ORIGINAL ARTICLE

Urban Metabolism Assessment in Malaysian Urbanised Cities

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ABSTRACT

Introduction: Urbanised cities are experiencing rapid and unpredictable growth, leading to changes in urban metabolism, particularly in economic aspects that significantly impact consumption patterns and behaviours. This study focuses on urban metabolism assessment in four selected urbanised cities: Kuala Lumpur, Penang, Melaka, and Johor Bahru. **Methods:** The study employed Material Flow Analysis (MFA) to examine material and energy waste from water, electricity, and food consumption within the studied cities. Additionally, the carbon footprint was estimated by considering activity data (AD) and emission factors (EF) to quantify CO_2 emissions resulting from water, electricity and food consumption in each city. **Results:** The study's results indicate differences in food, water, and electricity consumption quantities, as well as the resultant waste generation amounts. This highlights the notable environmental implications of these trends within the cities under examination. Factors such as socio-economic status, urban infrastructure, lifestyle choices, local policies, availability of resources, and awareness of sustainable practices may play a significant role in shaping consumption and waste generation patterns. This study could help in obtaining a good mitigation measure to reduce the carbon footprint impact on the environment such as implementing a low carbon lifestyle and a low carbon city. By understanding the carbon emission profile, it helps in developing strategies for further enhancement on the economic and environmental values. **Conclusion:** Low carbon urban planning and other city decision-making processes, are viewed as crucial feedback for enhancing the material flows sustainability, efficient performance in energy usage and to reduce the dependency on non-renewable sources.

Keywords: Material Flow Analysis; Carbon Footprint; Energy Consumption; Urban Planning

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INTRODUCTION

Urbanisation is the process of developing an area to accommodate a growing population (1), which has occurred rapidly in many cities and is expected to continue in the future (2). Improper urban development planning can cause cities to grow inexorably, resulting in broad economic, ecological, and social changes (3, 4). This demand links social processes to temporal and spatial attributes of flows of services whereby it can be translated to the temporal and spatial attributes of energy, water, and material flows and later increased the carbon footprint such as water consumption, electricity consumption, waste production and food consumption (5).

Recently, urban metabolism, an approach of systems that is able to understand the interrelationship between natural environment and urban socioeconomic status through resource utilization (6), has been used to assess city flow stocks and materials by quantifying urban inflows and outflows such as solid waste, sewerage, and carbon dioxide emissions, as well as monitoring their corresponding transformations and flows (5). The material flow analysis (MFA) framework is an application of the concept of urban metabolism that explains material flows both within and between cities (7). It entails measuring input and output materials as well as investigating the pathways and flux of each material flow throughout the system.

The urbanisation in Malaysia did not experience the emergence of a single dominant megacity. The increase in urban population was caused by heavy in-migration, both domestic and international, to urban centres and periphery in search of employment and education opportunities (8). This study of urban material flow analysis and carbon footprint was carried out in four Malaysian cities: Kuala Lumpur, Penang, Melaka, and Johor Bahru. Table I lists the reasons why these four regions were chosen for the study.

This study focuses on domestic consumption and its output in terms of food, water, and electricity consumption. The findings will help city dwellers in evaluating citizens' consumption footprints where the city lead sustainable urbanisation while also reducing environmental impacts to maintain the quality of life in terms of material consumption and resources for a better and healthier environment surrounding the city area. Furthermore, MFA and carbon consumption footprint in this study give decision-makers a better understanding of how their city works, allowing them to plan for and respond to current and future material flows and stock challenges.

MATERIALS AND METHODS

Study location

This study focuses on four selected cities in Malaysia: (i) Kuala Lumpur, (ii) Penang, (iii) Melaka, and (iv) Johor Bahru based on their urbanisation rate in 2019. Figure I illustrates the cities' urbanisation rate for demographics in 2019. By using 2019 data, the study could provide a baseline understanding of consumption and waste patterns before the pandemic's significant effects on lifestyles, economies, and environmental factors, allowing for a more focused examination of the pre-pandemic urban metabolism and carbon footprint in the selected cities.

Study design

This study used MFA approach (9) and carbon footprint calculation. MFA was used to show how a bottom-up environmental analysis framework may be used in conjunction with an urban metabolism framework (10). In this study, MFA was used to analyse the material and energy waste and emission of products includes water, electricity, and food consumption within a city.

Meanwhile, the carbon footprint was used to estimate the amount of carbon released from the water and electricity consumption and calculated using Equation I (11). As for carbon footprint, two primary parameters are required: (i) activity data (AD), and (ii) emission factor (EF). Activity data permits the quantification of a process; represents the magnitude of a specific activity under investigation, such as the amount of electricity, water or food consumed during a given period. Emission factor represents the mass of CO_2 emitted per unit of AD. Based on the values of AD and EF, the amount of carbon emitted is calculated for each city in 2019.

$$\text{Carbon footprint } (tCO_2e) = \text{Activity Data (AD)} * \text{Emission Factor (EF)} \quad \text{(Eq. I)}$$

Data collection

The secondary data of domestic input and output variables in 2019 were obtained from the national and state data that has been published by authorities such as the Department of Statistic Malaysia, National Water Service Commission (SPAN), and the Energy Commission Malaysia. The input data includes water, electricity, and food whereas the output data were wastewater, carbon emission, and food waste. Table II exhibits the different sources of input and output data for each city.

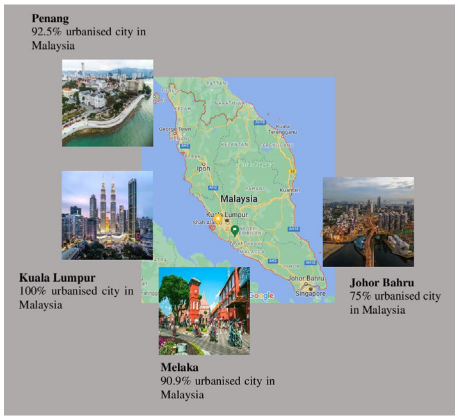

Figure 1 : Study sites.

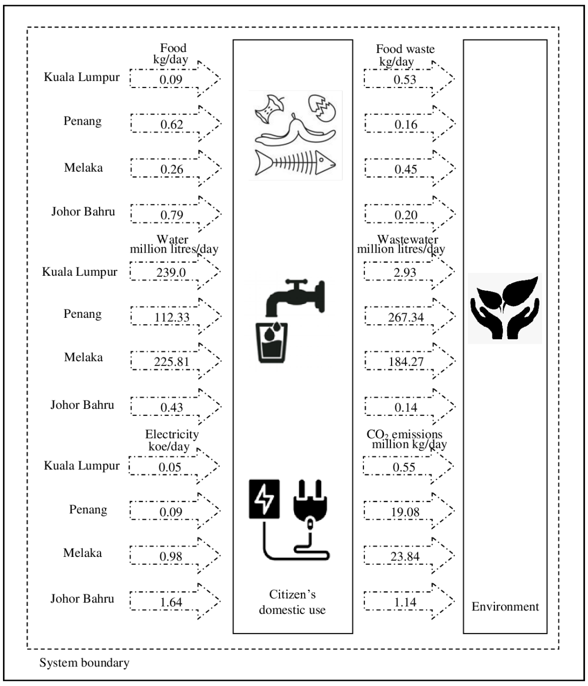

Figure 2 : Material flow analysis of cities.

RESULTS

MFA framework and results

Figure II shows the MFA framework for food consumption and food waste, water consumption and wastewater, and electricity and carbon emission for the four selected urbanised cities, Kuala Lumpur, Penang, Melaka, and Johor. The dotted line around the flow indicates the system boundary for the flow which consists of the citizen's consumption and balance of the products that are emitted to the

Table I : Selection of city and its significance

Cities	Significance
Kuala Lumpur	Capital city of Malaysia and the most populated city in Malaysia with 1.8 million dwellers.
Penang	Second-smallest city in Malaysia, however, was second in terms of population density in with 1,490 people per square kilometer (1.7 million dwellers)
Melaka	Popular tourist destination because of its UNESCO (United Nations Educational, Scientific and Cultural Organization) World Heritage status, which means it has an appealing value where the number of tourists per year increases (4 million tourists per year)
Johor Bahru	Capital state of Johor in southern West Malaysia and is separated from Singapore by a road and rail causeway. Johor Bahru has been designated as the growth intermediary for the south region of Peninsular Malaysia (500,000 dwellers)

Table II : Sources of secondary data for the selected cities

Cities	Data	Material	Source
Kuala Lumpur	Input	Energy	Department of Statistics (28), Tenaga Nasional Berhad (29)
		Food	Department of Statistics (28)
		Water	Department of Statistics (28), Air Selangor (30)
	Output	Carbon emissions	Department of Statistics (28), Tenaga Nasional Berhad (29)
		Food waste	Department of Statistics (28), SW Corp (31)
		Wastewater	Department of Statistics (28)
Penang	Input	Energy	Department of Statistics Malaysia (32)
		Food	Department of Statistics Malaysia (32)
		Water	Department of Statistics Malaysia (32)
	Output	Carbon emissions	Department of Statistics Malaysia (32)
		Food waste	Department of Statistics Malaysia (32)
		Wastewater	Perbadanan Bekalan Air Pulau Pinang (33)
Melaka	Input	Energy	Energy Commission Malaysia (34)
		Food	Department of Statistic Malaysia (17)
		Water	National Water Services Commission (35)
	Output	Carbon emissions	World Bank Data (36) Aja and Al-Kayiem (37)
		Food waste	Aja and Al-Kayiem (37)
		Wastewater	Indah Water Konsortium (38)
Johor Bahru	Input	Energy	Tenaga Nasional Berhad (29)
		Food	United Nations Department of Economic Social Affairs (25)
		Water	National Water Services Commission (35)
	Output	Carbon emissions	Tenaga Nasional Berhad (29)
		Food waste	United Nations Department of Economic Social Affairs (39)
		Wastewater	National Water Services Commission (35)

environment. Referring to the Figure II, the input (food, water, and electricity) will be utilised by citizen's domestic use and the waste will be released to the environment (food waste, wastewater, and carbon dioxide).

Figure II shows the consumption and waste of each product in the four urbanised cities studied. The kilogram of oil equivalent (koe) unit represents the amount of energy released by burning one kilogram of crude oil. This unit is often used to express the energy content of other fuels and energy sources in a way that is comparable to crude oil. Every day, Kuala Lumpur's residents consumed 0.09 kg of food, 239 kg of water and 0.05 koe per capita. All these consumptions generated waste, including food waste, wastewater, and carbon emission, which totalled up to 0.53 kg, 2.93 kg, and 0.55 koe, respectively. The study found that the electricity consumption that emits carbon dioxide for Kuala Lumpur residents in 2019 increased compared to 2016 which was 0.455 koe (12). Penang residents consumed 0.62 kg of food per day, resulting in 0.16 kg of food waste, and 112.33 kg of water per day, resulting in 267.34 kg of wastewater released into the environment. Penang residents also used 0.09 koe of electricity per day, resulting in 19.08 koe of carbon emissions.

Daily, a Melaka resident consumed 0.26 kg of food, 225.58 kg of water, and 0.98 koe of electricity. For each individual consumption, 0.45 kg of food waste, 184.27 kg of wastewater, and 23.84 koe of carbon will be generated. Finally, in Johor Bahru, a citizen will consume 0.79 kg of food, 0.43 m3 of water, and 1.64 t-CO2 of electricity, while producing 0.20 kg food waste, 0.14 m3 wastewater, and emitting 1.14 t-CO_2 carbon.

Carbon footprint from water consumption

Penang had the highest CO_2 emissions from water consumption in 2019, followed by Johor Bahru, Melaka, and Kuala Lumpur. Penang's water consumption contributes 289.64 million tCO_2e to the environment's carbon footprint. A study found that different wastewater treatment plant configurations may have different carbon footprints. The wastewater treatment plant is a major source of greenhouse gas emissions (13). The average total carbon footprint from water consumption in Johor Bahru was 3.5 million tCO_2e. Per capita calculation of Johor Bahru's average carbon footprint, where each household has five people, generated 2.35 t-CO_2 per year as the per capita carbon footprint in Johor Bahru (14). That figure for total household carbon footprint was found to be comparable to several European countries, including, Sweden (12.2 t-CO_2) and Norway (13.6 t-CO^2), as well as nearly half of Canadian household emissions for one year, at 19.5 t-CO_2.

Melaka's carbon footprint for water consumption is 2.48 million tCO_2e, higher than that of other cities, owing to the socioeconomic profile of the household, characteristics of the dwelling, and ownership of appliances being some of the factors that influenced the household's consumption (15). For Kuala Lumpur, water has a carbon footprint of 0.15 million tCO_2e due to the energy required to transport water to Kuala Lumpur, the energy used to treat and pump the water, and the energy used to dispose the city's wastewater. The energy used to transport water over long distances within cities, such as through pipelines, can be a significant contributor to the carbon footprint of water. The energy used to treat and pump water throughout the city of Kuala Lumpur, as well as the energy used to operate the infrastructure and equipment used for water treatment and distribution at the wastewater treatment plant, all contribute to a higher carbon footprint for water.

Carbon footprint from electricity use

Penang and Kuala Lumpur emit the most carbon for electricity consumption, estimated at 300 million tCO_2e, followed by Johor Bahru 67 million tCO_2e, Melaka at 0.67 million tCO_2e. In Penang, electricity, gas, and other fuels account for the greatest proportion of total expenditure (26.37 %) out (16). Johor Bahru, the state with the second highest carbon footprint contributor for electricity use, spent an average RM126 per month on electricity. Johor Bahru spent 22.8% of its income on electricity, gas and other fuels which is (3.57%) less than Penang (14). Melaka state spent an average of RM143 per month on electricity, which is slightly higher than Johor Bahru's average due to differences in commodity prices. However, Melaka, spent only 17.3% for electricity, gas, and other fuel consumptions expenditure, which is lower than Penang state and Johor Bahru (17). The average monthly electricity expenditure in Kuala Lumpur is RM155, and Kuala Lumpur spent (28.0%) of its income on electricity, gas, and other fuels, which was the largest contributor to overall consumption expenditure (10).

DISCUSSION

Food consumption and its food waste

Food consumption in each selected city can be calculated based on what citizens of each city consume in their households. Basic foods consumed by Malaysian on daily basis were considered for this study i.e., rice, chicken, beef, eggs, fruits: banana, pineapple, and apple, a type of vegetable: round cabbage, and a type of fish: Indian mackerel fish. Food waste generated in a household has had an impact on urbanised cities due to a variety of eating habits and easy access to food such as ready-to-eat food.

Easier access to food, such as a nearby convenience store or ordering food through an online platform, contributes to increased food waste and general household waste from the food packaging (18, 19).

Water consumption and wastewater
The amount of water consumed by citizens in each city is determined by the demand for water because of population growth and rising living standards in a household. Raw water for each city is treated and distributed throughout the city to ensure that citizens have access to water on a daily basis. Rapid urbanisation has increased the likelihood of water demand for domestic and non-domestic sectors over time, and population growth has the potential to inflate water consumption and demand (20, 21). Water demand can eventually lead to an increase in water scarcity, which is exacerbated by urbanisation (22-24).

Electricity use and carbon emissions
Based on the results of individual electricity consumption in four different cities, it can be concluded that it is dependent on the living lifestyle, the number and type of electrical appliances, and the hours used (25). In Malaysia, the economic groups are categorized based on household income levels, and they are commonly referred to as M40, B40, and T20. In Malaysia, the M40 group comprises households with moderate to comfortable incomes, falling between the 40th and 80th percentile of the income distribution. The B40 group represents lower-income households earning below the 40th percentile, while the T20 group consists of the highest-income households in the top 20% of the income distribution, enjoying a more affluent lifestyle. In Penang, the M40 group constitutes the largest proportion of households with the highest income, followed by the B40 group, while the T20 group comprises the smallest proportion of households among these three categories (16). People who live in urban areas such as Melaka (90.9% urbanised) and Kuala Lumpur (100%) can generally purchase higher-quality electricity appliances that conserve energy, such as products with Energy Efficient Star Labels (EESL). In relation to the previously mentioned household income group, the EESL appliances campaign has only targeted the T20 group because this group exhibits more energy-saving behaviour compared to those with lower incomes because EESL products are more expensive (26).

According to a household expenditure survey report by Johor state and administrative district, the monthly mean of electricity consumption in 2019 is 22.8%, with a 4.8% annual growth rate. The increase in residential urban development area has also increased household electricity consumption. The socioeconomic background, residential factors, climatic settings, economic growth, and behavioural factors all have a significant impact on electricity consumption (27). In this study, CO_2 emissions are only calculated for residential consumption. A case study discovered a wide range of carbon footprint rates as well as significant relationship between expenditures and carbon footprint (27).

Policies that promote resource efficiency and waste reduction can have a positive impact on MFA, resulting in lower material consumption and waste generation. Renewable energy targets and incentives for clean energy adoption help to reduce greenhouse gas emissions by shifting away from fossil fuels. Prioritising public transportation and pedestrian-friendly infrastructure reduces reliance on automobiles, while waste management policies that emphasise recycling and waste-to-energy conversion reduce material flow into landfills and incinerators. Water conservation policies, such as promoting water-saving practices and implementing water-efficient technologies, can lead to reduced water consumption and more sustainable water use patterns. Additionally, initiatives to protect water sources, preserve watersheds, and implement rainwater harvesting systems can contribute to enhancing water availability and quality. Furthermore, energy efficiency measures, green building standards, and low-carbon transportation initiatives all help to reduce carbon emissions and improve urban sustainability.

The study on material flow analysis of domestic usage in each city reveals sustainability challenges as citizens' lifestyles, household income, and targeted campaigns to specific household classes contribute to negative environmental impacts in all cities. The carbon footprint for water consumption and electricity consumption of each city demonstrates that it can endanger the environment when the carbon footprint for the selected consumption increases overtime. A shift in behaviour towards a greener approach is required to reduce environmental issues and energy consumption. Understanding household consumption behaviour, as a result, promotes energy conservation and improves energy efficiency. Low carbon lifestyle should be encouraged to reduce the CO_2 emissions, consumption and expenditure. Melaka Green City Action Plan, Penang Green Agenda, Kuala Lumpur Climate Action Plan 2050, and Low Carbon Society Blueprint for Iskandar Malaysia in 2025 have all been developed and implemented to improve the energy structure and promote more efficient energy utilisation.

CONCLUSION

Identifying the major contributors in each city through material flow analysis and carbon footprint assessment is critical for implementing decarbonisation strategies. Cities can combat environmental impacts such as temperature rise and work towards a more sustainable and climate-resilient future by reducing carbon dioxide and other greenhouse gas emissions. Exploratory research analysing the same frame in developing nations is required to discover unique trends to comprehend the correlations between movements and social situations. To improve the results of the future urban metabolism study, we should collect more data across planned and unplanned Malaysian cities and use robust life cycle assessment tools. In order to calculate carbon footprint, it would also be necessary to have the readily available data from agriculture, industry, and transportation sectors. Combating climate change will undoubtedly necessitate a strategic plan that integrates spatial planning, climate mitigation, and adaptation strategies in cities and other metropolitan areas. The outcomes of the study are vital for developing efficient regulations and tools for optimising the use of water and electricity in urban areas.

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