households use electricity for cooking with devices like induction heaters (Figure 4).

For transportation, the breakdown of commuting and school transportation methods, considering all household members who commute or attend school, is shown in Figure 5. It is clear that household heads commonly use two-wheelers for commuting, while bicycles, walking, and school buses are the main means of school transportation. Figure 5 also shows the breakdown of transportation methods used for daily activities other than commuting and school trips, such as shopping. It is evident that two-wheelers are the primary means of transportation.

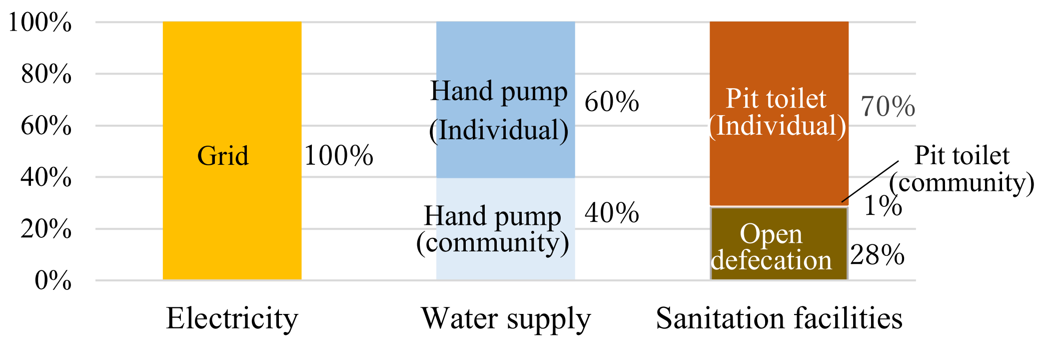

Figure 3: Electricity, water and sanitation (Area 1)

Source: Author's interview record

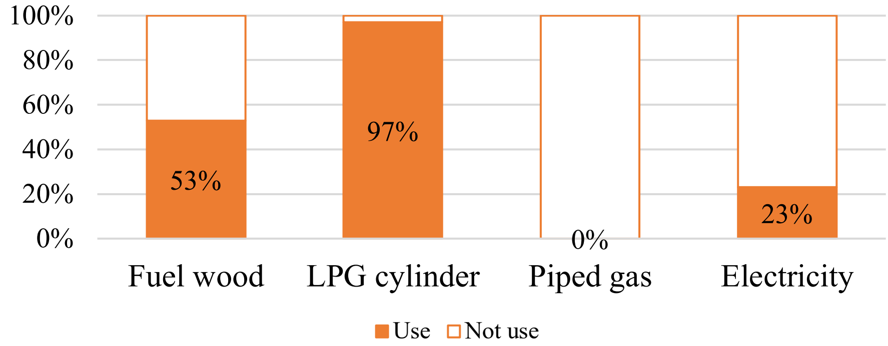

Figure 4: Cooking fuel (Area 1)

Source: Author's interview record

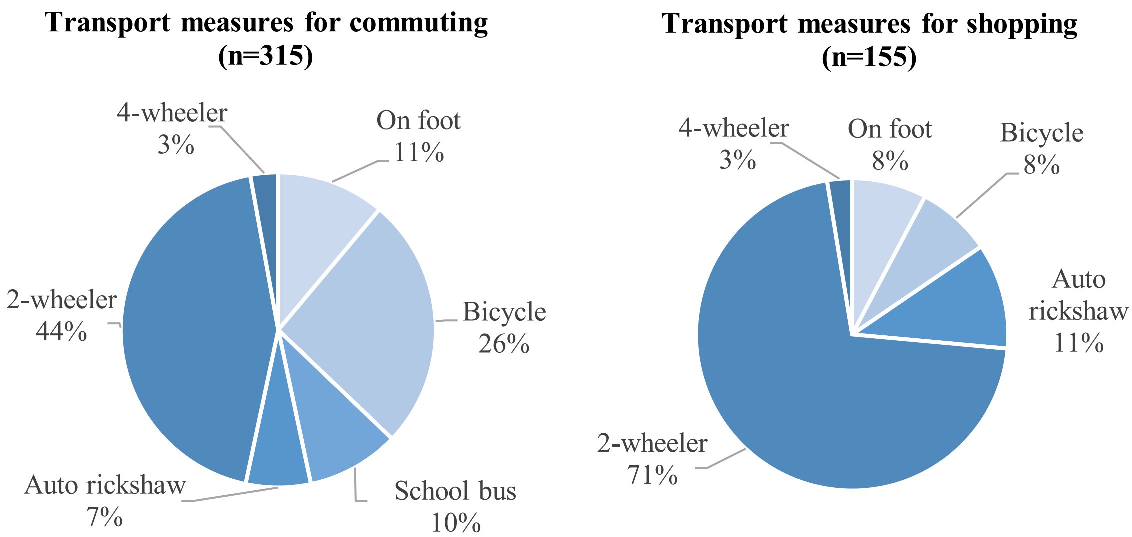

Figure 5: Transport measures for commuting and shopping, etc. (Area 1)

Source: Author's interview record

3.1.2 Outline of Area 2

In the area between approximately 10 to 20 kilometers from the center of Lucknow (Figure 6), a water supply system has been established, significantly reducing the time and labor required to collect domestic water. Furthermore, in areas around Lucknow where there are issues with groundwater contamination and over-extraction (Verma et al. 2013; Sinha 2021), these problems have been resolved in regions where the water supply system has been developed. For the interviews, 42 households were selected in this area. Over 70% of the households have a private water connection, while the rest use public water taps. All surveyed households receive electricity

Figure 6: Typical street view of Area 2

from the power grid and have installed pit latrines in their homes (Figure 7).

Regarding cooking fuel, nearly all households use LPG, although about 20% still also use fuelwood. Approximately half of the households use electricity for cooking with devices like induction heaters, a larger share than in Area 1 (23%) (Figure 8).

There is not much difference in transportation compared to Area 1, but the use of four-wheelers for commuting, schooling, and shopping is slightly higher (Figure 9).

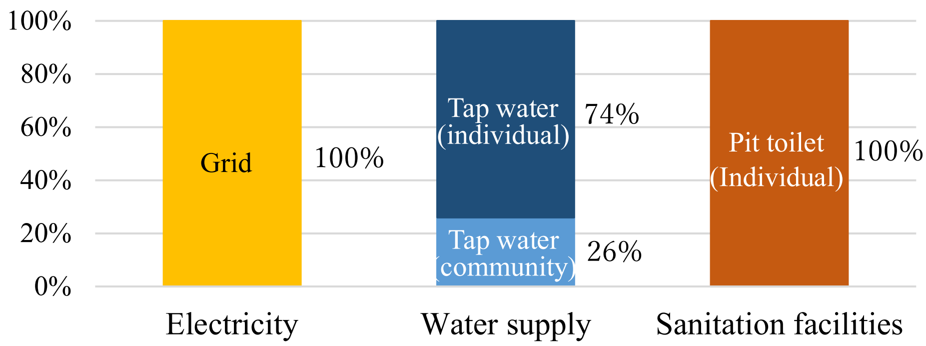

Figure 7: Electricity, water and sanitation (Area 2)

Source: Author's interview record

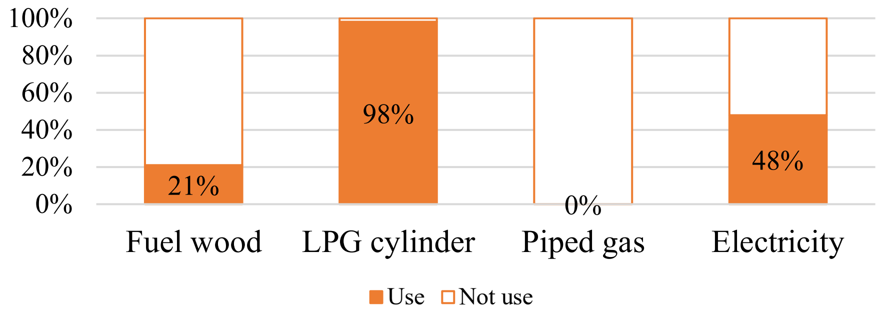

Figure 8: Cooking fuel (Area 2)

Source: Author's interview record

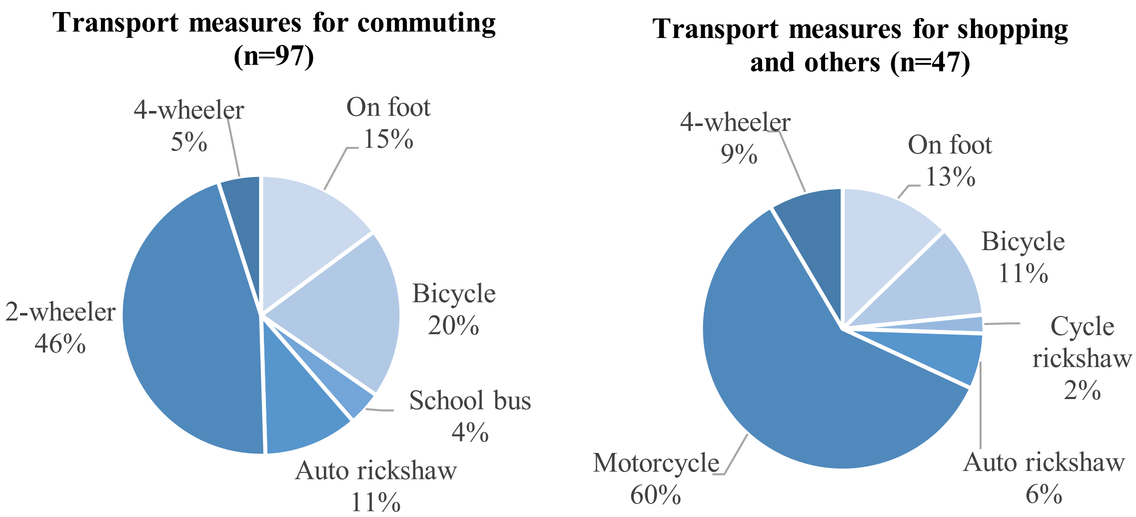

Figure 9: Transport measures for commuting and shopping, etc. (Area 2)

Source: Author's interview record

3.1.3 Outline of Area 3

As we move closer to the city center of Lucknow (Figure 10), the development of a sewer system has led to the installation of flush toilets in almost all households, reducing environmental pollution in the surrounding area and rivers. For the interviews in this area, 67 households were selected. All households receive electricity from the power grid, and about 80% have a private water connection, while the remaining 20% use public water taps. Although rare, some households do not have flush toilets in their homes and use public flush toilets instead (6%) (Figure 11).

Figure 10: Typical street view of Area 3

For cooking fuel, all households use LPG, and no households use fuelwood. About half of the households use electricity for cooking, similar to Area 2 (Figure 12).

Regarding transportation, the use of four-wheelers for commuting, schooling, and shopping is at a higher rate compared to Area 2, but the overall use of privately owned vehicles, including two-wheelers, is slightly lower. Instead, the use of public transportation, such as buses and auto-rickshaws, is a little more common. In some parts of Area 3, the proximity to metro stations has resulted in a small percentage of households using the metro (Figure 13).

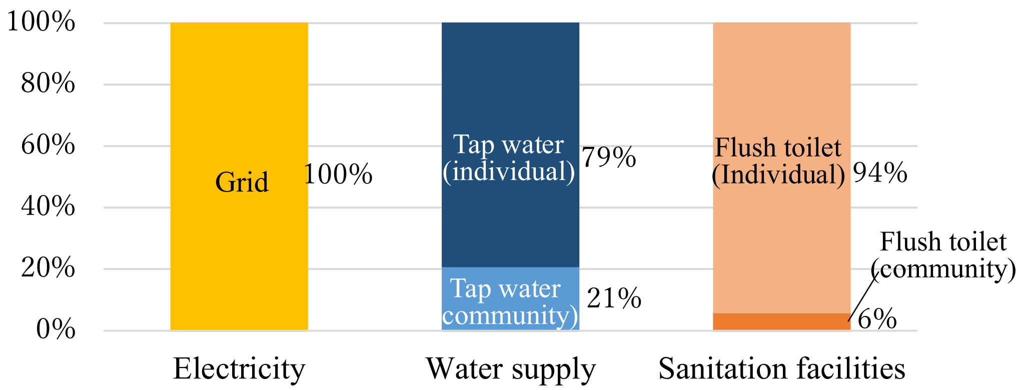

Figure 11: Electricity, water and sanitation (Area 3)

Source: Author's interview record

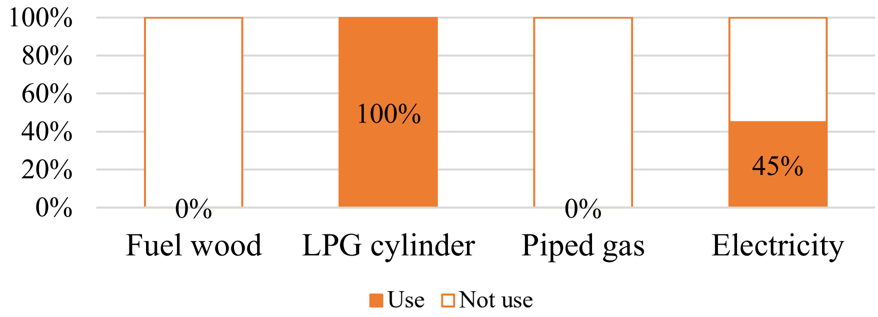

Figure 12: Cooking fuel (Area 3)

Source: Author's interview record

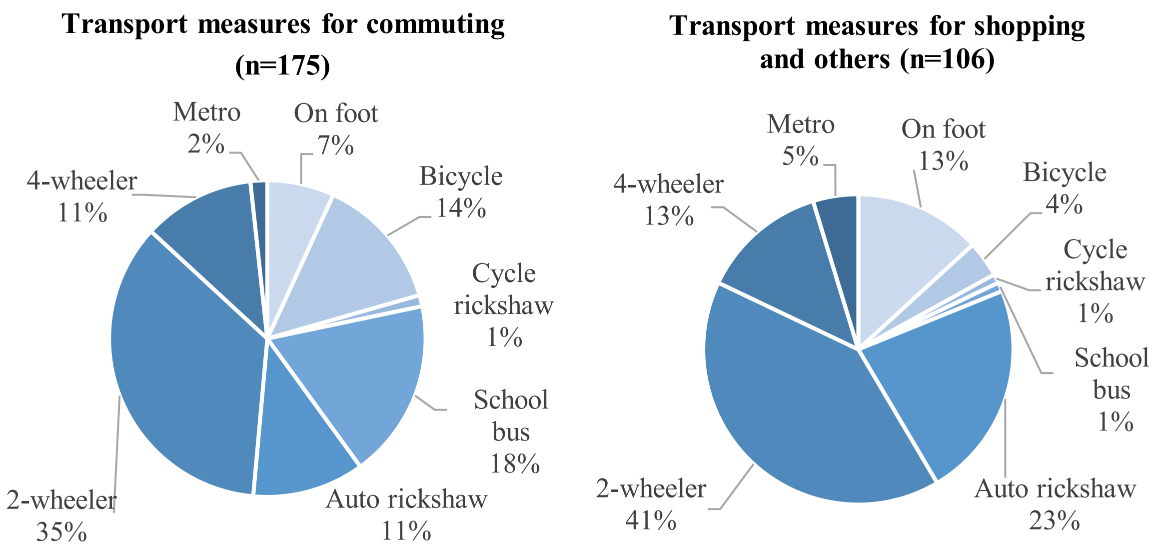

Figure 13: Transport measures for commuting and shopping, etc. (Area 3)

Source: Author's interview record

3.1.4 Outline of Area 4

In the most central part of Lucknow (Figure 14), a piped natural gas (PNG) network has been developed, and all households use PNG for cooking. However, since many areas have only recently gained access to PNG and supply remains unstable, more than half of the households continue to use LPG alongside it. In this area, 38 households were selected for the interviews. All households receive electricity from the power grid, nearly all have private water connections, and every household has a flush toilet (Figure 15).

Figure 14: Typical street view of Area 4

Regarding cooking fuel, in addition to PNG and LPG, 76% of households also use electricity for cooking, the highest share among all areas (Figure 16).

As for transportation, bicycles have disappeared as a commuting and shopping option, with the use of four-wheelers and the metro being more prevalent (Figure 17).

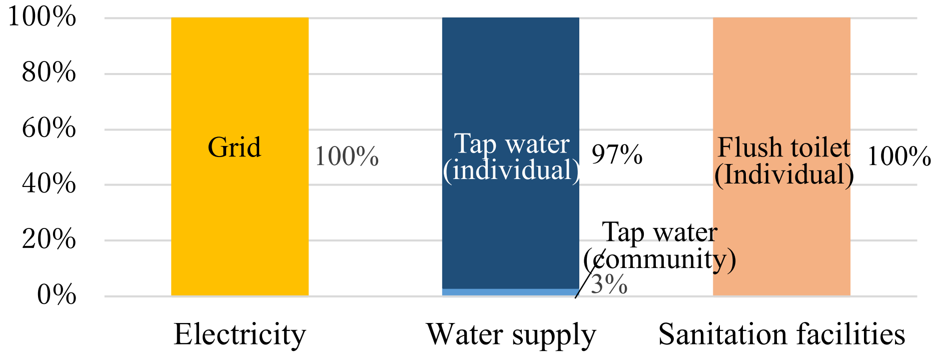

Figure 15: Electricity, water and sanitation (Area 4)

Source: Author's interview record

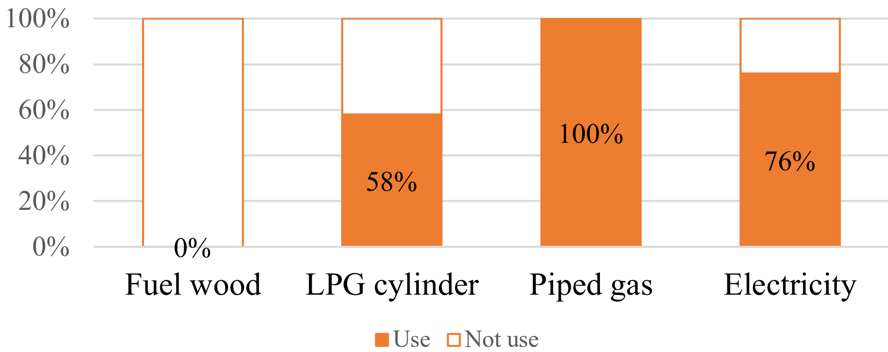

Figure 16: Cooking fuel (Area 4)

Source: Author's interview record

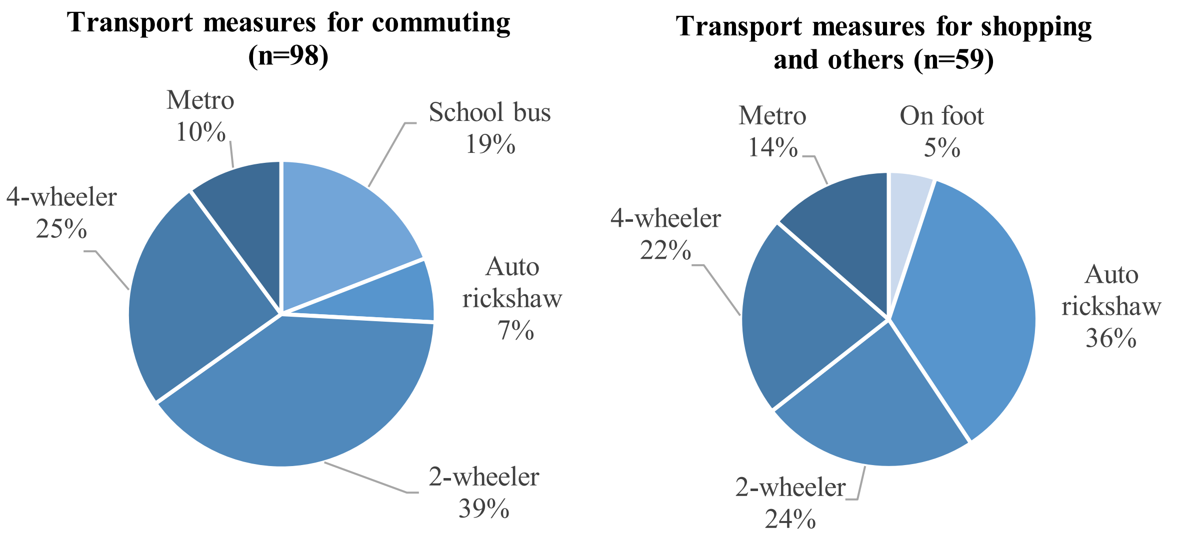

Figure 17: Transport measures for commuting and shopping, etc. (Area 4)

Source: Author's interview record

3.2 Calculation results of carbon footprint

The annual per capita expenditures by category, based on survey results for each area, are shown in Figure 18. The per capita direct and indirect CO_2 emissions calculated from these expenditures are also shown in Figure 19. According to previous research (Lee, Miguel, and Wolfram 2021), the average per-capita household CF in India ranges from around 0.3 to 1.5 t-CO_2/year, depending on their income levels, and the results of this study reveal that the CF levels are generally consistent with this range. As CF increases from Area 1 to Area 4, it is evident that households closer to the city center exhibit higher CF levels, influenced by various factors, including differences in infrastructure development and income levels.

Among the various types of infrastructure, the electricity network system contributes the most to the increase in CF, with its share being the largest in all areas. This is likely due to the high emission factor of electricity, as India's energy mix relies heavily on coal-fired power plants. Furthermore, as infrastructure improves, the use of electricity increases significantly. The next section provides a more detailed examination of electricity consumption by area to explore the reasons behind this increase.

Transportation is the second-largest contributor to CF after electricity. Even in rural areas, two-wheelers are widely used for commuting, schooling, and shopping (Figure 5). As we move closer to the well-developed city center, the ownership of private four-wheelers increases (Figure 17), leading to greater fossil fuel consumption. Additionally, households in Area 4 tend to have relatively higher incomes, resulting in more frequent and longer travel for leisure. Travel by air also significantly contributes to the increase in CF. The next section will examine transportation-related expenditures in more detail to investigate the reasons for CF growth.

In the areas around Lucknow, use of LPG is already relatively widespread, even in rural areas (Figure 4), so the shift from LPG to PNG, along with the development of piped gas infrastructure, is progressing (Figure 16). Since the amount of energy required for cooking does not change significantly when switching from LPG to PNG, there is little evidence of an increase in CF-related cooking due to piped gas infrastructure development. Because piped gas infrastructure is still relatively new in Lucknow, supply remains unstable in some areas. As supply stabilizes over time, the shift from LPG to PNG may be facilitated. However, as long as its use is limited to cooking only, a rise in CF would not be expected.

There is little difference in CF from food consumption across areas based on the level of infrastructure development. While spending on dining out slightly increases in Areas 3 and 4, it does not result in a significant difference in CF. The development of water and sewage infrastructure greatly improves convenience and sanitation, but the associated CF is negligible. The "Other" category includes CF attributable to spending on clothing and services such as medical care, education, and communication. Although spending and CF in these categories tend to increase closer to the center of Lucknow, it is unlikely that infrastructure development is the cause; rather, income level differences play a more significant role.

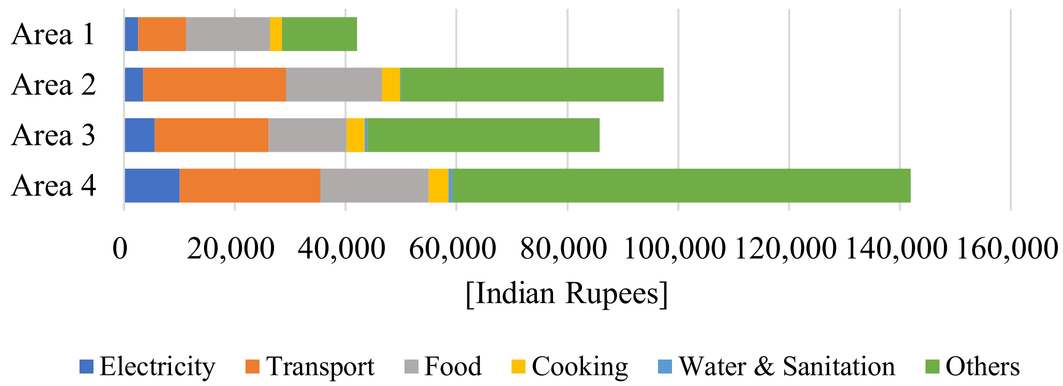

Figure 18: Per-capita annual expenditure

Source: Author’s calculation

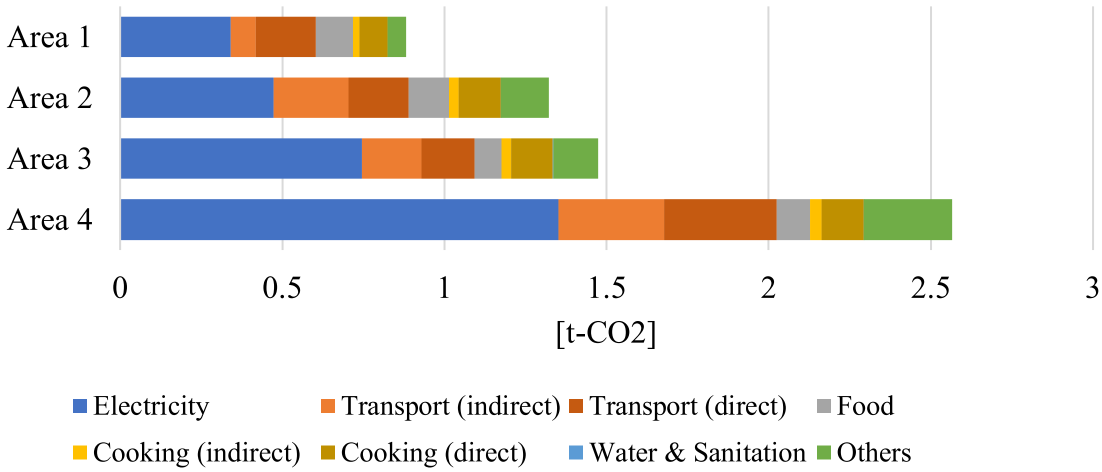

Figure 19: Per-capita annual carbon footprint

Source: Author's calculation

4. Discussion

As mentioned in the previous section, this section examines the reasons behind the increase in electricity consumption and CFs related to transportation, which are the main factors contributing to the rise in the total CFs vis-à-vis infrastructure development. Further, based on survey results regarding time use and consumption intentions in each region, the relationship between time use and energy consumption, as well as the relationship between consumer intentions and the state of infrastructure development, are analyzed. Based on these analyses, the possible interaction between infrastructure development and consumption patterns are discussed from the perspective of social practice.

4.1 Factors contributing to the increase in electricity consumption

4.1.1 Increased use of appliances for air conditioning

The household ownership rates of summer appliances such as fans and evaporative coolers do not vary significantly by region. However, the ownership rates of air conditioners and winter electric heaters increase significantly as households are closer to the city center (Figure 20). In particular, the ownership rate of air conditioners is exceptionally high in Area 4, contributing to the increase in electricity consumption. Studies have indicated that urbanization is advancing in the Lucknow city area (Areas 3 and 4), with the heat island effect increasing as well (Saumya and Rashmi 2023). The accumulation of commercial buildings and multi-family residences is likely driving up the ownership rate of air conditioners. Additionally, differences in income levels lead to differences in the number of rooms per household, particularly in Area 4, where the number of rooms per person is the highest (Table 4). This results in a multiplicative increase in electricity demand for heating and cooling in the area.

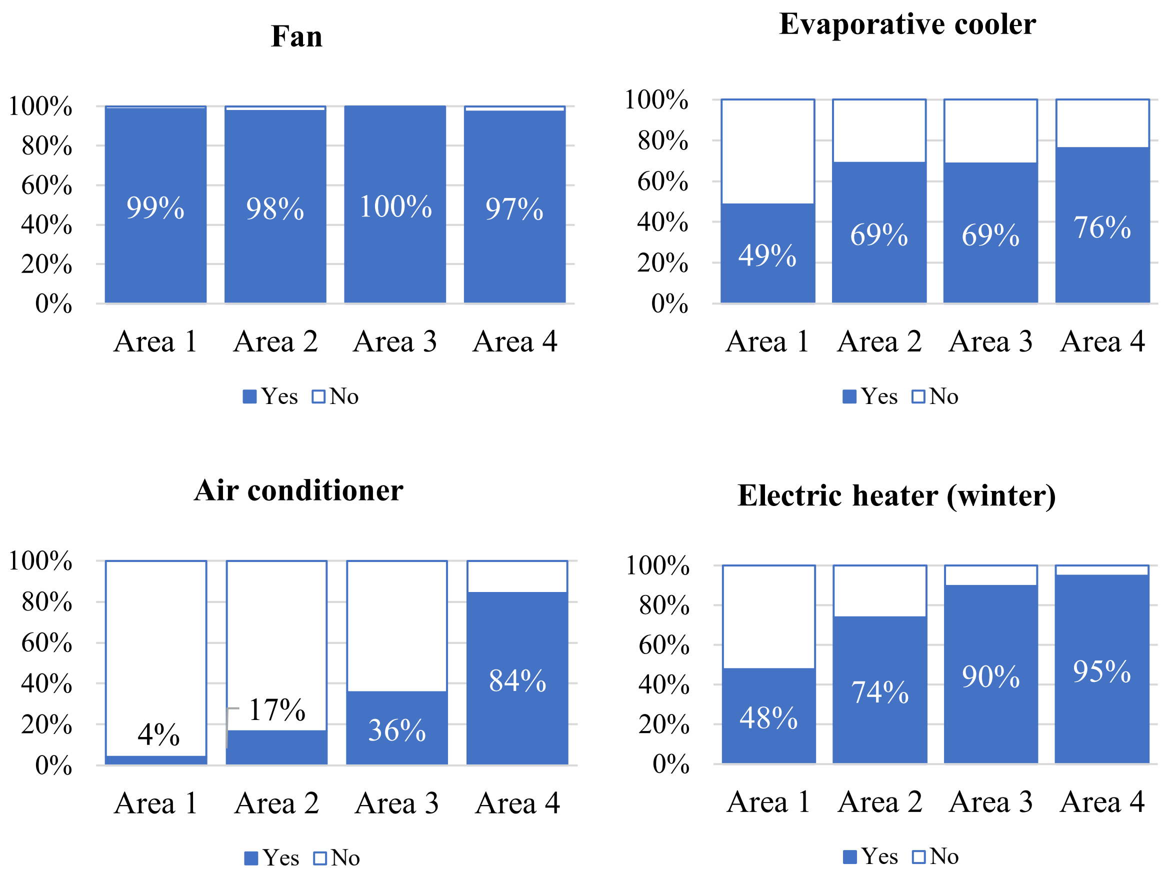

Figure 20: Per household ownership of air conditioning appliances

Source: Author's interview record

Table 4: Average number of rooms per person

	Area 1	Area 2	Area 3	Area 4
Number of people per household	4.1	4.9	5.2	5.0
Number of rooms per household	3.2	3.8	3.9	5.1
Average number of rooms per person	0.8	0.8	0.8	1.0

Source: Author's interview record

4.1.2 Replacement of fuel wood with electricity for water heating

In rural and suburban areas such as Areas 1 and 2, fuel wood is primarily used to heat water for bathing. However, in Area 3, the use of fuel wood has become rare, and in Area 4, nearly all water heating is done with electricity (Figure 21). In India, electric water heaters, known as "geysers," are predominantly used, which is likely contributing to the increase in electricity consumption. Areas 3 and 4 are urbanized areas where it becomes difficult to find and burn fuel wood due to environmental conditions. Starting from Area 2, with the development of water infrastructure, the availability of both electricity and water infrastructure makes water heating very convenient, but it also creates a circumstance conducive to increased electricity consumption. A similar trend is observed in cooking fuels, where fuel wood is no longer used in Areas 3 and 4, while electricity usage increases (Figures 12 & 16).

While the reduction of fuel wood use is desirable from the perspective of preventing forest degradation, in a case like India, where most electricity comes from fossil fuels, this may lead to an increase in CF.

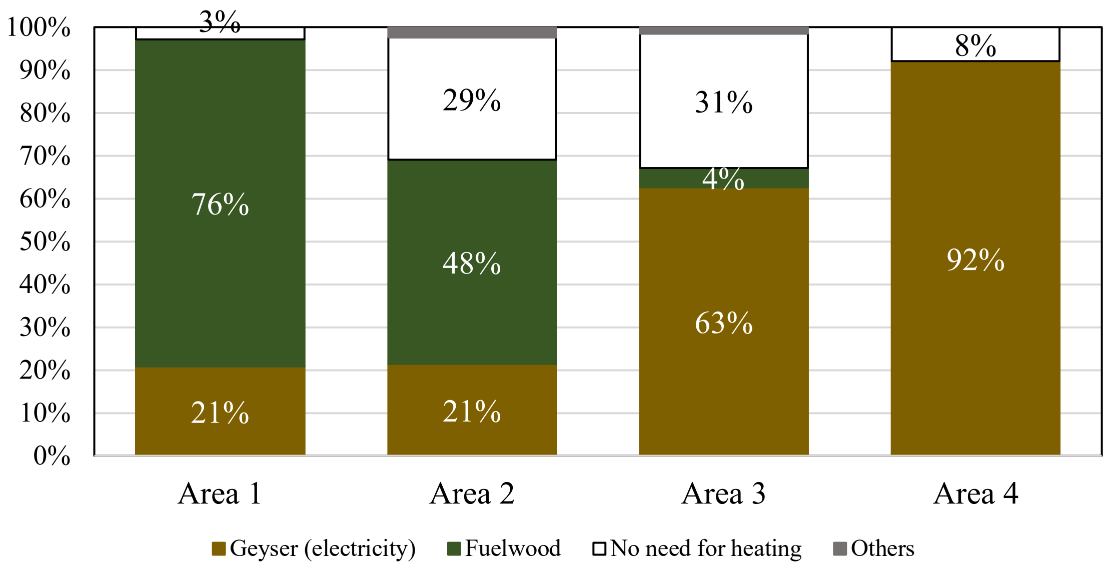

Figure 21: Fuel use for heating water for bathing

Source: Author's interview record

4.1.3 Increased use of other household appliances

The household ownership rates of electrical appliances that are likely contributing to the increase in electricity consumption are illustrated in Figure 22. There is a trend toward increased ownership of these appliances among households closer to the city center. The use of these appliances brings benefits such as a reduction in household labor and a decrease in the time required for household tasks. While the purchase and use of these time-saving appliances incur costs, including electricity fees, they are considered worthwhile when the benefits outweigh these costs (Binswanger 2004).

The adoption of time-saving technologies for general household purposes is anticipated to have a dual effect on energy consumption in the residential sector. First, the increased use of such technologies for basic tasks like cooking and cleaning can directly raise energy consumption, as many time-saving devices tend to be more energy-intensive than those requiring more time investment. Second, these technologies free up time for household members, potentially increasing the frequency of certain activities (e.g., preparing more meals at home as cooking becomes quicker) or allowing them to engage in other tasks or leisure activities (like watching TV, reading, or traveling), which may or may not demand additional energy. To the extent that time is reallocated to energy-intensive activities in the home, residential energy use will increase as households adopt time-saving appliances (Brenčič and Yound 2009).

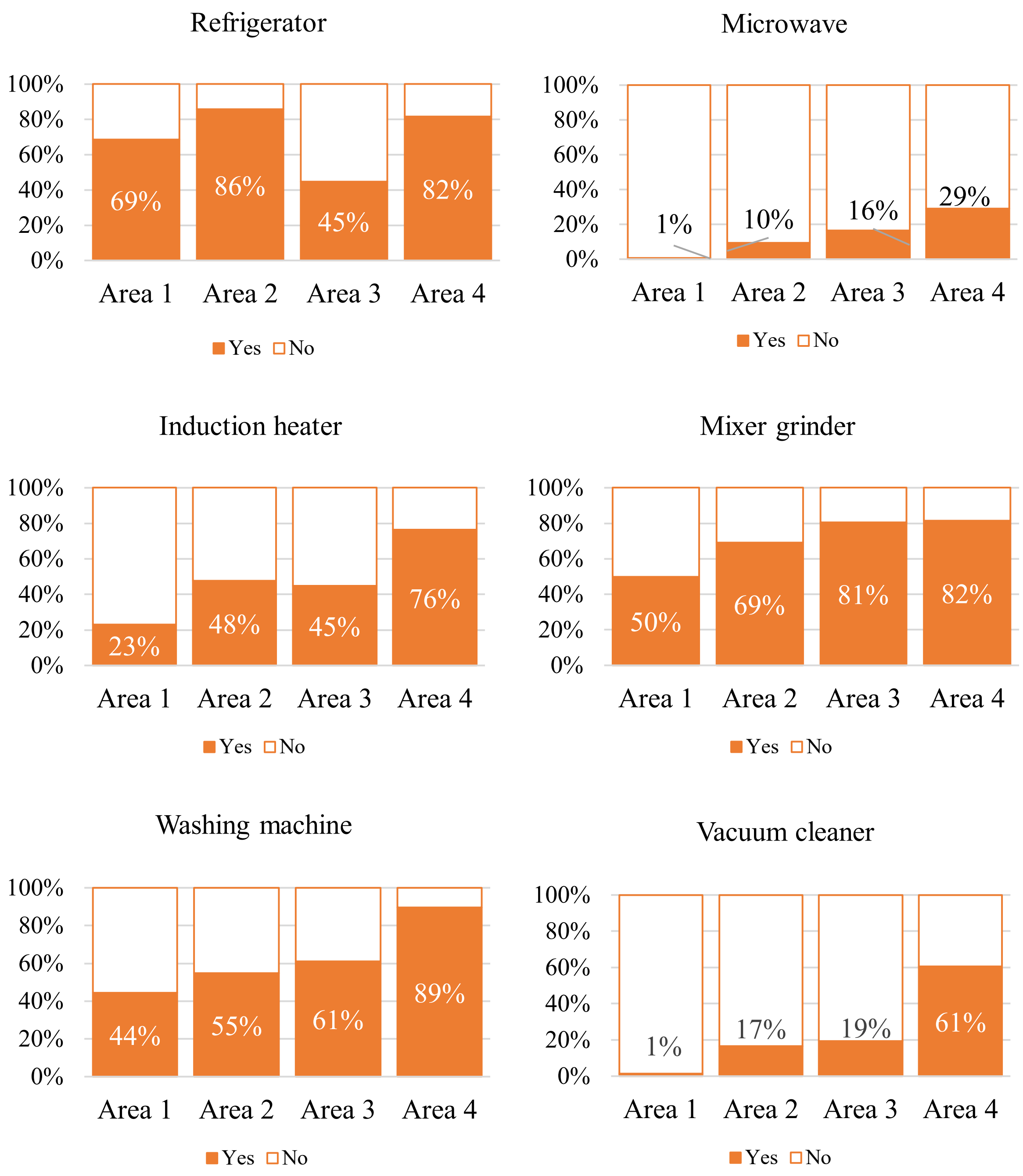

Figure 22: Ownership of other household appliances

Source: Author's interview record

4.1.4 Reduction in household chore time

To confirm whether the household ownership rates of electrical appliances are related to the time spent on household chores, interviews were conducted with the heads of households and their spouses regarding their daily time use by region (Figure 23). According to the survey results, the amount of time male heads spend on household chores shows little variation across regions, averaging between 2.8 and 3.9 hours per day, which is significantly less than female heads, who spend 7.4 to 9.7 hours on similar tasks. Notably, female heads of households in Area 4 reported an increase in time allocated for employment, resulting in less time available for housework. This may be attributed to their practice of using more electric appliances for time-saving purposes (Greenwood and Seshadri 2005).

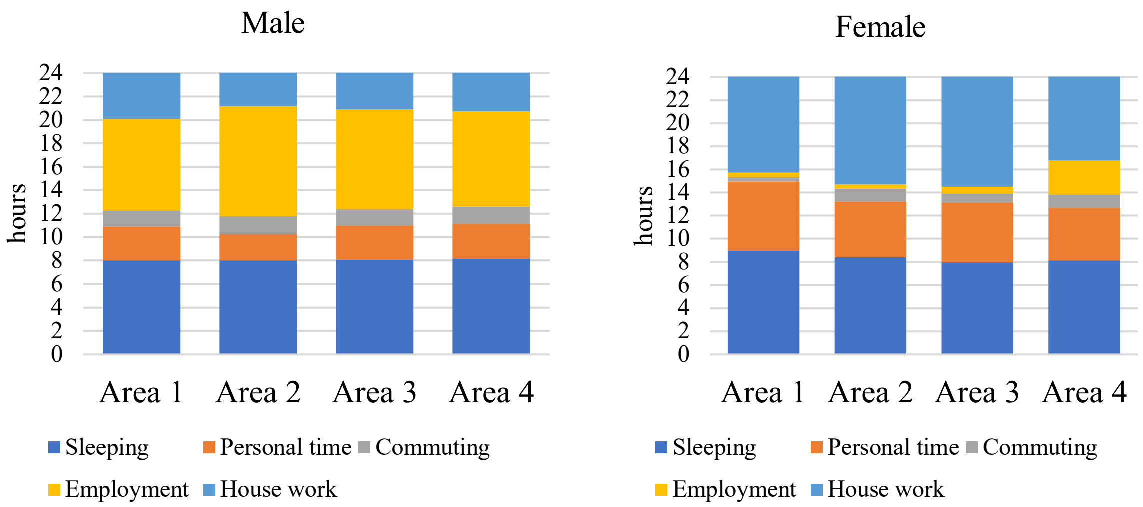

Figure 23: Average daily time-use of household heads

Source: Author's interview record

In addition to the six appliances illustrated in the Figure, an electric iron was added to classify a total of seven appliances as "time-saving appliances." The correlation coefficients between the number of appliances owned, the working hours of the household heads, household chore time, and total per-capita household expenditure were calculated (Table 5). There is a trend of increasing appliance ownership as working hours increase and household chore time decreases, although the correlation is not statistically significant. In contrast, the correlation with total expenditure level is strong, indicating that households with greater economic strength tend to have a higher ownership rate of appliances.

In households with weaker economic power, it is possible that female heads are compelled to work, which results in insufficient time for household chores, but they lack the purchasing power to buy many appliances. This suggests that the inverse correlation between household chore time and appliance ownership is not necessarily strong. In other words, the dominant factor influencing the ownership rate of appliances is the household's purchasing power. Even in cases where sufficient household chore time is available, households with greater economic strength are more likely to purchase a greater number of appliances to reduce household labor. Among these housewives with increased time availability, some will enter the workforce and allocate more time to paid work.

Table 5: Correlation coefficients

	Number of time-saving appliances owned
Time allocated for employment by the female head	0.244
Time allocated for housework by the female head	-0.025
Household total per-capita expenditure	0.735

Source: Author's calculation

4.1.5 Communication and entertainment

The household ownership rates of electrical devices used for communication and entertainment were also surveyed (Figure 24). The electricity consumption associated with the use of these devices is considered relatively low, and the contribution of CF from communication services does not constitute a significant proportion of the total. However, an increase in energy use from these activities is still unignorable, particularly when the surplus time created by the ownership of time-saving household appliances is directed toward them (rebound effect).

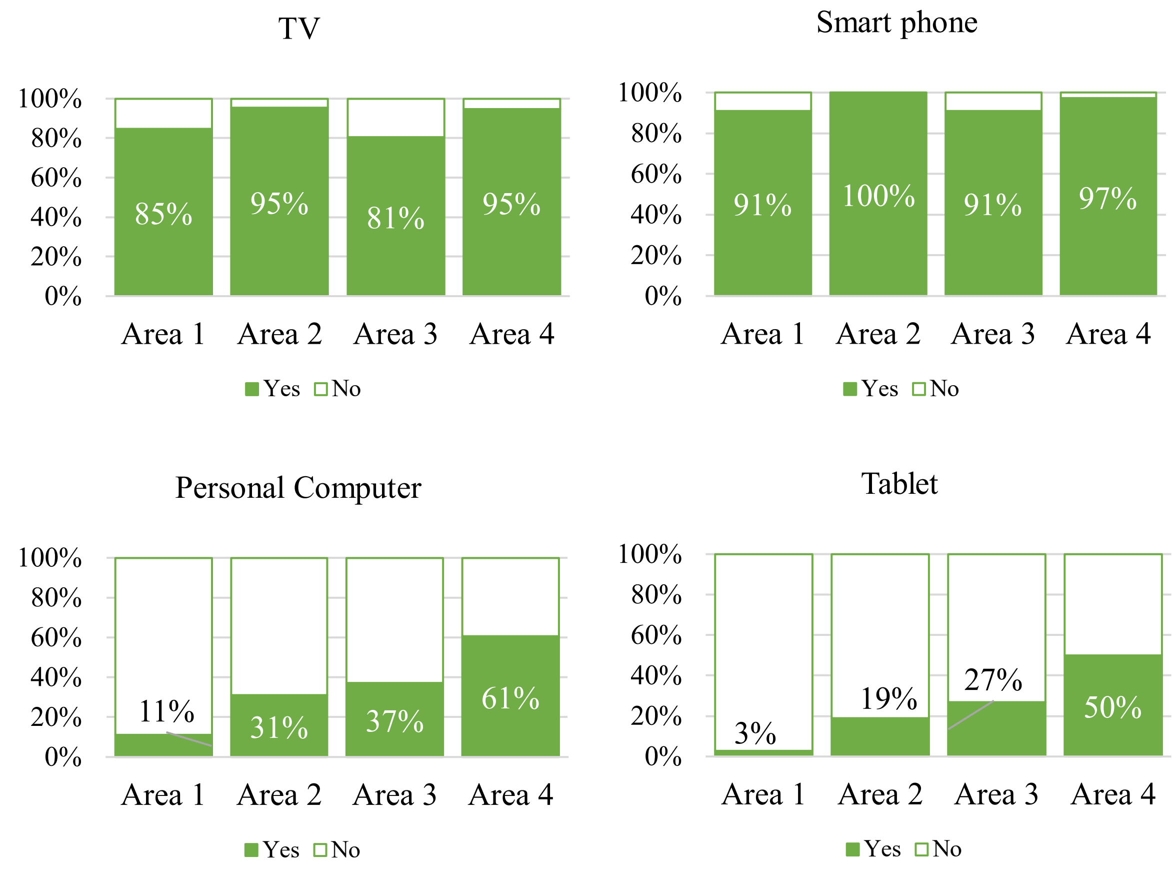

Figure 24: Ownership of electrical devices for communication and entertainment

Source: Author's interview record

4.2 Factors contributing to the increase in carbon footprint from transportation

Figure 25 presents the direct and indirect CO_2 emissions associated with transportation, including commuting, shopping, medical visits, and occasional long-distance travel, such as visiting relatives several times a year. As shown in Figures 5, 9, and 13, the proportion of four-wheeler use becomes gradually higher from Area 1 to Area 3, but this does not lead to a significant increase in direct and indirect emissions. In Area 4, however, there is a substantial increase in emissions due to personal vehicle usage, which is likely related to the significant rise in ownership and use of four-wheelers in that area (Figure 26).

It has also been found that households in Area 4 that use the metro for commuting or schooling pay slightly less (about 8%) in monthly gasoline expenses compared to those who do not use the metro, which is equivalent to an annual reduction of 0.04 t-CO_2 of per-capita CF (direct and indirect emissions combined). This suggests that promoting the use of public transportation, such as metros, may contribute to reducing the carbon footprint.

From Area 2 to Area 4, the carbon footprint associated with the use of auto-rickshaws, buses, trains, and subways has increased. However, these uses are largely for occasional long-distance travel rather than for daily commuting or shopping. In Area 2, although there is no metro, the carbon footprint from train travel during long-distance trips is accounted for. In Area 4, the longer distances for these trips often involve air travel or maritime transport, which further adds to the carbon footprint.

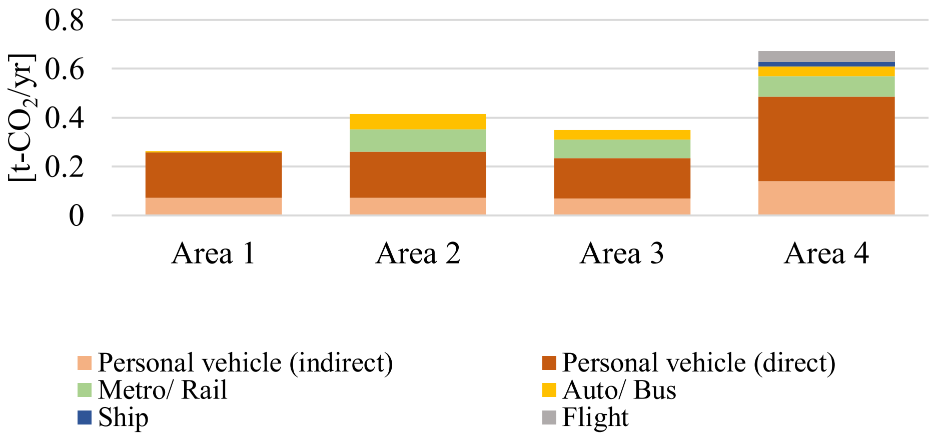

Figure 25: Carbon footprint from transport

Source: Author's interview record

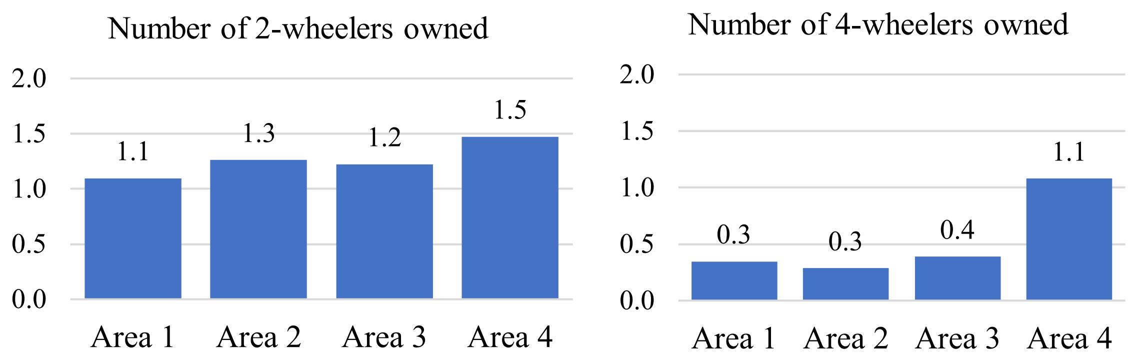

Figure 26: Average number of privately owned vehicles
Source: Author's interview record

4.3 Consumer Intent Survey

The following three questions were asked of the respondents during the survey: "(i) What would you like to purchase if your household income increased?; (ii) what would you like to do if you had more free time?; and (iii) what would you like to request to the government regarding infrastructure improvements?"

The answers to the 1st question are shown in Figure 27. The proportion of households wishing to purchase or renovate housing is the highest in all areas, followed by those wishing to purchase a means of transportation, such as two-wheelers or four-wheelers.

The answers to the 2nd question are shown in Figure 28. Area 1 shows that the most common response is to increase involvement in agriculture. This is likely due to the fact that a significant number of households in this area are already engaged in agriculture or growing their own crops. In the other areas, the most common responses are to travel or spend time with family/friends. The resultant CF would vary significantly depending on which of these two options is chosen, so it may be beneficial to encourage the latter, which has a lower CF as far provided there is no need to travel far.

Regarding requests for infrastructure improvements to the government (Figure 29), about half of the households in Area 1 wish for road improvements, followed by a desire for improvements in sewage and drainage facilities. In Area 2, the most common request is for improvements to water supply infrastructure, followed by road and sewage/drainage improvements at almost the same rate. In Area 3, the primary concern is sewage and drainage improvements, while in Area 4, the focus is on expanding medical services, with an increased demand for housing improvements for impoverished households. This suggests that disparities may be widening in Area 4 while infrastructure development has largely been completed.
Area 2 and Area 3 have recently established their water supply and sewage systems, which may

temporarily lead to higher demands for improvements due to insufficient service quality. As shown in Table 6, in Area 4, the stability of electricity and water supply has increased, and there are no requests for service improvements. Interestingly, from Area 1 to Area 4, the demand for road improvements inversely correlates with the number of owned two-wheeled and four-wheeled vehicles (Figure 26). As road conditions improve, there may be an increase in the number of personal vehicles and travel distances, and vice versa. It seems that previously underdeveloped infrastructure had served as a bottleneck limiting consumption, but improvements in infrastructure have led to increased consumption.

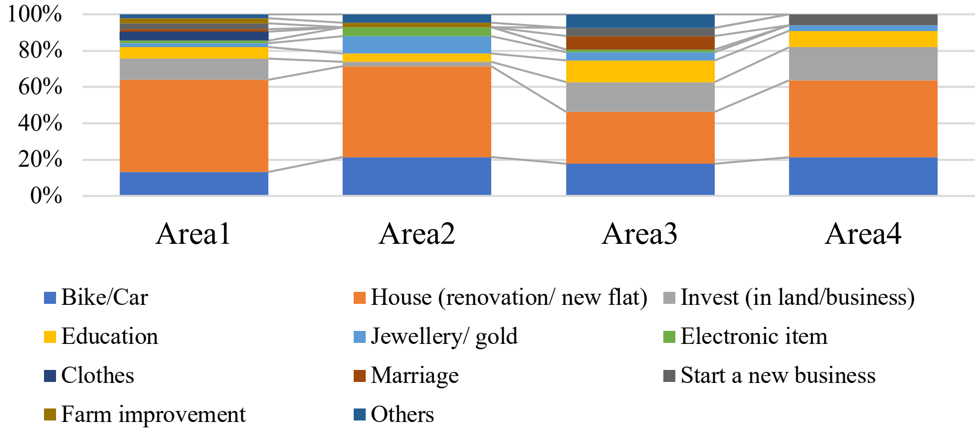

Figure 27: What would you like to purchase if your household income increases?

Source: Author's interview record

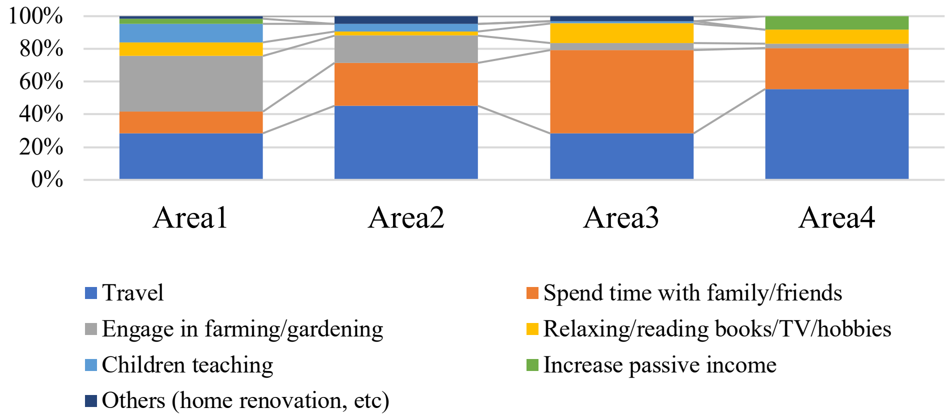

Figure 28: What would you like to do if you have more free time?

Source: Author's interview record

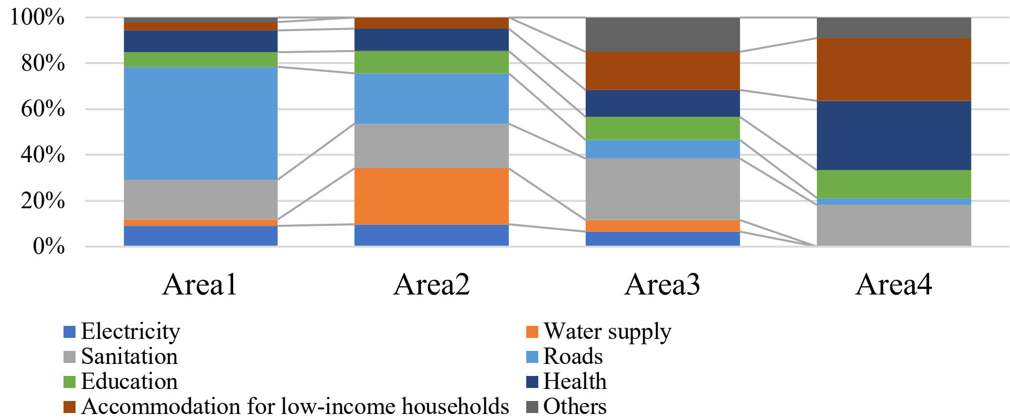

Figure 29: What would you like to request for infrastructure improvements?

Source: Author's interview record

Table 6: Stability of utility supply (observation by the residents)

	Area 1	Area 2	Area 3	Area 4
Daily hours of electricity supply [hrs]	22	22	23	23
Daily hours of water supply [hrs]	0	14	13	16

Source: Author's interview record

4.4 Interpretation from the perspective of social practice

It has become clear that everyday practices affecting CF differ at various stages of infrastructure development. In terms of energy use, fuel wood that was traditionally used for cooking and water heating becomes increasingly difficult to utilize due to urbanization. However, the establishment of infrastructure such as electricity, water supply, and gas provides alternative methods (cooking with electricity or gas, and water heating with electricity) that become widely adopted. In urban centers, even if one wishes to use fuel wood, the environmental conditions do not allow for it; thus, infrastructure development, along with urbanization, drives transformation in everyday practices related to cooking and water heating.

Regarding the increasing demand for electricity, if the urban heat island phenomenon caused by urbanization is taken into account, it becomes difficult to endure the heat in urban centers without air conditioners. This also exemplifies how urban conditions supported by advanced infrastructure limit the choices in people's everyday practices.

Transportation practices are significantly influenced by infrastructure development as well. For instance, the increase in personal ownership of four-wheeled vehicles can be a result of improved road infrastructure. Conversely, the establishment of metro systems offers new low-carbon practice options for moving around urban areas. The development process around transportation infrastructure serves as a prime example of how infrastructure both shapes and is shaped by the conventions of a community of practice (Star 1999).

5. Conclusion

Infrastructure development plays a significant role in converging conventions of comfort, cleanliness, and convenience (Shove 2003), and it is essential for more people to benefit from this in order to achieve the SDGs. This is no exception in the surveyed areas: it is evident that as infrastructure such as electricity, water supply, sewage, PNG, and metro progress from the suburbs of Lucknow toward the city center, the quality of people's lives significantly improves. Therefore, it is crucial to actively promote the development of such foundational infrastructure that enhances the quality of life.

On the other hand, infrastructure development, in conjunction with the accompanying rise in income levels, encourages the consumption of the goods and services provided through infrastructure, thus increasing environmental burdens. In particular, the development of power supply and transportation infrastructure, such as roads, contributes significantly to increased CF, provided that the services they offer are derived from fossil fuel consumption.

This empirical study demonstrates that in Lucknow city and its surrounding areas, the increased contributions to CF from electricity use and fuel consumption for transportation are significant, whereas those from water supply and urban gas are not substantial. In terms of water supply, it is possible that there is an indirect contribution to increased electricity consumption due to water heating demand, indicating that infrastructure development has aspects that increase environmental burdens as a synergistic effect. To suppress the CF increase associated with infrastructure enhancement, it is important to focus on investigating and addressing the increase in direct and indirect CO_2 emissions related to electricity use and transportation.

The factors contributing to increased electricity use can be attributed to both structural changes associated with urbanization and increased purchasing power due to rising income levels. An example of such structural factors is the decrease in the use of fuel wood for cooking and water heating, with a corresponding increase in the proportion of electricity used for these purposes. In addition, the influence of urbanization around Lucknow city is believed to contribute to the urban heat island effect, leading to a significant increase in the usage rate of air conditioners in the city center. The usage rate of other electrical appliances tends also to increase as one approaches the city center, likely due to the influence of rising income levels. Use of these electrical appliances leads to higher electricity consumption as well as time savings in domestic chores. However, depending on how the surplus time is utilized, there is a risk of a rebound effect. This could result in increased electricity consumption from such activities as communication and entertainment.

As mentioned above, the increase in electricity use is strongly linked to the constraints on choices in social practices, making a certain increase unavoidable. Therefore, it is essential to make efforts to introduce a power supply as clean as possible on the supply side to reduce emissions coefficients. Given that demand is expected to continue to grow, measures such as supplying additional power capacity primarily through renewable energy (such as biomass that does not lead to deforestation) will be necessary. On the demand side, since there is significant interest in new housing construction and renovations in the area, it may be effective to promote the introduction of energy-saving technologies, such as enhancing insulation efficiency, as well as implementing energy-saving device dissemination strategies centered around home appliances. If electricity consumption continues to increase, introducing economic incentives to suppress usage by reconsidering pricing according to income levels will be worth considering.

Regarding the increase in CF associated with transportation, the main factors are thought to be the rising ownership of low-fuel-efficiency four-wheeled vehicles in addition to two-wheelers, as well as an increase in long-distance travel, such as occasional trips. Both of these factors are considered to stem primarily from rising income levels. However, in the city center of Lucknow, it becomes more challenging to travel by bicycle or on foot, which may relate to the ongoing improvement of road infrastructure for four-wheelers. On the other hand, utilizing low CF public transportation, such as metros, for daily commutes, shopping, and other activities can help reduce the fuel consumption of personal vehicles, making it important to promote both the dissemination of such infrastructure and its usage. In urban areas like Area 4, where the number of four-wheeled vehicle owners is increasing, it is also important to provide a greater range of low CF transportation options to potential buyers, e.g., infrastructure for car sharing and establishing dedicated lanes for bicycles and buses.

As already mentioned, the increase in household appliances tends to save time on domestic chores, resulting in an increase in leisure time. If more leisure time becomes available, spending time with family and friends rather than traveling could help to suppress CF, making awareness-raising activities effective. The government of India has already initiated "Mission LiFE (Lifestyle for Environment)" since 2021 as the nationwide awareness campaign for encouraging individuals to undertake simple acts in their daily lives that can contribute significantly to climate change.[3] It is essential to establish low CF social practices at an early stage of urbanization by improving not only hard infrastructure but also the economic and institutional environment, along with consumer awareness activities. CF mitigation measures related to electricity, housing, and transportation infrastructure have already been implemented or are considered in developed countries. However, in developed countries, reconstructing infrastructure once established and changing people's social practices often requires substantial costs and time. In rapidly developing countries like India, it is crucial to implement CF mitigation measures incorporating infrastructure formation, institutional building, and awareness activities from the outset in urban areas where CF increase is expected in order to realize sustainable consumption through changing people's social practices (Seto et al. 2016).

[3] https://www.niti.gov.in/life

The results of this study revealed not only the differences in the environment due to the state of infrastructure development but also the impact of income level differences on consumption behavior. Future studies will need to focus on a more detailed analysis with an attempt to eliminate the impact of income level differences, possibly by extracting households with a specific income level from each of Areas 1 to 4.

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Abstract in Japanese

要　約

インフラ開発は、生活の質を向上させる上で必要不可欠なサービスを提供するが、一方で消費を促進し環境負荷を増加させる可能性がある。インフラは社会的慣行への影響を通じて消費の持続可能性に影響を与えうるが、具体的にどのような影響を及ぼすのかを包括的に探る事例研究はほとんど行われてこなかった。本研究では、インドのウッタル・プラデーシュ州に着目し、電気、水道、下水道、都市ガス、交通などのインフラ発展段階が異なる地域において、各世帯の消費行動がどのように異なるのか、それがカーボンフットプリント（CF）にどのような影響を与えるかを分析した。この結果、インフラが高度に発展した地域ほど、主に電力使用量の増加と移動に伴う化石燃料使用量の増加によって世帯の CF が高くなることが明らかになった。環境負荷を抑制しながら生活の質を向上させていくには、電力や住宅、交通インフラの開発の初期段階において、低 CF での消費行動を可能とする選択肢を提供するとともに、こうした消費行動を促す政策介入や啓発活動を行うことで、社会的慣行を形成していくことが重要である。

キーワード：持続可能な消費、家計消費に伴うカーボン・フットプリント、インフラ開発、社会的慣行、時間の使い方