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A survey and partial dependency analysis to assess residential solid waste recycling awareness in Saudi Arabia

Moahd Khaled Alghuson✉ & Abdullah Alghuried

Rapid industrialization, rise in population, and urbanization have led to severe environmental degradation and health concerns for inhabitants due to regular household waste (RHW). Implementing sustainable waste management practices, such as regular household waste recycling, is an imminent need in Saudi Arabia and other nations. Yet, the analysis of the awareness regarding RHW recycling and its influencing elements in the Kingdom of Saudi Arabia (KSA) has rarely been conducted. Efficient management of home waste is currently a major concern, particularly in economically developing countries, as inappropriate disposal of waste results in financial losses and detrimental effects on the environment and public health. The objective of this study is to assess the level of awareness among Saudi households on RHW, the environmental issues associated with improper waste disposal, and their readiness to participate in the recycling of RHW. Therefore, we conducted a two-stage analytic investigation that included a total of 909 households from different areas of Saudi Arabia. In addition to the analysis of questionnaire responses, partial dependency (PDP) analysis was also conducted using two supervised machine learning algorithms, Multi-Layer Perceptron (MLP) and Decision Tree (DT), to evaluate how sociodemographic factors influence waste recycling awareness. Based on the study results, most respondents are knowledgeable and worried about the adverse environmental effects of solid waste. Most respondents are motivated to support a large-scale recycling program, provided enough facilities are available. Also, the PDP analysis revealed that sociodemographic factors such as age, gender, salary, and marital status also significantly impact the awareness of waste recycling. Finally, considering the rising amount of waste produced by the Saudi population, the authorities must implement a recycling program to address this harmful waste and promote the development of a sustainable world.

Keywords Recycling awareness, Residential solid waste, Public awareness, Questionnaire survey, Partial dependency analysis

Residential solid waste (RSW), also called regular household waste (RHW), consists of the daily materials that homes dispose of, such as food scraps, packaging, paper, glass, plastics, metals, textiles, and yard clippings. A significant amount of household waste is produced in urban areas as a consequence of fast economic development, rising populations, and urbanization[1,2]. Residential solid waste contains a large volume of organic content, including vital mineral nutrients, and is a substantial carbon source[3,4]. Several measures have been implemented to recycle and categorize this garbage at the individual, community, and governmental levels. However, significant quantities of mixed industrial and residential waste are disposed improperly[5–8]. The management of municipal solid waste significantly impacts the entire quality of life in communities, including factors such as cleanliness, health, and productivity[9–11]. Effective and timely implementation of solid waste management is essential for societies' continued existence and proper operation[12]. Inadequate waste management pollutes the biosphere, including oceans, rivers, and seas.

The rise in economic development and the fast urbanization process are strongly correlated with increased global garbage generated per person[13,14]. The annual worldwide production of municipal solid waste from urban areas is roughly 2.01 billion tons, with over 33% of it not being handled ecologically safely[15]. According to a study conducted by Farmanbordar, Amiri and Karimi[16], the global rate of residential garbage production varies

Department of Industrial Engineering, Faculty of Engineering, University of Tabuk, 47512 Tabuk, Saudi Arabia. ✉email: malghuson@ut.edu.sa

from 0.11 to 4.54 kg per individual per day, with an optimal amount of 0.74 kg per individual per day. High-income nations, representing just 16% of the globe's population, produce approximately 683 million tons of RSW, accounting for 34% of the total worldwide RSW[17,18]. According to research conducted by Hoque and Rahman[19], worldwide municipal waste is projected to increase to 3.4 billion tons by 2050. Consequently, the cost of managing municipal garbage is much higher in metropolitan locations[20,21]. Waste management is the largest portion of the budget in low-income nations, accounting for over 20% of the budget al.located to municipal services worldwide. In countries with middle incomes, it comprises more than 10% of the total expenditure, while in high-income ones, it represents about 4%[22]. Elaborate waste management procedures incur significant expenses and need financial support, as well as essential resources such as safe drinking water, medical care, public schooling, and other facilities[23].

Developing nations lack the infrastructure to regulate municipal solid waste creation and continue to use open landfills for waste disposal[24,25]. Regrettably, the Middle East and several emerging nations in Asia and Africa lack effective integrated waste management systems. Deficient municipal solid waste management systems are characterized by inadequate working conditions, financial constraints, insufficient accurate governance instruments, inappropriate selection and use of technology, low awareness, and reliance on imported equipment and materials. The member nations of the Gulf Cooperation Council produce the largest per capita municipal solid waste worldwide, and in many of these countries, such waste is just disposed of in various landfill sites. In Oman, the total volume of municipal solid waste amounted to 2.0 million tons per year[26]. This type of landfill disposal of waste occupies a significant land area and contributes to environmental and climate change challenges[27]. This is also particularly true in developing Middle Eastern nations like Saudi Arabia[28]. Saudi Arabia is situated in the southwestern region of Asia and borders the Arabian Gulf to the east and the Red Sea to the west. The nation has a substantial population of 34.8 million, according to the 2020 World Bank data[29,30]. In recent decades, a significant amount of solid waste has been documented in Saudi Arabia due to fast industrialization, urbanization, and population expansion. A population growth rate of around 3.4% was seen over the last four decades, accompanied by a 50–80% rise in urbanization from 1970 to the present[31,32]. The significant increase in population and urbanization in Saudi Arabia has resulted in a substantial volume of solid garbage being abandoned. Therefore, numerous issues remain to be resolved regarding recycling management in Saudi Arabia. The Saudi government is encountering challenges in monitoring the national recycling rate. It must identify the most suitable approach for managing the recycling system to effectively include local communities in establishing a more structured and efficient recycling management framework[33–36].

The annual total of municipal solid garbage produced in Saudi Arabia amounts to about 50 million tons, with an average rate of 1.7 kg per capita per day[37]. The report also emphasizes that the Kingdom produces almost 7 million tons of plastic garbage yearly. This municipal solid waste is managed by the Local Affairs & Ministry of Municipalities and carried out by local municipalities. These municipalities collect, transport, and dispose of garbage at landfills and dump sites without using energy[38,39]. Uncontrolled garbage is typically disposed of employing incineration and landfill disposal. Compost facilities are used to convert organic wastes into compost[40]. The widespread improper waste disposal methods result in significant environmental harm, as they may lead to contamination of surface waterways and soil and generate unpleasant smells[11,41].

Waste recovery, reuse, and healthy disposal methods have recently been the focus of waste management strategies in some nations, thanks to environmental legislation that aims to improve RHW management[42]. There was also a noticeable increase in the private sector's role in collecting organic, plastic, and metal garbage for recycling and reuse. Sustainable waste management includes recycling and reusing resources and energy to create new products while decreasing trash pollution[43,44]. Ultimately, educating the public is crucial for effective municipal solid waste (MSW) recycling and reuse programs[45]. The reason is that people's day-to-day activities, which in turn are influenced by sociodemographic characteristics, directly correlate to their level of garbage reuse and recycling consciousness[46]. A person's sociodemographic factors are associated with their trash creation, according to previous research done all over the globe[44,47]. Similarly, the attitude of households toward recycling—that is, their propensity to sort and recycle—is strongly predicted by social influence[48]. Important factors that impact citizens' intent to sort garbage include their viewpoint, social impact, perceived control over behavior, economic benefits, regulatory supporters, and awareness[49]. Similarly, in both the low-income and high-income groups, attitudes and readiness to sort and recycle garbage were moderated by income and market incentives. Furthermore, the correlation between market incentives and the propensity to sort and recycle trash was moderated by the participants' gender[50–52].

Different suggestions were provided by previous studies conducted on similar interests, such as the significance of children's participation in segregating solid waste for family-level recycling, which must be emphasized for a better waste recycling community[29]. Comparable findings are seen in a study by Tuffaha, Alghamdi and Mazher[30], whereby recognizing recycling's significance acted as the primary incentive for children to engage in these activities. In a separate study, the survey findings from Jatau and Binbol[53] revealed that students recycle household garbage at a rate above the regional norm. The existing infrastructure and collection techniques need enhancement to increase recycling rates. Public engagement in recycling activities is often driven by educational initiatives emphasizing environmental conservation and waste management's long-term benefits[54]. Additionally, a study by Radwan, Khan and Elmanfaloty[55] found that individuals with higher levels of recycling knowledge were more likely to participate in waste segregation efforts, underscoring the need for targeted awareness campaigns.

Thus, previous studies in Saudi Arabia have primarily focused on investigating the relationship between sociodemographic factors and the generation of RHW. However, these studies have overlooked the direct and indirect impacts of a household's awareness of waste recycling. The study also found that money and economic incentives had a moderating role in the relationship between attitude and desire to sort and recycle garbage in both low-income and high-income groups. Furthermore, the participants' gender played a role in influencing the

connection between economic incentives and the motivation to sort and recycle garbage in both men and women. Therefore, the objective of this study was to evaluate the level of awareness among households about recycling their regular household waste (RHW) and to investigate the factors that influence their recycling behaviors. The partial dependency analysis was used to determine the degree to which a household's demographic features are associated with their level of knowledge and practices of household trash recycling.

Composition of waste

A large portion of Saudi Arabia's massive RHW consists of organic materials, including paper and food scraps, making up over 66% of the total. Restaurants, hotels, households, and canteens are just a few of the many places that generate food waste[56]. A survey conducted by Elmosaad, Al Rajeh, Llaguno, Alqaimi, Alsalman, Alkishi, Hussain, Alhoudaib, Alnajim and Belal[57] indicated that the average daily rate of residence solid waste production in Saudi Arabia is 0.95 kg per inhabitant per day, mostly consisting of paper and cardboard, food, plastics, wood, metals, and glass. The high volume of single-use plastic bags and containers used for food and drink during the Hajj and Ramadan contributes to plastic's status as one of Saudi Arabia's most abundant solid wastes[58]. A significant portion of Saudi's MSW comprises textiles, wood items, glassware, bottles, pottery, and light bulbs. Solid garbage, which includes items such as knives, aluminum cans, wire bottles, foils, etc., also contains certain metals and minerals, making up a significant portion, 8.3%. In addition to the aforementioned contaminants, the municipal solid trash of Saudi Arabia also contains rubber, fibers, dirt, yard debris, tires, electronics, and appliances, as illustrated in Fig. 1[56].

Materials and methods

The authors conducted the survey questionnaire with human activities, and all experiments were performed in accordance with relevant guidelines and regulations by the University of Tabuk, Saudi Arabia. Additionally, the University of Tabuk, Saudi Arabia, research ethics committee approved the experiments, including any relevant details mentioned in the supplementary file. The following statements are confirmed by the University of Tabuk, Saudi Arabia research ethics approval committee:

- A statement to confirm that all methods were carried out in accordance with relevant guidelines and regulations by the University of Tabuk, Saudi Arabia.

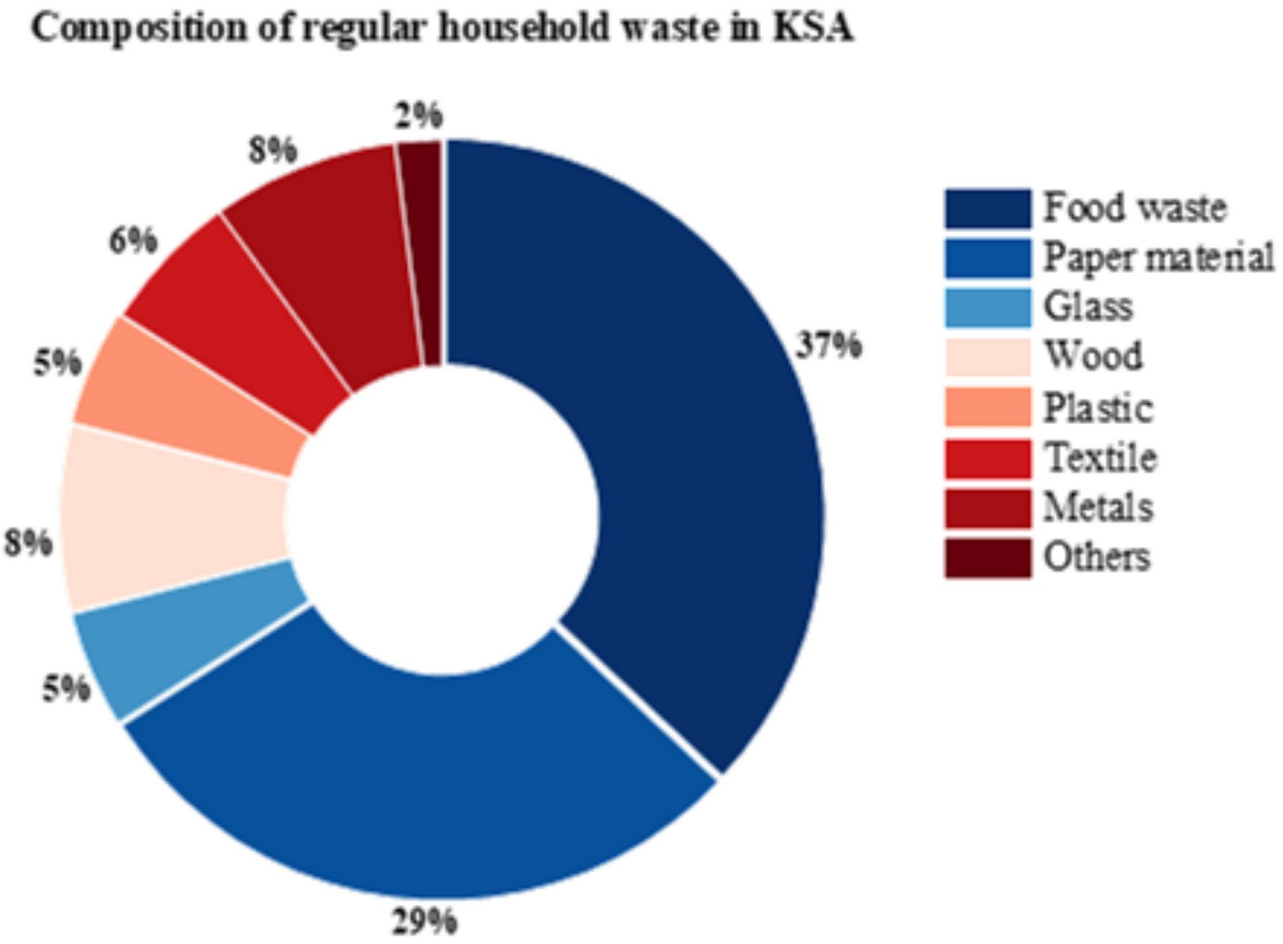


Fig. 1. Components of Saudi RHW[56].

- A statement to confirm that all experimental protocols were approved by a University of Tabuk, Saudi Arabia, research ethics approval committee.
- It is confirmed that the above-mentioned consent was obtained from the civil engineering department, the University of Tabuk, Saudi Arabia, and the university research ethics approval committee (see enclosed related file).
- It is confirmed that experiments were conducted involving human participants for the questionnaire survey. Informed consent was obtained from the civil engineering department, the University of Tabuk, Saudi Arabia, and the university research ethics approval committee (see enclosed related file).

Survey location

A questionnaire study was done to evaluate the level of recycling awareness among the residents of Saudi Arabia, specifically in Tabuk City, with a focus on RHW. However, during the data processing, respondents residing in cities other than the target city also participated in this survey, as seen in Fig. 2.

Questionnaire design and distribution

The primary research instrument used in this study was a questionnaire that had questions with multiple response options (see Appendix). The questionnaire was divided into four distinct sections. The first portion gathered demographic data pertaining to respondents' gender, age, marital status, current occupation, monthly income, and number of family members. The second portion investigated the level of public awareness and understanding of RHW. The third portion examined the extent to which the public is willing to engage in recycling and how they incorporate recycling into their everyday lives. The fourth section examined the extent to which the population generally tends to engage in an open recycling program if they have the opportunity. Based on the above-mentioned segmentation, in this questionnaire survey, a total of 19 questions were prepared and distributed among the residents of Saudi Arabia, specifically in Tabuk City. Prior to performing the comprehensive survey, a pilot survey was conducted using online data sharing and collection technology. The questionnaire was subsequently modified and refined based on the feedback received from the preliminary survey. The questionnaire was then randomly distributed using several methods such as online survey platforms,

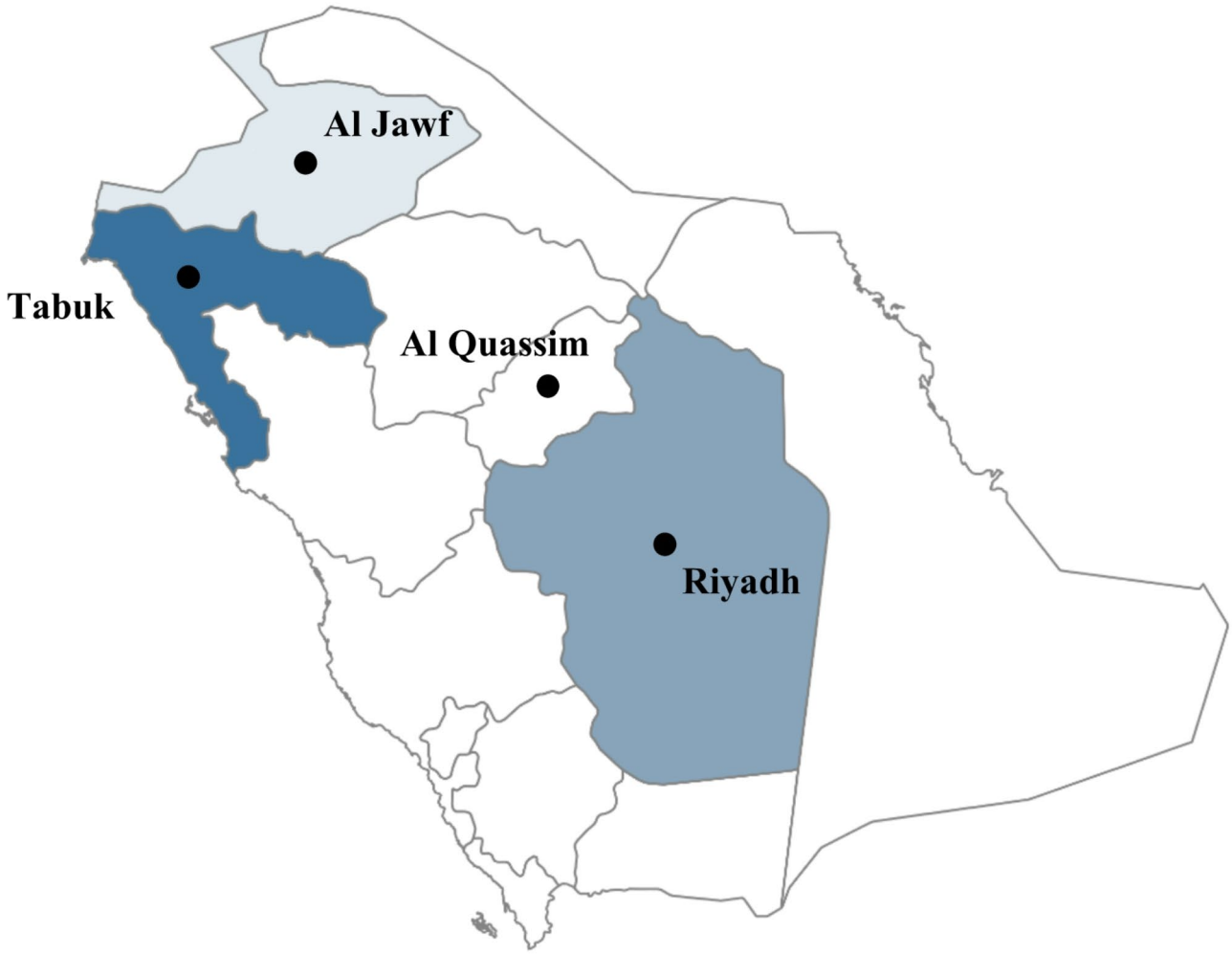


Fig. 2. Location of cities where surveys were conducted.

including social media, spreading the QR code in public places, meeting people face to face, and asking them questions. Some were also distributed as printed papers on cars and handed to people walking on the streets.

However, several strategies, such as random and stratified sampling techniques, were employed to ensure randomness and representativeness in the questionnaire distribution. Additionally, questionnaires were distributed online and offline to avoid selection bias, allowing access to participants from various technological backgrounds. This helped reach participants who may not be easily accessible through just one distribution mode. Furthermore, the survey received responses from 909 participants, which increased the likelihood of obtaining a representative sample of the population and improved the reliability of the results.

Statistical and parametric analyses

The data obtained from the questionnaire survey were analyzed using IBM SPSS V27. We endeavored to elucidate the sociodemographic variables (gender, age, married status, present employment, monthly income, and number of family members) that impact public behavior, public awareness, and public desire to engage in RHW recycling. Additionally, the study examined the correlations between sociodemographic parameters and public awareness of recycling using decision trees and multilayer perceptron algorithms based on partial dependency plot (PDP) analysis. The PDP may be seen as the anticipated target response based on the input properties of interest. This study will use one-way PDPs to examine the relationship between recycling awareness and demographic characteristics, as shown by a specific survey question. Single-dimensional Partial Dependence Plots (PDPs-1D) are highly effective for depicting how one particular input variable correlates with the predicted result. In general, PDPs shed light on the significance of each input factor in influencing the model's predictions. As a holistic tool, they analyze all instances to expose the broader link between a feature and the projected outcome. PDP consists of fixing each predictor variable at a specific value and then averaging the response for this model over all observations in the data[59,60]. This is done by computing the average expected response across all observations in the dataset (Eq. 1), holding constant all other predictor variables.

$$\widehat{f}_s\left(x_s\right) = E_{X_c}\left[\widehat{f}_s\left(x_s X_c\right)\right] = \int \widehat{f}_s\left(x_s X_c\right) dP\left(X_c\right) \tag{1}$$

where dP (X_C) is the distribution over other features, X_C is the other features of the model, X is the entire feature space, E is the expectation operator, and $\widehat{f}_s\left(x_s\right)$ is the expected value of ML model output for a collection of feature(s) x_s of interest.

Additionally, to evaluate the partial dependency of recycling awareness on demographic factors, we used two distinct machine learning (ML) algorithms. The Decision Tree (DT) method is a supervised ML technique. The DT approach is unique among supervised learning algorithms in that it may be used for regression and classification tasks. The primary reason for using a DT is to construct a training model capable of predicting the class or value of the target variable by acquiring simple decision rules derived from training data. On the other hand, Multi-layer perceptron (MLP) is an artificial neural network (ANN) that has many layers of neurons. The neurons in the MLP often use nonlinear activation functions, enabling the network to acquire intricate patterns in data. MLPs are crucial in the field of machine learning due to their ability to acquire knowledge about nonlinear connections within data, rendering them very effective algorithms for applications such as classification, regression, and identification of patterns. Due to their adaptability in design and capacity to simulate any function under specific circumstances, they serve as a crucial foundation in deep learning and neural network investigation. In this study, DT is chosen for its capability of identifying feature interactions and thresholds. These features make them ideal for extracting insights from structured data. Their inherent ability to handle non-linear relationships aligns well with the objectives of partial dependence analysis, as it aims to quantify the marginal effect of predictor variables on the target outcome. On the other hand, Multi-Layer Perceptron, a type of artificial neural network, is particularly effective in modeling complex, non-linear patterns in data due to its ability to learn high-dimensional representations.

Respondents demographic information

Table 1 presents a concise overview of the demographic information of the individuals who took part in the research. Out of the 909 participants, 437 were male and 292 were female, while others did not reveal their gender. The age group with the highest number of individuals was between 18 and years old, while those beyond 60 years old were not well represented (0.50%, $n=4$). The majority of individuals in the sample group (54.3%, $n=494$) had a lower wage, whereas a small number of study participants (2.3%, $n=21$) had high-paying positions.

The majority of responders were either unemployed or students. Regarding the size of families in homes, 67.1% of households had more than five members, while 12.5% had less than three members. The amount of solid waste created was determined based on the crucial family size and age criteria. This is because teenagers have a higher propensity to purchase fast food, beverages, and other food products, many of which are subsequently discarded[61,62]. Conducting research on disposal and recycling behavior is beneficial for identifying key socioeconomic groups that can be used to assess the effectiveness of waste management policies.

Results and discussion

Measuring awareness based on an individual's behavior and belief about recycling

Q1: Have you heard of recycling before

Figure 3 displays the response rate with which respondents are familiar with the term recycling. The data shows that 618 respondents (67.93% out of the total sample) are familiar with the term "Recycling" and have fundamental knowledge about how the recycling process works for household waste. Additionally, 106 respondents (11.7% of the total survey population) are unaware of recycling. However, a large number of people

	No. of participants	Valid percentages
Gender		
Male	437	59.9
Female	292	40.1
Age		
< 18	24	3.3
18–40	657	90.1
41–60	44	6.1
> 60	4	0.5
Marital status		
Married	195	27.8
Unmarried	506	72.2
Salary range		
More than 20,000 SAR	21	2.9
10,000–20,000 SAR	96	13.2
5000–10,000 SAR	118	16.2
Less than 5000 SAR	494	67.7
Job status		
Employed	278	38.1
Other	31	4.2
Retired	9	1.2
Student	265	36.3
Unemployed and not seeking work	10	1.4
Unemployed and seeking work	136	18.8
Family Members		
Less than 3 people	113	12.5
Between 3 to 5 people	184	20.3
More than 5 people	610	67.2

Table 1. Demographic information of participants.

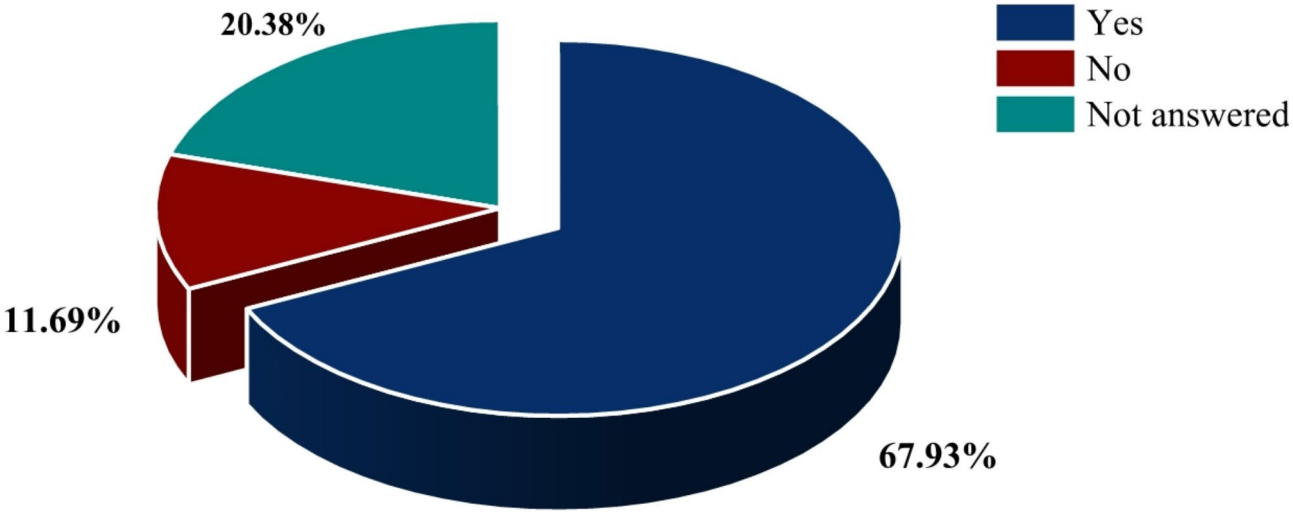


Fig. 3. Response based on the survey question: "Have you heard of recycling before?"

(185 respondents) did not answer this particular question. This breakdown provides a concise overview of the varying levels of awareness regarding recycling of RHW among Saudi residents. From the breakdown of respondents, it is concerning that a large percentage of the total population does not know about recycling, which means they do not engage in and practice sustainable recycling processes. Many of the population likely lacks awareness about recycling due to insufficient public education and awareness campaigns regarding waste management and sustainable practices[63]. Similar results can be obtained from a separate study conducted by

Alshehrei and Ameen[56], where they stated that a considerable number of citizens in the urban cities of Saudi Arabia are not concerned about proper waste disposal and recycling, even though the management preferred mass incineration for the solid waste management process[56].

Q2: To what extent do you believe recycling is important

Figure 4 portrays the beliefs and knowledge of respondents about waste recycling. From the response, it can be seen that 464 respondents (51.05% out of the total sample) are very concerned about recycling, and they believe recycling is essential for a cleaner and sustainable world. In contrast, only four respondents (0.40% of the total survey population) do not believe that recycling is important for our society, which is very marginal. Again, a large number of people (185 respondents) were not interested in providing their opinion on this particular question. From the analysis of participants' responses and comparing them with previous survey question responses, it is noteworthy that although a large portion of participants are familiar with the term recycling, not all of them believe it is significant for the environment. González-Torre and Adenso-Díaz[64] said that cultural factors, humanitarian motives, and regulatory variables play significant roles in the development of strong recycling practices in particular communities. However, Radwan and Mangi[65] reported similar findings, stating that although the majority of citizens in KSA are aware of environmental degradation and challenges, not all of them tend to practice recycling.

Q3: Do you believe that the best way to dispose of waste is by recycling it?

Recycling plays a crucial role in sustainable waste management by reducing garbage pollution and recovering valuable raw materials and energy, sometimes referred to as "misplaced resources"[66,67]. Without any doubt, recycling is the best possible way of reducing pollution and conserving natural resources from RHW[68]. Based on this, we developed a question to understand the awareness of residents and how they think about recycling their waste. Figure 5 depicts the respondents' thoughts on the positive impact of waste recycling. From the response, it can be seen that 294 respondents (32.3% out of the total participants) believed that recycling is the best way to a cleaner and more sustainable world, while an additional 6.6% of participants believe recycling is a sustainable solution to some extent. In contrast, only 0.6% of respondents do not believe that recycling is the best way of waste disposal. As mentioned previously, almost 539 respondents (59.3%) were not interested in providing their opinion on this question. From this particular segmentation, it can be concluded that people have a positive attitude toward recycling solid waste and its impact on a sustainable world. Scheinberg[69] observed evidence suggesting that higher recycling rates are linked to higher tipping prices at garbage disposal sites. Increased disposal charge positively impacts the recovery of produced solid waste.

Q4: Do you throw away leftover food?

The amount of waste from food in Saudi Arabia is comparable to that of other affluent nations, such as the United States or European countries. Food waste has become a significant problem in the Gulf Countries, notably KSA, due to the region's limited agricultural resources and water supply[70]. Individuals tend to discard leftover food to avoid consuming the same meal again. Younger individuals and youngsters throw partly consumed packages of chips, chocolates, burgers, and beverage bottles[71]. These objects create trash on the road and serve as proof of food that has been squandered. The combination of excessive consumption and wastefulness has a negative impact on the economy and hinders the ability to save money[72]. The extravagance is indefensible and detrimental to both economic growth and food availability.

In this study, about 35.26% of the participants did not respond when questioned about their tendency to throw away their leftover food. It is apparent that only 25.97% of the participants never threw away their remaining food, while 31.47% of participants sometimes disposed of their leftovers. Conversely, 7.29% of respondents consistently throw away their leftovers without considering the detrimental impact on the environment, as displayed in Fig. 6. According to the analysis of Whitman[73] in a seminar titled "Reducing Food Waste" in Riyadh,

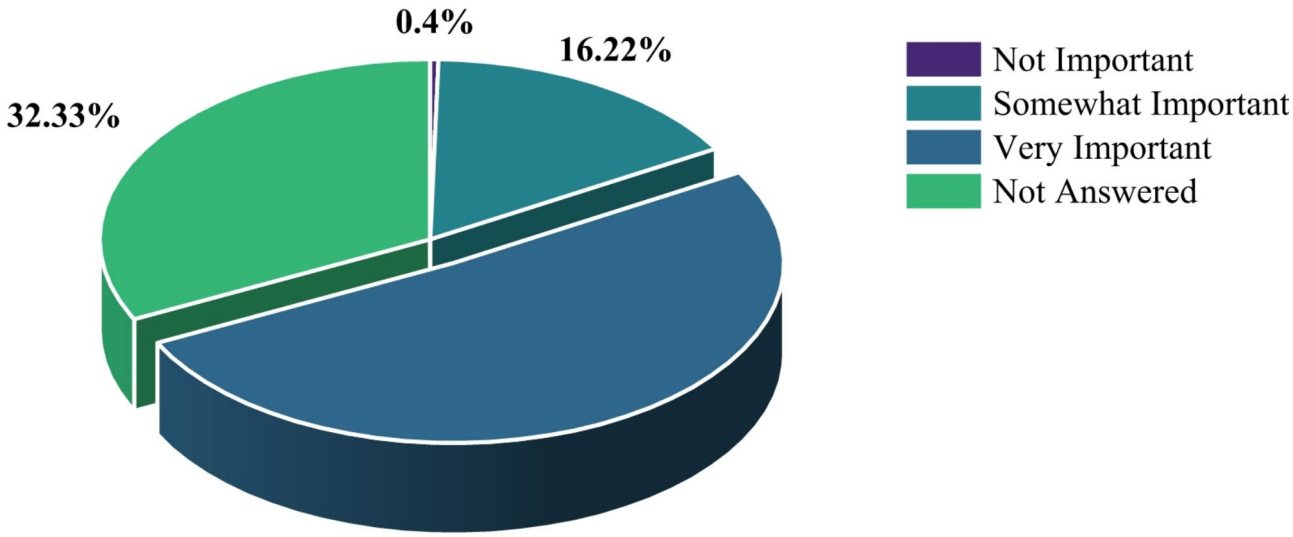


Fig. 4. Response based on survey question: "To what extent do you believe recycling is important?"

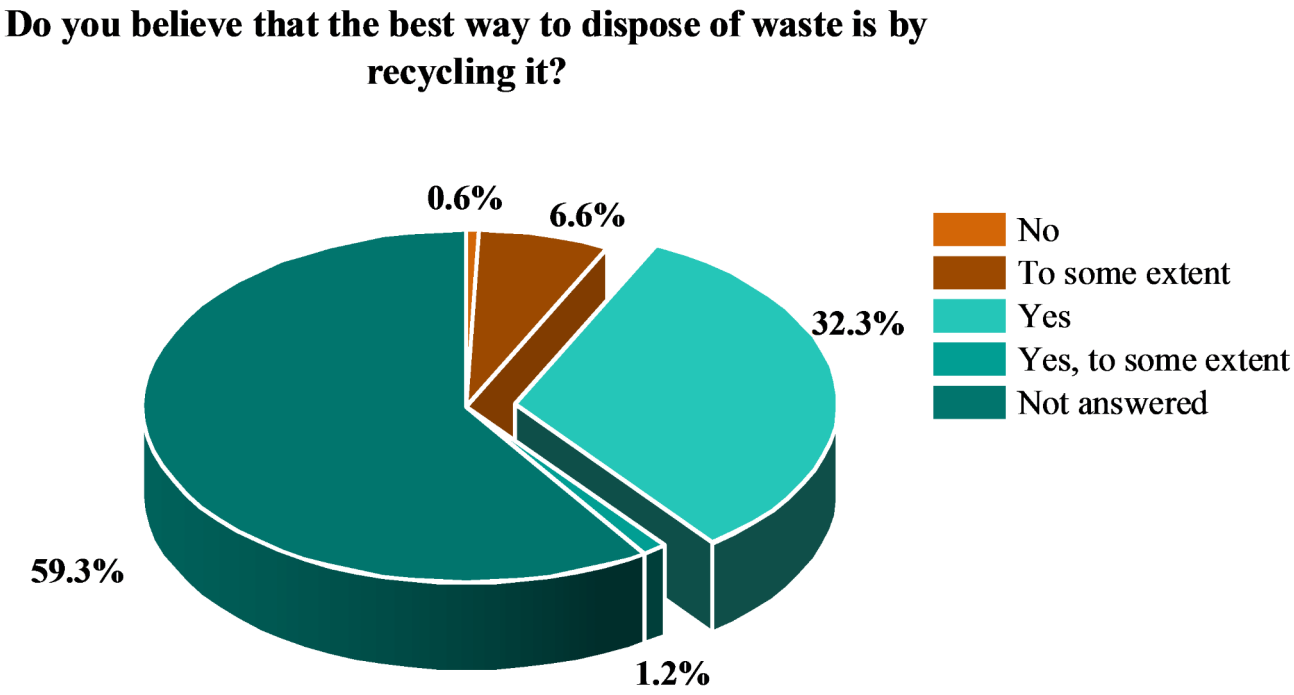


Fig. 5. Response based on the survey question: "Do you believe that the best way to dispose of waste is by recycling it?"

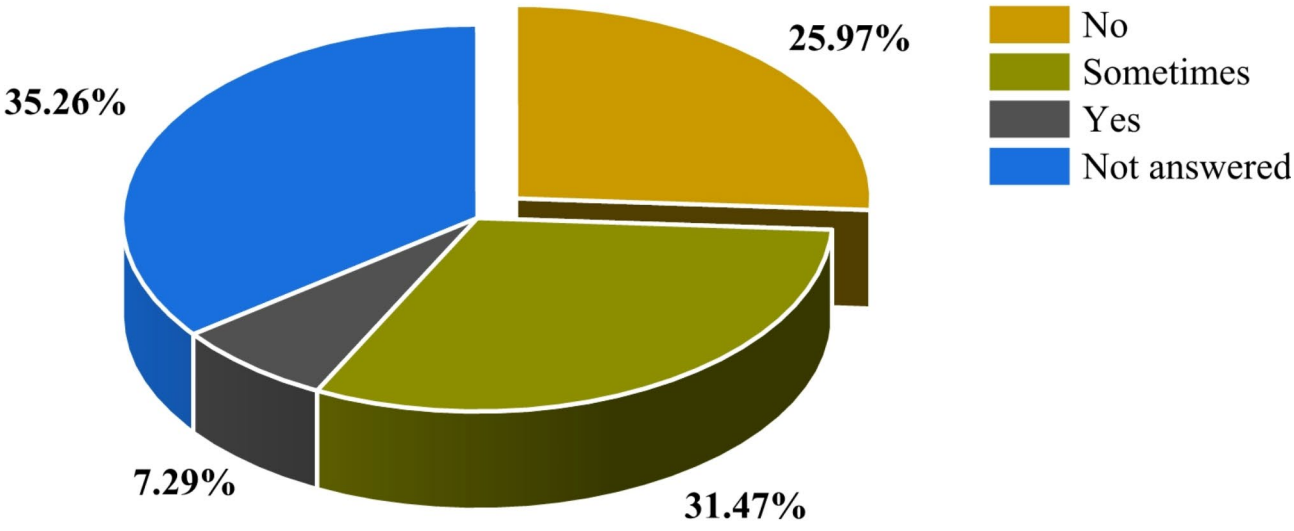


Fig. 6. Segmentation of response based on participant's leftover food recycling behavior.

it was found that Saudis throw away food costing US $35 million per day, which adds up to US $15 billion annually. According to reports, the typical citizen in the Kingdom of Saudi Arabia wastes between 1.2 and 1.4 kg of food every day, which adds up to 511 kg annually. One possible reason for this is that the average Saudi person eats excessive food, resulting in over 50% of it being wasted at home. The tendency to discard leftover food in Saudi Arabia is largely driven by concerns over potential health risks, a preference for variety in meals, and cultural practices of excessive consumption, particularly during public gatherings[70]. Similar to KSA, in Qatar, despite high literacy rates and government-led sustainability initiatives, a survey revealed that concerning number of households did not engage in regular recycling, citing limited public awareness campaigns and inadequate infrastructure as key barriers[74].

Q5: Have you ever searched for recycling centers?

Figure 7 illustrates how a person exhibiting care for the environment searches for a recycling facility in order to dispose of their garbage. The result reveals that 436 participants (48% out of the total participants) did

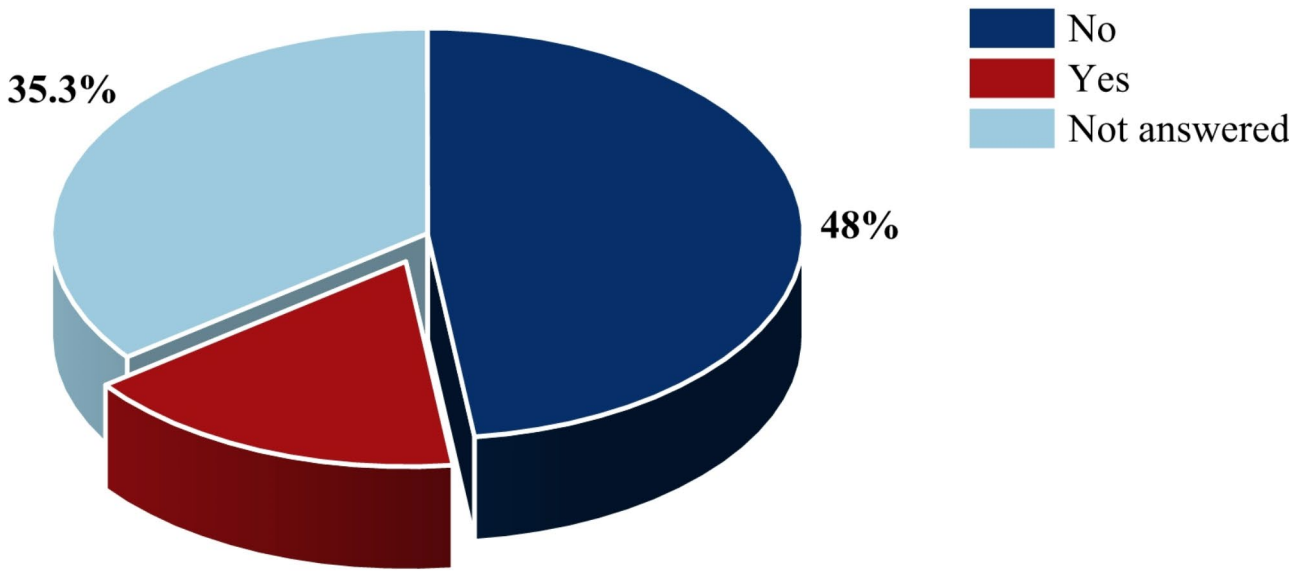


Fig. 7. Response based on the survey question: "Have you ever searched for recycling centers?"

not actively seek out a recycling center. Only 16.7% of respondents proactively looked for a recycling facility to dispose of their garbage. Based on this segmentation, it can be inferred that individuals exhibit a reduced tendency to seek out recycling centers. Consequently, the relevant authorities should intensify their advertising efforts to promote the positive effects of recycling. Additionally, they need to increase the number of recycling centers to enhance their accessibility.

González-Torre and Adenso-Díaz[64] noted that those who regularly deposit their general waste in the bins are more inclined to recycle specific items at home. Typically, as the distance to the recycling bins reduces, there is a rise in the number of fractions that individuals separate, sort, and collect their solid waste at home. The average Saudi Arabian not to search for recycling centers is influenced by limited accessibility and awareness, as research shows that proximity to recycling facilities significantly increases the likelihood of recycling behavior at home[28]. Minghua, Xiumin, Rovetta, Qichang, Vicentini, Bingkai, Giusti and Yi[75] suggested that to enhance recycling rates, local authorities could promote the advertisement for recycled products and enhance the workforce in recycling enterprises.

Q6: Would you support the culture of recycling in our country if the services were available?

Bui, Tseng, Tseng and Lim[76] categorized the primary obstacles to recycling into four categories: circumstances barriers (such as insufficient containers, limited space at home, and not reliable collections); behavioral barriers (such as household disorganization, lack of time or regular routine); knowledge barriers (such as not knowing what to recycle or the fundamental aspects of the recycling program); and attitude barriers (such as not believing in the environmental benefits and lack of incentives or acknowledgment for recycling efforts). From their study, it can also be clear that enhancing the recycling services provided by the government will encourage local citizens to support a recycling culture. Based on the output of this survey statistics, it can be concluded that the Saudi government needs to increase the recycling facility to involve all their residents in developing a sustainable country by recycling RHW.

Based on this context, when the participants are asked if their country has enough recycling available services, would they support the recycling culture or not? Remarkably, the reaction is quite favorable, as seen in Fig. 8. A total of 52.1% of the respondents express strong support for the culture, while an additional 11.7% indicate moderate support. By contrast, a negligible 0.3% of participants actively discourage the culture, indicating a very marginal stance. The poll findings indicate that if the government can effectively implement and make convenient recycling services available, the majority of the public would wholeheartedly embrace the culture of recycling to improve the country. The majority of respondents show positive support for the culture of recycling in Saudi Arabia because of the environmental benefits of recycling and are willing to participate if convenient and reliable services are made available, addressing common barriers such as accessibility, knowledge gaps, and insufficient infrastructure[61]. A similar trend can also be observed in other Middle Eastern countries. For example, in Jordan, a study has shown that while the majority of residents support waste segregation and recycling initiatives, inadequate waste segregation infrastructure and limited public awareness campaigns have hindered participation[77].

Measuring awareness based on agree or disagree with a statement

In this segment of our questionnaire, we investigated the degree to which the survey participants engaged in recycling and how they integrated recycling into their everyday lives. In Saudi Arabia, only 10–15% of this garbage is recycled, while the rest is disposed of in landfills[78]. A significant amount of the food waste produced in urban households gets repurposed at food banks and distributed to those facing food insecurity. This method may be

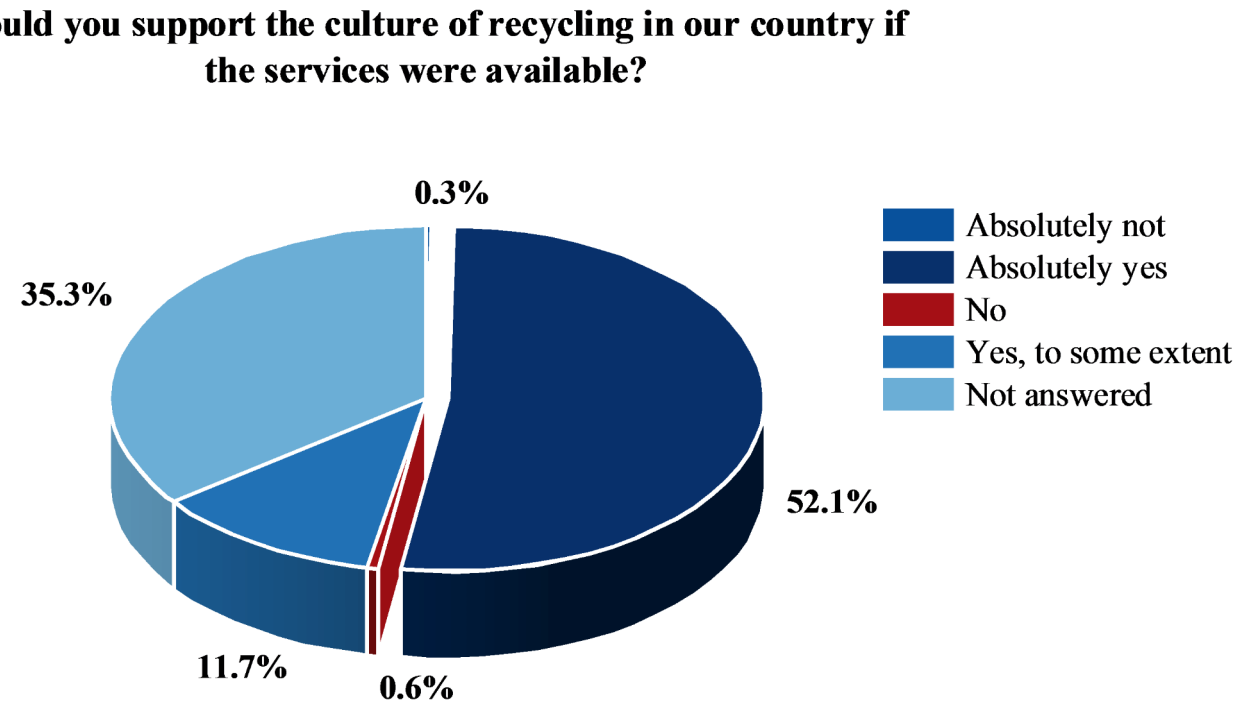


Fig. 8. Analysis of public attitude on the adoption of recycling practices in Saudi Arabia, dependent upon the availability of adequate recycling services.

universally applied to any garbage that can be recycled to minimize negative environmental impacts, preserve valuable resources, generate energy, and contribute to developing a more robust economy. Several writers have emphasized that the primary reasons for female households not recycling garbage at the source include a lack of knowledge, awareness, desire for recycled items, and supportive recycling regulations[78]. However, to measure the individual's recycling practice, we developed four statements that represent the individual's behavior and thinking about recycling. The first two statements are listed below:

Statement 1: I use plastic water bottles at home.

Statement 2: I support the implementation of strict laws against littering.

Figure 9 depicts the positive response to waste recycling among participants. When surveyed, around 34.7% of Saudi Arabian residents admitted to using plastic water bottles in their households. In contrast, barely 6% of participants refused to use plastic water bottles in their own households. These statistics suggest that plastic water bottles are frequently found among locals; however, not all bottles are recycled correctly due to a lack of awareness. When questioned about their opinions on enforcing strict laws against littering, 38.7% of respondents expressed their support for such measures. Remarkably, only 2% of participants expressed disagreement with the statement, which is undeniably noteworthy. This analysis suggests that the implementation of strict regulations by the government will be welcomed with approval by the majority of residents, leading to an enhancement in recycling behavior and practices throughout the country.

In the same context, it is notable that Saudi Arabia has implemented an extensive legislative structure at the national level to regulate and manage recyclable materials. The legal framework is defined by the General Environmental Regulations and the Solid Waste Law, which delineate the specific obligations for handling waste, as well as the National Environmental Standards[79]. The waste disposal regulatory structure is established following key concepts of waste management, including the waste hierarchy, the responsibility of treatment, and the nearby approach. The framework also offers explicit instructions for waste disposal to ensure the safeguarding of human health and the preservation of the environment[80]. Furthermore, in Kuwait, where per capita waste generation is among the highest in the region, recycling awareness remains low, and most waste is disposed of in landfills, largely due to insufficient policy enforcement and a lack of public education on recycling benefits[81].

Inadequate management of solid waste is a primary cause of pollution and environmental problems, including many challenges and shortcomings. Food waste contributes to the overutilization of substances, such as pesticides and fertilizers, used in food production[82]. Emissions of methane arise from industrial processes, agricultural practices, waste management activities, and the decomposition of food. It is recognized as one of the most detrimental greenhouse gases that contribute to climate change. Although methane has a shorter lifespan in the atmosphere compared to carbon dioxide, it is 25 times more effective and potent at trapping radiation as a greenhouse gas[83]. Large quantities of food discarded in landfills emit significant greenhouse gases, including methane, carbon dioxide, and chlorofluorocarbons. These gases trap infrared radiation and contribute to the warming of the Earth's atmosphere, leading to global warming and climate change[83].

However, efficient solid waste recycling is crucial for mitigating resource limitations and promoting widespread sustainable economic development globally[84]. Local and federal governments should implement

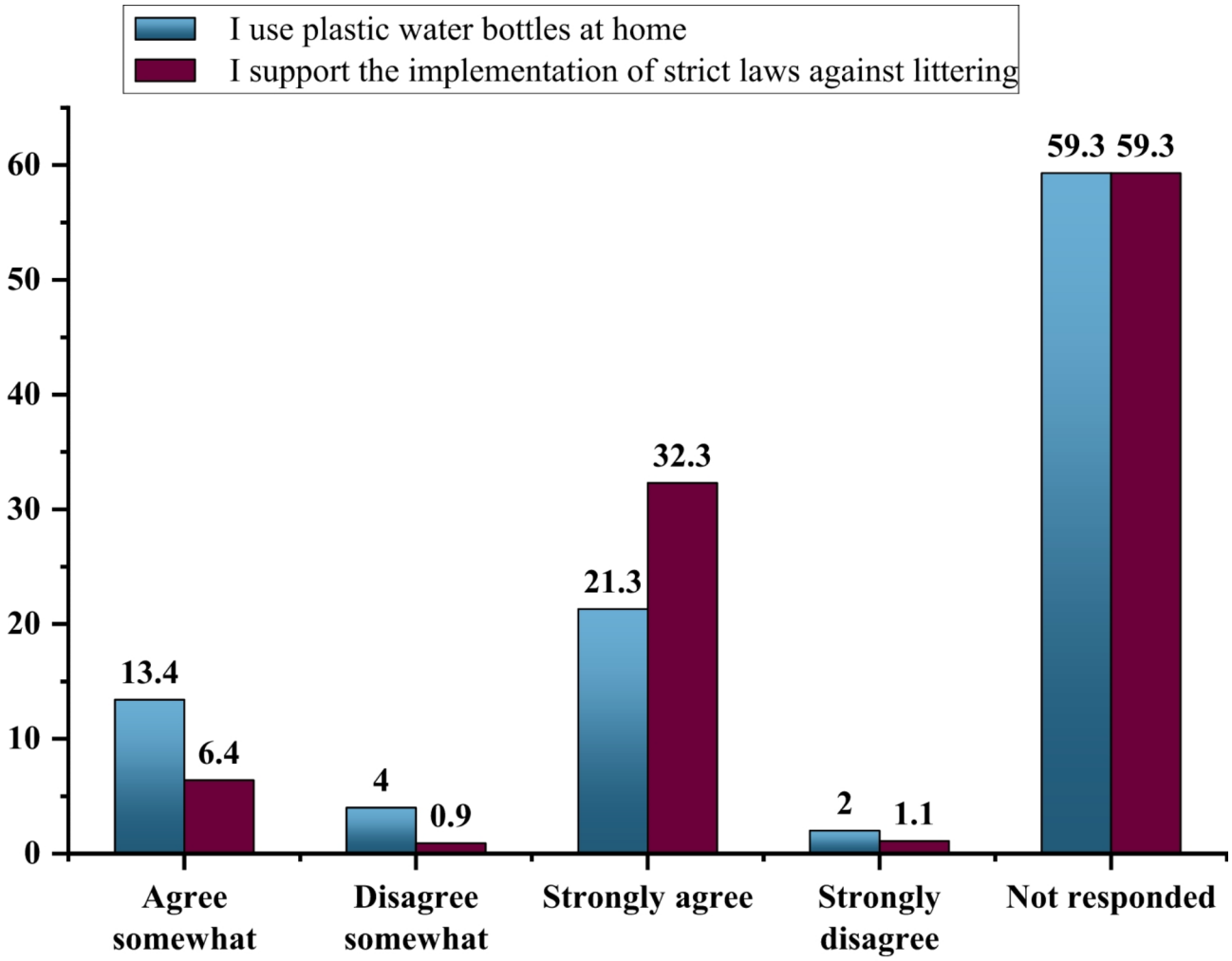


Fig. 9. Analyze the rate of engagement of Saudi Arabians in using plastic materials and their opinions on the strict regulations against littering.

a zero-waste strategy by adopting durable, reusable items, which will contribute to the sustainable growth of the economy[85]. The items should be built to align with their optimal endurance and the recyclability of their parts. Implementing a zero-waste policy facilitates the integration of industries, enterprises, and communities by ensuring that the trash produced by one entity is used as a raw material by another, effectively preventing pollution[86].

Considering this context, we formulated two statements that reflected participants' beliefs regarding the significance of recycling for both economic and environmental sustainability.

Statement 3: I agree that waste is harmful to the environment and society.

Statement 4: I believe that recycling is economically beneficial.

According to Fig. 10, most survey participants (37.3%) strongly believe that trash harms the environment, while a small percentage (3.1%) just agree with this perspective. Conversely, a very small proportion (0.3%) of respondents believe that waste is not harmful to our environment. In our last statement, 7% of the participants agree, while 33.1% strongly agree that recycling waste can contribute to economic sustainability. A relatively small percentage of participants, specifically 0.5%, do not consider recycling to be an economically advantageous method of waste disposal. Nevertheless, many participants maintain a neutral viewpoint in both situations.

Measuring awareness based on an individual's willingness to practice recycling

When the participants were asked if they had enough opportunity to sell their recyclable garbage, most survey participants (32.3%) strongly agreed that they would support the idea and would recycle more garbage, while an additional 6.4% just agreed with this initiative. Simultaneously, a negligible proportion (0.9%) of respondents strongly opposed this idea, with an additional 1.1% somewhat opposing this initiative, as shown in Fig. 11. Solid waste management initiatives in developing nations are facing significant challenges, such as inefficient sorting and collection systems for recyclable garbage and inadequate incentives from local authorities. Furthermore, inadequate infrastructure, poor regulatory measures, and low public knowledge may lead to improper disposal, such as mixing plastic and electronic waste with regular home garbage[87].

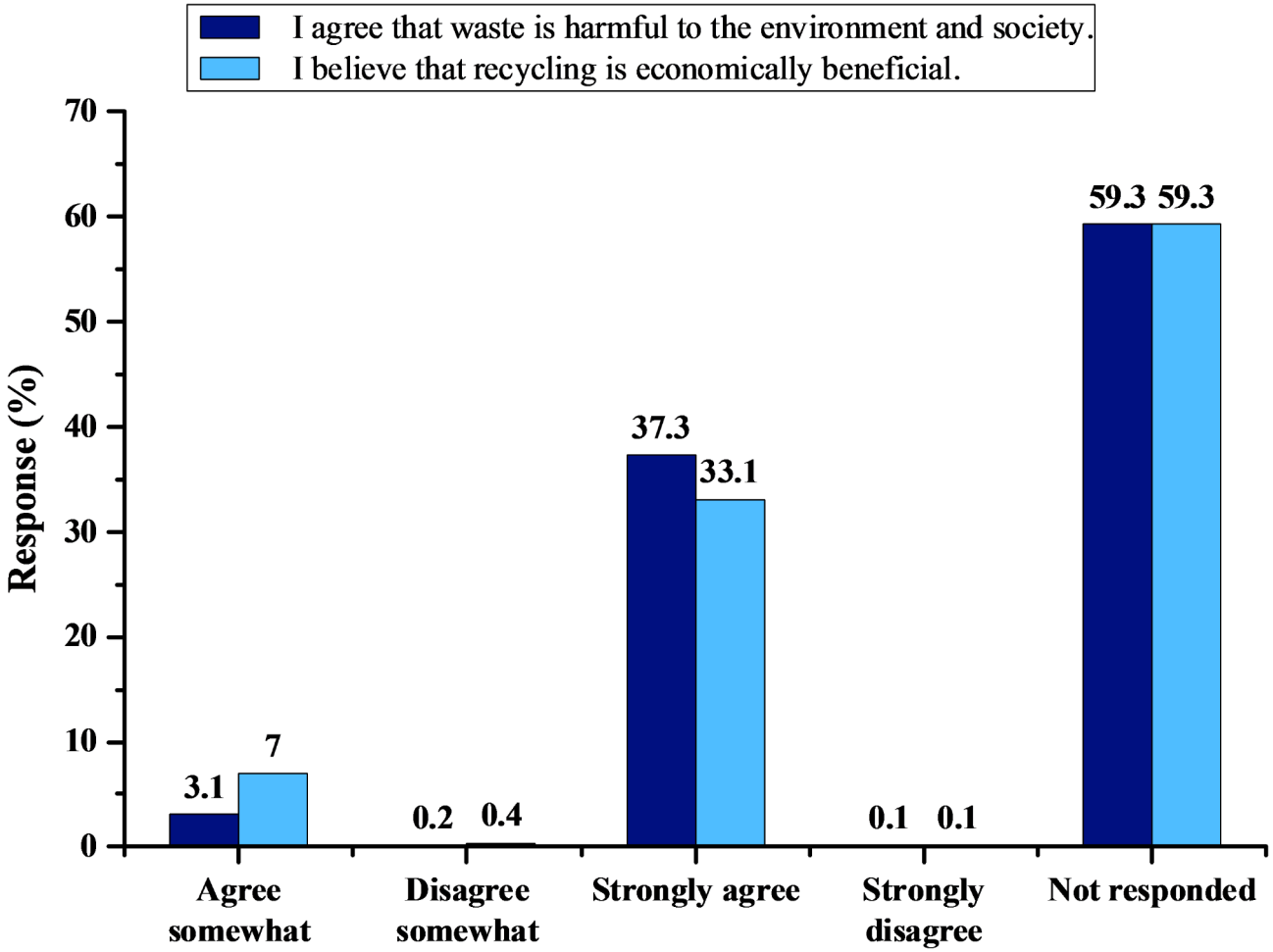


Fig. 10. Analysis of the rate of Saudi Arabian's opinions on the environmental and economic benefits of waste recycling.

In Saudi Arabia, trash recycling was non-existent before 2017. The National Transformation Program (NTP) 2020 set a goal to raise the proportion of processed waste by 40% of the total garbage produced. Also, Saudi Arabia Vision 2030 targeted 100% recycling[88,89]. SAV2030 is also planning a strategic cooperation to handle the garbage produced in the nation effectively. Saudi Arabia has formed partnerships with the Ministry of Environment, Water and Agriculture, Saudi Investment Recycling Company, National Recycling Center, and Ministry of Municipal and Rural Affairs companies to effectively handle garbage by implementing recycling practices[63]. Enhancing the effectiveness of municipal solid waste management systems is a key objective for SAV2030 [63]. Thus, Saudi citizens are expected to soon get proper facilities and opportunities to sell their surplus and contribute to sustainable development.

Regression analysis

A regression analysis was conducted to examine the relationship between individuals' support for recycling services and various environmental attitudes and behaviors, including plastic bottle usage at home, support for strict littering laws, beliefs about waste harm, the perceived economic benefits of recycling, and the willingness to engage in recycling surplus sales. According to the analysis results shown in Table 2, the support for strict littering laws and the belief in the economic benefits of recycling show a significant positive association with recycling support. This suggests that when individuals perceive recycling as economically beneficial or tied to strict littering regulations, they are more likely to support recycling services. As it is seen, the relationship between individuals' support for recycling services and plastic bottle usage at home has an intercept value of 3.81, representing the baseline support level, while the coefficient is 0.077. These findings stated that the relationship is statistically insignificant ($P = 0.539$), with a 95% confidence interval ranging from −0.171 to 0.326, indicating no clear impact. Similarly, the relationship between support for recycling and the belief in the economic benefit of recycling shows an intercept of 3.782 and a highly significant coefficient of 0.2084 ($P = 0.0002$), with a confidence interval from 0.098 to 0.318.

In contrast, other beliefs, such as the belief that waste is harmful, have a borderline significant association ($P = 0.071$) with a coefficient of 0.078 and a confidence interval from −0.0087 to 0.164, showing a weak relationship. Similarly, the support for recycling surplus sale displays a non-significant negative coefficient of

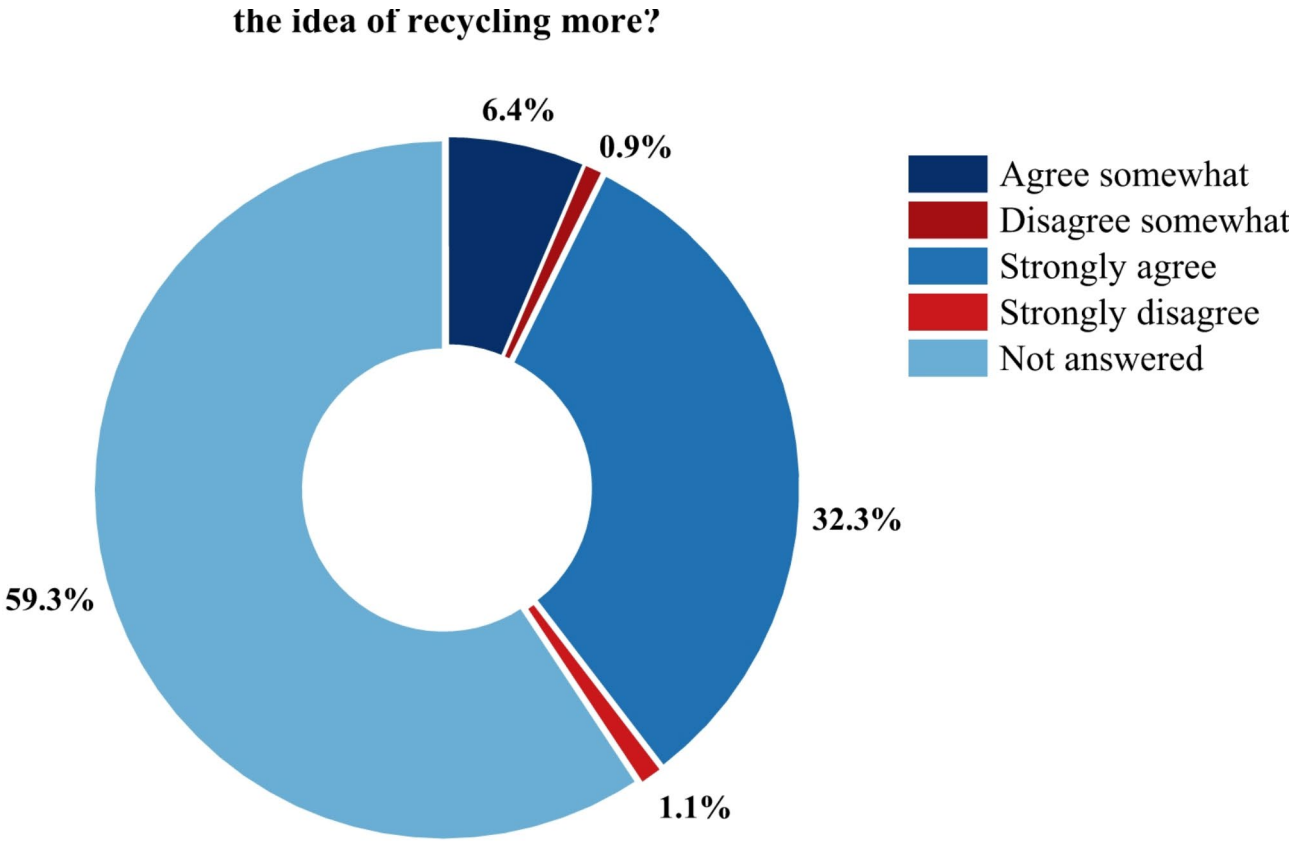


Fig. 11. Response of participants to sell their recyclable waste if they have adequate opportunities.

	Coefficient	Standard Error	t-value	P-value	95% confidence interval	
					Lower	Upper
Relationship between support for recycling service and plastic bottle usage at home						
Intercept (const)	3.810	0.610	6.238	1.22E-09	2.609	5.011
Recycling support	0.077	0.126	0.613	0.539	-0.171	0.326
Relationship between support for recycling service and support for strict littering laws						
Intercept (const)	3.395	0.432	7.853024	4.49E-14	2.544985	4.245
Recycling support	0.265	0.089	2.963626	0.003	0.089	0.441
Relationship between support for recycling service and belief that waste is harmful						
Intercept (const)	4.519	0.210	21.514	4.63E-67	4.106	4.932
Recycling support	0.078	0.043	1.808	0.071306	-0.006	0.164
Relationship between support for recycling service and belief in economic benefit of recycling						
Intercept (const)	3.782	0.269	14.012	4.76E-36	3.251	4.313
Recycling support	0.208	0.055	3.726	0.0002	0.098	0.318
Relationship between support for recycling service and support for recycling surplus sale						
Intercept (const)	5.272	0.389	13.534	3.29E-32	4.505	6.039
Recycling support	-0.116	0.081	-1.435	0.152	-0.276	0.043

Table 2. Regression analysis outcomes.

-0.116 ($P = 0.152$), with a confidence interval of -0.276 to 0.043, indicating that this factor may not strongly influence support for recycling services.

Partial dependency of factors on recycling awareness

Figure 12 displays partial dependence plots (PDP) illustrating the relationships between variables such as the age, gender, marital status, and salary range of participants and their behavior regarding leftover food. As the value increases, the respondent's positive behavior in recycling awareness also increases.

The PDP analysis reveals that the age of participants significantly influences their attitude toward littering waste. Individuals aged 20 to 40 have a greater tendency to discard their leftover foods. Among them, the participants aged 20 to 30 years have the least awareness about waste recycling. However, older people are more aware of the detrimental effects of waste and demonstrate a commendable level of engagement in the recycling process, as seen in Fig. 12(a). Figure 12(b) illustrates the influence of participants' gender on recycling awareness. Interestingly, male participants have a higher level of awareness about waste littering compared to female participants. In the Saudi context, males are generally more exposed to public discourse on environmental initiatives due to higher workforce participation and increased engagement with formal waste management systems. Furthermore, practical barriers such as limited mobility and traditional domestic roles may result in women having fewer opportunities to engage directly with recycling infrastructures, thereby impacting their overall awareness levels[90]. The observed discrepancy in awareness between genders highlights the need for targeted awareness campaigns that effectively engage women and promote accessible recycling participation strategies across different demographic groups. In contrast, many studies have also shown that gender does not significantly determine recycling behavior[91,92].

Several studies suggest that there is a correlation between age and recycling behavior. Specifically, older individuals tend to engage in recycling programs more than younger individuals. However, other surveys have shown no significant association between age and recycling. Several research studies have shown that higher-income households are more likely to engage in recycling programs than low-income families. However, other studies have shown no significant correlation between salary and recycling[61,93]. In a study conducted by Ojeda-Benítez, Armijo-de Vega and Marquez-Montenegro[94], the authors examined the patterns of RHW production in Mexico and determined that the family has a significant and enduring impact on the attitudes and actions of its members, particularly in terms of consumption and waste management. Therefore, it is crucial to prioritize family-oriented educational initiatives regarding the environment. Furthermore, the recycling behavior of Saudi families is also affected by their marital status, as seen in Fig. 12(c). The study reveals that the partial dependency value for the married status is lower than that of the single status, indicating that married individuals are more accountable for littering garbage than their single counterparts.

Their monthly income significantly influences individuals' recycling awareness. Based on our survey data and PDP analysis, individuals in the modest income range of 5000–10,000 SAR have the least tendency to throw away leftovers. As affluence rises, individuals tend to become less conscious of the need for recycling. Also, people with low incomes tend to have less knowledge of garbage littering than those in the moderate-income category, as illustrated in Fig. 12(d).

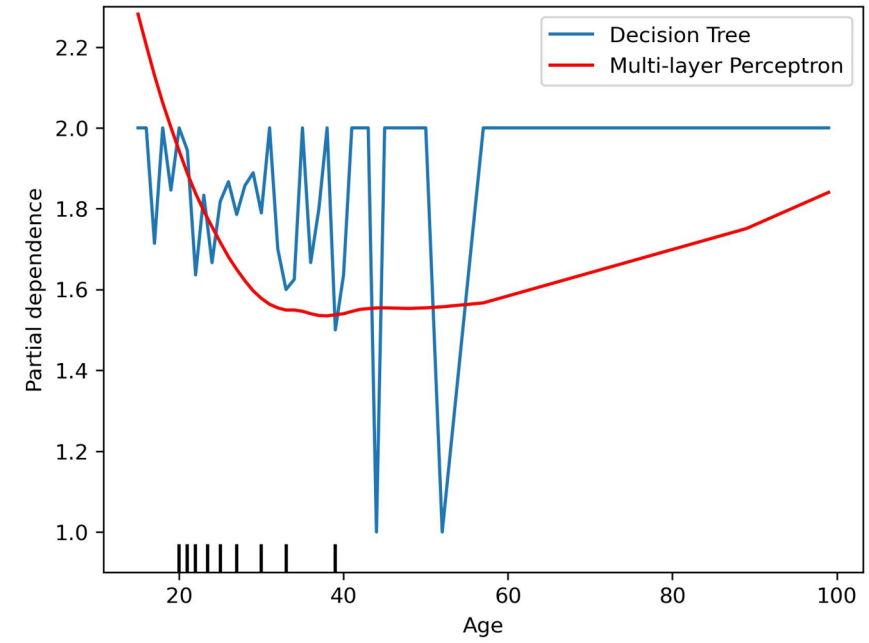
Figure 13 displays partial dependence plots illustrating the relationships between sociodemographic factors and the positive belief of participants on waste recycling. These beliefs are mainly indicating the awareness of a specific group of respondents. As is seen in Fig. 13(a), people aged between 22 and 34 have the lowest belief in recycling, and they don't believe recycling is the best way to dispose of solid waste. Senior citizens 45 years old or older have the highest partial dependency on waste recycling, indicating that they have positive thoughts about sustainable recycling practices.

Again, male participants responded better than female participants when asked if they believed recycling was the best waste disposal system. As illustrated in Fig. 13(b), the response is surprising because male respondents are more severe and aware of recycling, although the majority of female residents stayed home in Saudi Arabia. When considering participants' marital status, married people are more optimistic about waste recycling. The response is displayed in Fig. 13(c), which is controversial compared to the results illustrated in Fig. 12(c). By analyzing those dependency plots, it can be concluded that married participants have high morale about recycling, and their belief is more positive comparing single people. However, married participants are more liable for throwing away leftover food.

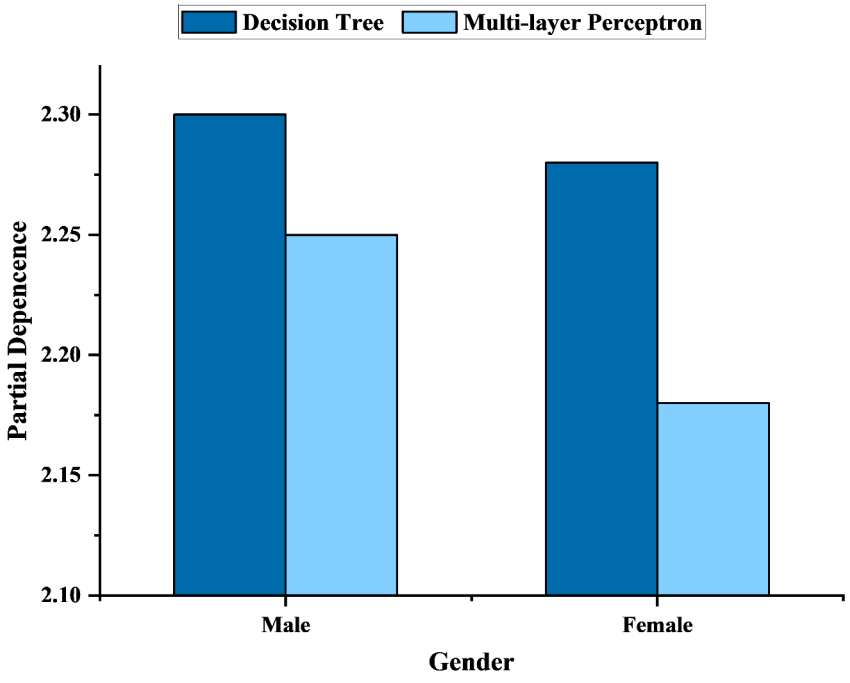
According to a study conducted by Al-Khraif, Abdul Salam and Abdul Rashid[95], people with families and children need to buy more groceries than bachelors. Not all those groceries are consumed, and a significant portion are thrown away as leftovers. That is why married people have a high rate of food waste. Most of those leftover groceries are teenage and children's products such as chips, beverages, fast foods, and other items. Figure 13(d) illustrates the effect of participants' monthly salary on their recycling thoughts. As seen in previous dependency plots, the residences with an average income of 5000-10,000 SAR have the highest dependency value, indicating that they have the highest awareness about waste recycling. As predicted, lower-income people have the lowest recycling awareness. Awareness among these underprivileged groups of people must be increased through direct advertisement or any educational and practicing sessions conducted by local authorities. However, when the income of individuals increases, the awareness about recycling also linearly decreases, which is a concerning behavior.

Limitations and future recommendations

Although the response to the questionnaire survey and analysis revealed a wide range of information on the current waste management and recycling trend in Tabuk City of KSA, there are still some limitations to this study. The reliance on self-reported data can introduce potential biases such as social desirability and recall bias, which may impact the accuracy of responses. To mitigate this, the study employed random and stratified



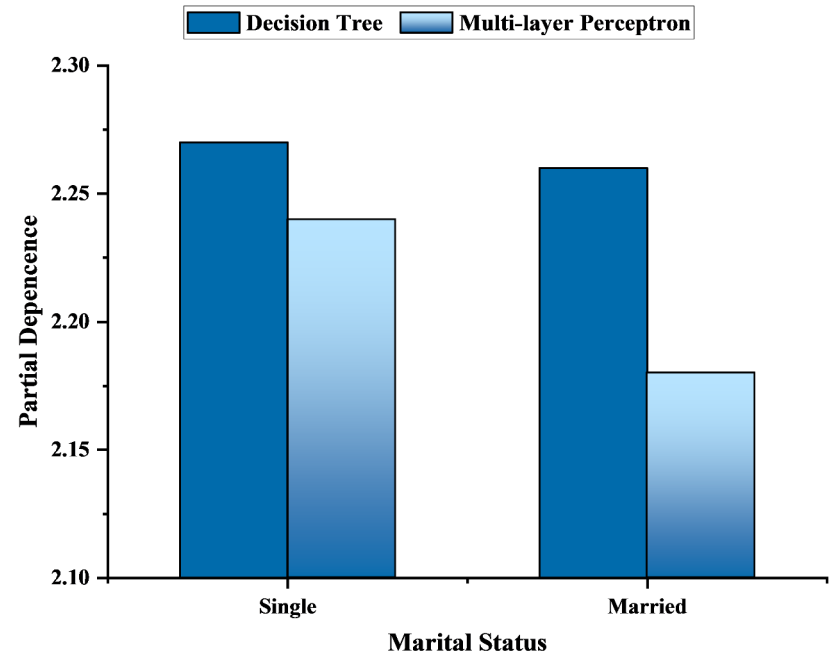
(a)



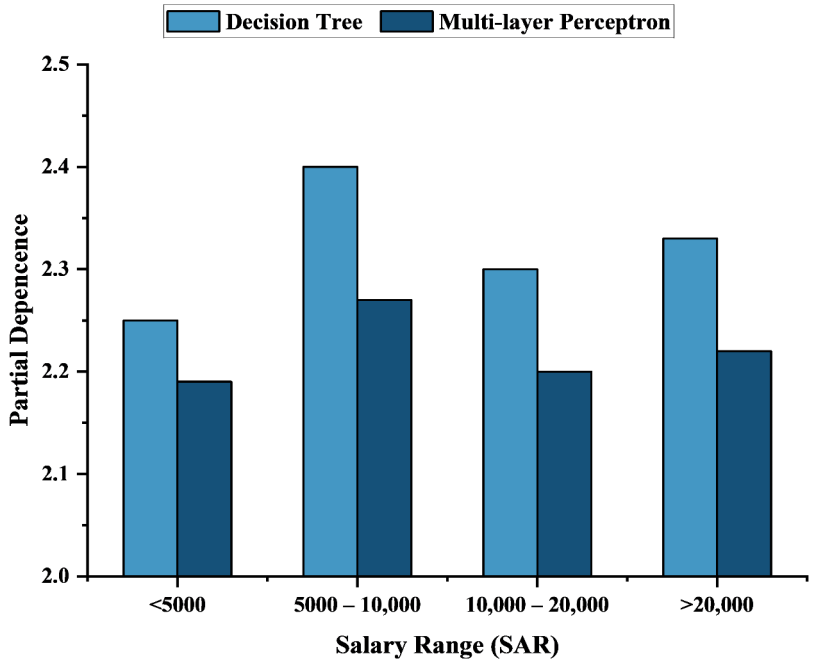
(b)

Fig. 12. Partial dependency of influential factors (**a**) Age of participants, (**b**) Gender, (**c**) marital status, and (**d**) salary range of participants on recycling awareness based on leftover food thrown away concern.

sampling techniques to ensure representativeness and distributed questionnaires both online and offline to capture a diverse participant base. Additionally, the survey achieved a relatively large sample size of 909 participants, which enhances the robustness of the findings. However, the regional focus of the study, primarily in Tabuk City, limits the generalizability of the results to the broader Saudi population or other cultural contexts. Future studies could address this limitation by expanding the geographic scope of data collection and employing



(c)

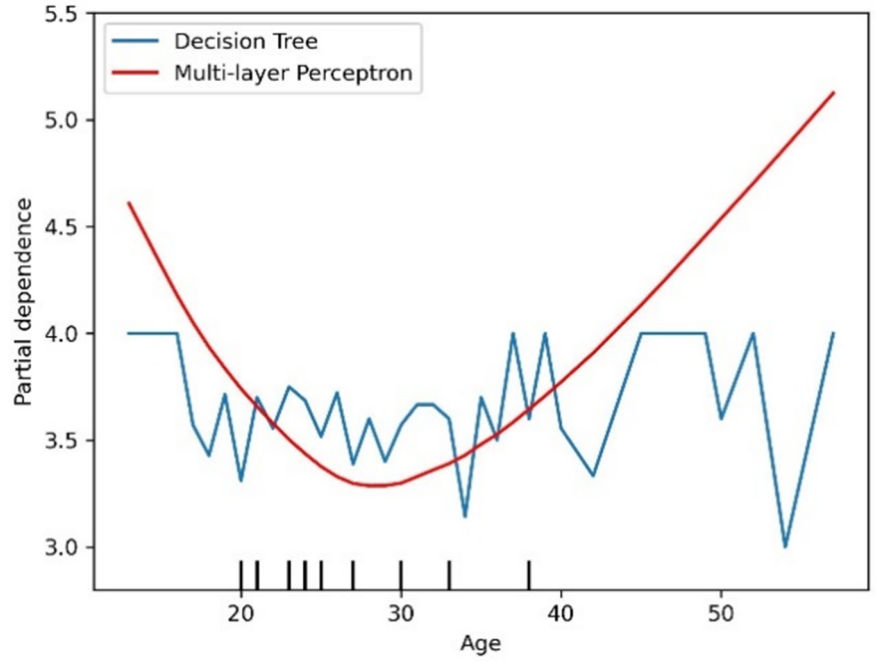


(d)

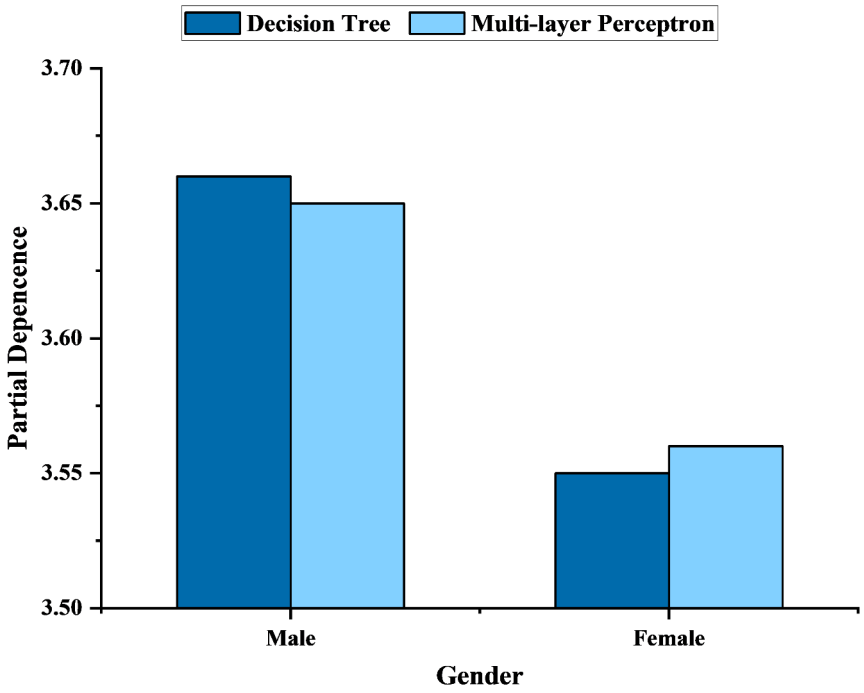
Figure 12. (continued)

mixed-method approaches, including observational studies or experimental designs, to validate and supplement self-reported findings.

While collecting data, it was observed that the city's solid waste recycling system is still in its early stages. Moreover, municipal solid garbage was still collected in a single container. Separate recycling containers are still not used on a significant basis. However, the city reports that certain private sector businesses gather bulk aluminum cans, steel, and plastic containers from landfills. A private contractor collects mixed MSW from bins spread equally across the district streets as part of the general garbage collection system. To date, there have been



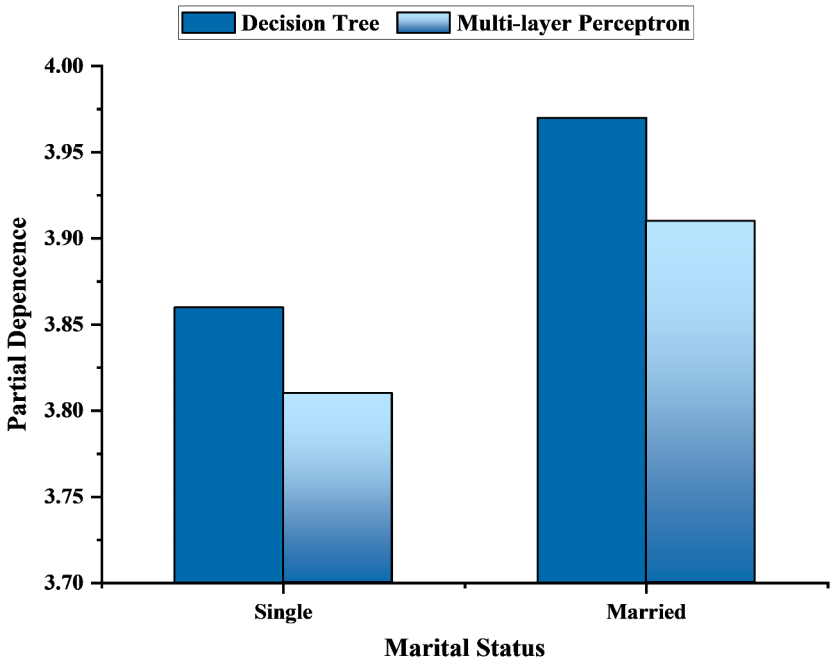
(a)



(b)

Fig. 13. Partial dependency of influential factors (**a**) Age, (**b**) Gender, (**c**) marital status, and (**d**) monthly income of participants on their belief of the positive impact of waste recycling.

hesitant efforts to separate MSW. For example, there are separate bins for collecting bread waste, which is used to feed cattle. Based on the findings of this study, it can be seen that the majority of the residents are highly willing to participate in the waste segregation and recycling programs, but due to lack of such initiatives, the system is not implementable. Also, considering the increasing volume of garbage generated by the Saudi population, the government highly needs to establish a recycling program with strict rules to tackle this detrimental waste and



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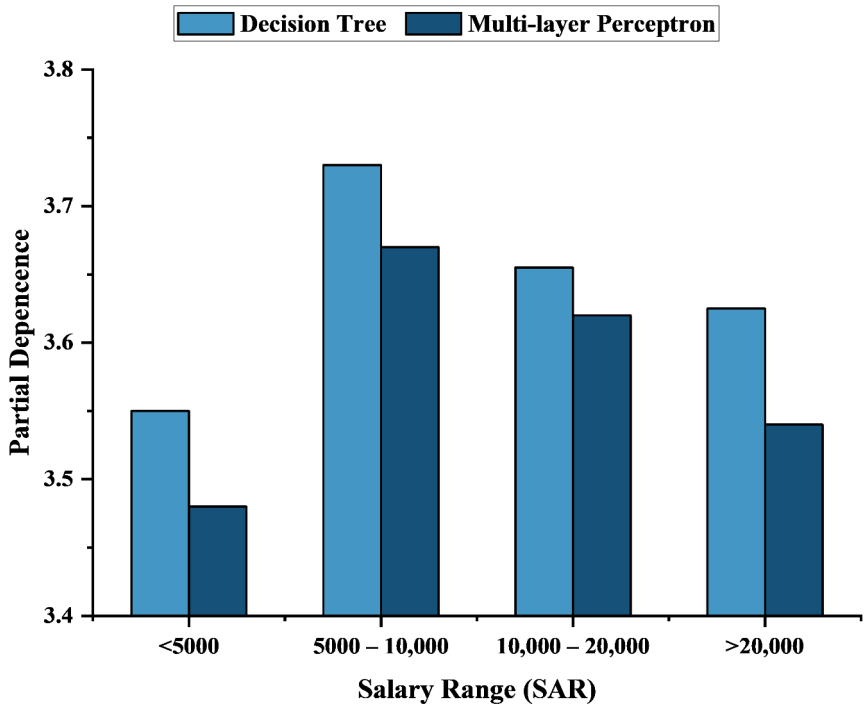

(d)

Figure 13. (continued)

encourage waste recycling for the betterment of the community. The local government should work hard to establish a solid waste legislation framework based on our study results.

Furthermore, a comprehensive analysis of the widely utilized RHW management technique is necessary immediately since this approach can deal with a lot of waste disposal and energy production, including hazardous waste and specific wastes generated by dwelling residents[96]. In addition, the government should provide education and promote awareness about the adverse impacts of solid waste to the public in order to foster a widespread propensity towards recycling. As can be seen from the survey data, the majority of the respondents

are young students, unemployed, and have lower income; thus, the outcomes reflect mostly their characteristics, and we need to focus more on this particular group of people to enhance the waste management and recycling system. Thus, spreading waste recycling awareness through education campaigns for students and lower-income groups of people is a crucial need. Research indicates that a person's knowledge, verbal commitment, and feeling of responsibility impact the constancy of their attitude toward the environment and their conduct[39,97]. Educating students about solid waste may increase awareness and support for waste management strategies to improve the community environment and also reduce spreading of deseases. To get public support for addressing solid waste issues, it's crucial to educate every part of the population on the problem and the government's aims.

Conclusions

This survey attempted to assess the respondents' knowledge and motivation to recycle RHW. Proper waste recycling is crucial for mitigating environmental issues and may also provide economic advantages. Based on the findings of the research, the following suggestions can be summarized:

In this questionnaire survey, the majority were headed by males, with 437 men participating. Simultaneously, a total of 292 women took part in the research. The age group that had the most representation was those between the ages of 18 and 40. On the other hand, unemployed individuals and students are the main participants in this survey who have salaries lower than 5000 SAR. According to the study findings, 67.93% of the participants were familiar with recycling. Among them, 51.05% believe that recycling is significant for their community. Only 32.03% of the entire study population believe that recycling is the optimal method of garbage disposal. This suggests that a significant portion of the population still does not consider the sustainable waste recycling process. However, there was a positive attitude that 52.1% of participants supported waste recycling if the government provided adequate facilities.

In the third stage of the questionnaire round, 34.7% of Saudi Arabian residents admitted to using plastic water bottles in their households. After that, when questioned about their opinions on enforcing strict laws against littering, 38.7% of respondents expressed their support for such measures. In every stage, the majority of participants showed a positive attitude toward recycling. However, a remarkable number of the population did not share their opinion and remained silent every time. In the last stage of the survey, 32.3% of respondents expressed their support for selling their surplus for economic benefit if they had the opportunity to do so. The partial dependency plot showed that older people have a greater awareness of the detrimental effects of waste and demonstrate a commendable level of engagement in the recycling process. Similarly, male and single participants are more aware of waste littering than their counterparts. The analysis also visualized that people with moderate incomes are the group most responsible for waste recycling.

The findings of this study, while focused on Saudi Arabia, hold significant implications for other developing nations facing similar challenges in residential solid waste management and recycling. Many developing countries experience rapid urbanization, population growth, and inadequate infrastructure, resulting in improper waste disposal and its associated environmental and health risks. The outcomes and recommendations of this study regarding the influence of sociodemographic factors on recycling awareness, as well as the importance of providing adequate facilities and promoting public education, can serve as a valuable reference for policymakers in these regions. Specifically, the identified need for accessible recycling infrastructure and targeted awareness campaigns could be universally applied to encourage public participation in sustainable waste management practices. Finally, by adapting the strategies suggested in this study, decision-makers of such nations can address their unique waste management challenges and take necessary steps to enhance their waste management and recycling practices.

Data availability

Our objective is to maintain control over unsupervised usage that may lead to unintentional duplication of research efforts or reduced novelty in future studies. however, the dataset will be provided upon request. Please contact Moahd Khaled Alghuson (malghuson@ut.edu.sa) if anyone needs the data for this study.

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References

1. Mir, M. A., Chang, S. K. & Saudi Arabia, E-W. Management strategies, challenges and opportunities, effect on health and environment: A strategic review. *Emerg. Contam.* **10**, 100357 (2024).
2. Su, L. et al. Creep characterisation and microstructural analysis of municipal solid waste incineration fly Ash geopolymer backfill. *Sci. Rep.* **14**(1), 29828. https://doi.org/10.1038/s41598-024-81426-7 (2024).
3. Liu, R., Jiang, S., Ou, J., Kouadio, K. L. & Xiong, B. Multifaceted anomaly detection framework for leachate monitoring in landfills. *J. Environ. Manag.* **368**, 122130. https://doi.org/10.1016/j.jenvman.2024.122130 (2024).
4. Mishra, M., Das, D., Laurinavicius, A., Laurinavicius, A. & Chang, B. H. Sectorial analysis of foreign direct investment and trade openness on carbon emissions: A threshold regression approach. *J. Int. Commer. Econ. Policy*. https://doi.org/10.1142/s1793993325500036 (2024).
5. Mishra, M. Quantifying compressive strength in limestone powder incorporated concrete with incorporating various machine learning algorithms with SHAP analysis. *Asian J. Civil Eng.* https://doi.org/10.1007/s42107-024-01219-1 (2024).
6. Sobuz, M. H. R. et al. Microstructural behavior and explainable machine learning aided mechanical strength prediction and optimization of recycled glass-based solid waste concrete. *Case Stud. Constr. Mater.* **22**, e04305. https://doi.org/10.1016/j.cscm.2025.e04305 (2025).
7. Islam, M. H., Prova, Z. N., Sobuz, M. H. R., Nijum, N. J. & Aditto, F. S. Experimental investigation on fresh, hardened and durability characteristics of partially replaced E-waste plastic concrete: A sustainable concept with machine learning approaches. *Heliyon* **11**(2), e41924. https://doi.org/10.1016/j.heliyon.2025.e41924 (2025).

8. Safayet, M. A. et al. Combined influence of eggshell powder and nylon fiber on self-compacting concrete production: Experimental assessment and machine learning quantifications. *Mater. Res. Express*. **12**(2), 025003. https://doi.org/10.1088/2053-1591/adb0a6 (2025).
9. Ugwu, C. O., Ozoegwu, C. G. & Ozor, P. A. Solid waste quantification and characterization in university of Nigeria, Nsukka campus, and recommendations for sustainable management. *Heliyon* **6**(6), e04255 (2020).
10. Omran, A. & Gebril, A. O. Study of household attitude toward recycling of solid wastes: A case study. *Acta Technica Corviniensis-Bulletin Eng.* **4**(1), 79 (2011).
11. Mishra, M., Keshavarzzadeh, V. & Noshadravan, A. Reliability-based lifecycle management for corroding pipelines. *Struct. Saf.* **76**, 1–14. https://doi.org/10.1016/j.strusafe.2018.06.007 (2019).
12. Bui, T. D., Tsai, F. M., Tseng, M. L. & Ali, M. H. Identifying sustainable solid waste management barriers in practice using the fuzzy Delphi method. *Resour. Conserv. Recycl.* **154**, 104625 (2020).
13. Zhao, S., Zhang, L., Peng, L., Zhou, H. & Hu, F. Enterprise pollution reduction through digital transformation? Evidence from Chinese manufacturing enterprises. *Technol. Soc.* **77**, 102520. https://doi.org/10.1016/j.techsoc.2024.102520 (2024).
14. Qiao, G., Hou, S., Huang, X. & Jia, Q. Inclusive tourism: Applying critical approach to a web of science bibliometric review. *Tourism Rev.* https://doi.org/10.1108/TR-04-2024-0332 (2024).
15. Wang, S., Yan, W. & Zhao, F. Recovery of solid waste as functional heterogeneous catalysts for organic pollutant removal and biodiesel production. *Chem. Eng. J.* **401**, 126104 (2020).
16. Farmanbordar, S., Amiri, H. & Karimi, K. Synergy of municipal solid waste co-processing with lignocellulosic waste for improved Biobutanol production. *Waste Manag.* **118**, 45–54 (2020).
17. Tayeh, H. N. A., Azaizeh, H. & Gerchman, Y. Circular economy in Olive oil production–olive mill solid waste to ethanol and heavy metal sorbent using microwave pretreatment. *Waste Manag.* **113**, 321–328 (2020).
18. Mallick, J. Municipal solid waste landfill site selection based on fuzzy-AHP and geoinformation techniques in Asir region Saudi Arabia. *Sustainability* **13**(3), 1538 (2021).
19. Hoque, M. M. & Rahman, M. T. U. Landfill area Estimation based on solid waste collection prediction using ANN model and final waste disposal options. *J. Clean. Prod.* **256**, 120387 (2020).
20. Rathore, P. & Sarmah, S. P. Economic, environmental and social optimization of solid waste management in the context of circular economy. *Comput. Ind. Eng.* **145**, 106510 (2020).
21. Dahlawi, S. & El Sharkawy, M. F. Assessment of solid waste management practice in the university campus. *Int. J. Sustain. High. Educ.* **22**(3), 561–575 (2021).
22. Luttenberger, L. R. Waste management challenges in transition to circular economy–case of Croatia. *J. Clean. Prod.* **256**, 120495 (2020).
23. Smyth, D. P., Fredeen, A. L. & Booth, A. L. Reducing solid waste in higher education: The first step towards 'greening'a university campus. *Resour. Conserv. Recycl.* **54**(11), 1007–1016 (2010).
24. Umar, T. Greenhouse gas (GHG) emissions from municipal solid waste (MSW) in Oman. *Int. J. Social Ecol. Sustainable Dev. (IJSESD)*. **13**(1), 1–26 (2022).
25. Umar, T. Municipal solid waste generation, composition, and resident awareness of recycling in Oman. *Int. J. Social Ecol. Sustainable Dev. (IJSESD)*. **13**(1), 1–22 (2022).
26. Umar, T. Estimating greenhouse gas (GHG) emissions from municipal solid waste (MSW) in Oman using different frameworks. *J. Solid Waste Technol. Manag.* **47**(2), 332–348 (2021).
27. Umar, T. Frameworks for reducing greenhouse gas (GHG) emissions from municipal solid waste in Oman. *Manag. Environ. Qual. Int. J.* **31**(4), 945–960 (2020).
28. Anjum, M. et al. Solid waste management in Saudi Arabia. *Appl. Agric. Biotechnol.* **1**, 13–26 (2016).
29. Labib, O. A., Abd Manaf, L. B., Bin Sharaai, A. H., Zaid, S. S. B. M. & Khalil, M. S. The influence of Socio-Psychological factors on residents' willingness to practice sustainable waste handling in Dammam City, Saudi Arabia. *Sustainability* **15**(18), 13654 (2023).
30. Tuffaha, F. M., Alghamdi, A. O. & Mazher, K. M. Explanation of household recycling barriers through interruptive structural modeling (ISM) in the Eastern Province, Saudi Arabia. *Arab. J. Sci. Eng.* **49**, 1–26. (2024).
31. Shahzad, K. et al. Biodiesel production potential from fat fraction of municipal waste in Makkah. *PLoS ONE* **12**(2), e0171297 (2017).
32. Rahman, M. & Sobuz, H. R. Comparative study of IPS & PPVC precast system—A case study of public housing buildings project in Singapore. In *Proceedings of the 4th International Conference on Civil Engineering for Sustainable Development (ICCESD 2018), KUET, Khulna, Bangladesh*, 9–11 (2018).
33. Madkhali, H. et al. A comprehensive review on e-waste management strategies and prediction methods: A Saudi Arabia perspective. *Knowledge* **3**(2), 163–179 (2023).
34. Rana, J., Hasan, R., Sobuz, H. R. & Tam, V. W. Y. Impact assessment of window to wall ratio on energy consumption of an office Building of subtropical monsoon Climatic country Bangladesh. *Int. J. Constr. Manag.* **22**(13), 2528–2553. https://doi.org/10.1080/15623599.2020.1808561 (2022).
35. Rana, M. J., Hasan, M. R. & Sobuz, M. H. R. An investigation on the impact of shading devices on energy consumption of commercial buildings in the contexts of subtropical climate. *Smart Sustainable Built Environ.* **11**(3), 661–691. https://doi.org/10.1108/SASBE-09-2020-0131 (2022).
36. Rana, M. J., Hasan, M. R., Sobuz, M. H. R. & Sutan, N. M. Evaluation of passive design strategies to achieve NZEB in the corporate facilities: The context of Bangladeshi subtropical monsoon climate. *Int. J. Building Pathol. Adaptation*. **39**(4), 619–654 (2021).
37. Gazette, S. https://saudigazette.com.sa. Accessed 10 July, 2024 (2024).
38. Ouda, O. K., Cekirge, H. M. & Raza, S. A. An assessment of the potential contribution from waste-to-energy facilities to electricity demand in Saudi Arabia. *Energy. Conv. Manag.* **75**, 402–406 (2013).
39. Debrah, J. K., Vidal, D. G. & Dinis, M. A. P. Raising awareness on solid waste management through formal education for sustainability: A developing countries evidence review. *Recycling* **6**(1), 6 (2021).
40. Nizami, A. S. et al. An argument for developing waste-to-energy technologies in Saudi Arabia. *Chem. Eng. Trans.* **45**, 337–342 (2015).
41. Mishra, M., Das, D., Laurinavicius, A., Laurinavicius, A. & Chang, B. H. Sectorial analysis of foreign direct investment and trade openness on carbon emissions: A threshold regression approach. *J. Int. Commer. Econ. Policy* 2550003 (2024).
42. Ma, Q., Zhang, Y., Hu, F., Zhou, H. & Hu, H. Nip it in the bud: The impact of China's large-scale free physical examination program on health care expenditures for elderly people. *Humanit. Social Sci. Commun.* **12**(1), 1–16. https://doi.org/10.1057/s41599-024-04295-5 (2025).
43. Ribić, B., Voća, N. & Ilakovac, B. Concept of sustainable waste management in the City of Zagreb: Towards the implementation of circular economy approach. *J. Air Waste Manag. Assoc.* **67**(2), 241–259 (2017).
44. Wang, H. et al. Key factors influencing public awareness of household solid waste recycling in urban areas of China: A case study. *Resour. Conserv. Recycl.* **158**, 104813 (2020).
45. Struk, M. Distance and incentives matter: The separation of recyclable municipal waste. *Resour. Conserv. Recycl.* **122**, 155–162 (2017).
46. Oribe-Garcia, I., Kamara-Esteban, O., Martin, C., Macarulla-Arenaza, A. M. & Alonso-Vicario, A. Identification of influencing municipal characteristics regarding household waste generation and their forecasting ability in Biscay. *Waste Manag.* **39**, 26–34 (2015).

47. Xu, L. et al. Path analysis of factors influencing household solid waste generation: A case study of Xiamen Island, China. *J. Mater. Cycles Waste Manag.* **18**, 377–384 (2016).
48. Qiao, G., Chen, H., Li, G., Liu, H. & Wang, X. The role of filial piety in filial tourism: An intergenerational analysis of decision-making. *Asia Pac. J. Tourism Res.* **29**, 1–15. https://doi.org/10.1080/10941665.2024.2362199 (2024).
49. Atiq, A., Siddiqui, T., Khan, A. & Siddiqui, F. The pathway to zero waste: Case study of Saudi Arabia's solid waste management techniques. *Int. J. Sci. Eng. Res.* **10**, 7–11 (2019).
50. Labib, O., Manaf, L., Sharaai, A. H. & Zaid, S. S. M. Moderating effects on residents' willingness in waste sorting to improve waste handling in Dammam City, Saudi Arabia. *Recycling* **6**(2), 24 (2021).
51. Malik, N. K. A., Abdullah, S. H. & Abd Manaf, L. Community participation on solid waste segregation through recycling programmes in Putrajaya. *Procedia Environ. Sci.* **30**, 10–14 (2015).
52. Sobuz, M. H. R. et al. AI-driven modeling for the optimization of concrete strength for Low-Cost business production in the USA construction industry. *Eng. Technol. Appl. Sci. Res.* **15**(1), 20529–20537. https://doi.org/10.48084/etasr.9733 (2025).
53. Jatau, S. & Binbol, N. Assessing barriers to household waste recycling: A case study of Coventry university postgraduate students. *Int. J. Sci. Res. Publications (IJSRP)*. **10**, 542–549 (2020).
54. Brasika, I. B. M. et al. G. M. Evaluating the collection and composition of plastic waste in the digital waste bank and the reduction of potential leakage into the ocean. *Waste Manag. Res.* **41**(3), 676–686 (2023).
55. Radwan, N., Khan, N. A. & Elmanfaloty, R. A. G. Optimization of solid waste collection using RSM approach, and strategies delivering sustainable development goals (SDG's) in Jeddah, Saudi Arabia. *Sci. Rep.* **11**(1), 16612 (2021).
56. Alshehrei, F., Ameen, F. & Vermicomposting A management tool to mitigate solid waste. *Saudi J. Biol. Sci.* **28**(6), 3284–3293 (2021).
57. Elmosaad, Y. M. et al. Self-Reported household waste recycling and segregation practices among families in Eastern region of Saudi Arabia: A Cross-Sectional study. *Int. J. Environ. Res. Public Health*. **20**(3), 1790 (2023).
58. Zafar, S. Waste management outlook for the Middle East. In *The Palgrave Handbook of Sustainability: Case Studies and Practical Solutions*, 159–181 (2018).
59. Sobuz, M. H. R. et al. Microstructural behavior and explainable machine learning aided mechanical strength prediction and optimization of recycled glass-based solid waste concrete. *Case Stud. Constr. Mater.* **22**, e04305 (2025).
60. Sobuz, M. H. R., Khatun, M., Kabbo, M. K. I. & Sutan, N. M. An explainable machine learning model for encompassing the mechanical strength of polymer-modified concrete. *Asian J. Civil Eng.* **26**, 1–24 (2024).
61. Mu'azu, N. D., Blaisi, N. I., Naji, A. A., Abdel-Magid, I. M. & AlQahtany, A. Food waste management current practices and sustainable future approaches: A Saudi Arabian perspectives. *J. Mater. Cycles Waste Manag.* **21**, 678–690 (2019).
62. Abiad, M. G. & Meho, L. I. Food loss and food waste research in the Arab world: A systematic review. *Food Secur.* **10**, 311–322 (2018).
63. Almulhim, A. I. Household's awareness and participation in sustainable electronic waste management practices in Saudi Arabia. *Ain Shams Eng. J.* **13**(4), 101729 (2022).
64. González-Torre, P. L. & Adenso-Díaz, B. Influence of distance on the motivation and frequency of household recycling. *Waste Manag.* **25**(1), 15–23 (2005).
65. Radwan, N. & Mangi, S. A. Municipal solid waste management practices and opportunities in Saudi Arabia. *Eng. Technol. Appl. Sci. Res.* **9**(4), 4516–4519 (2019).
66. Ma, Q., Zhang, Y., Hu, F. & Zhou, H. Can the energy conservation and emission reduction demonstration City policy enhance urban domestic waste control? Evidence from 283 cities in China. *Cities* **154**, 105323. https://doi.org/10.1016/j.cities.2024.105323 (2024).
67. Hu, F. et al. Digitalization empowerment for green economic growth: The impact of green complexity. *Environ. Eng. Manag. J.* **23**(3), 519–536. https://doi.org/10.30638/eemj.2024.040 (2024).
68. Wu, S., Cao, J. & Shao, Q. How to select remanufacturing mode: End-of-life or used product? *Environ. Dev. Sustain.* 1–21. https://doi.org/10.1007/s10668-024-04515-7 (2024).
69. Scheinberg, A., Wilson, D. C. & Rodic Wiersma, L. Solid waste management in the world's cities. *United Nations Human Settlements Programme (UN-HABITAT)*, 1–228 (2010).
70. Baig, M. B., Al-Zahrani, K. H., Schneider, F., Straquadine, G. S. & Mourad, M. Food waste posing a serious threat to sustainability in the Kingdom of Saudi Arabia–A systematic review. *Saudi J. Biol. Sci.* **26**(7), 1743–1752 (2019).
71. Aziz, A. Food is largest part of waste in Kingdom. Article published in the Daily Arab News on Wednesday 31 October 2012 (2012).
72. Baig, M. B. et al. Food waste in Saudi Arabia: Causes, consequences, and combating measures. *Sustainability* **14**(16), 10362 (2022).
73. Whitman, E. Oil-rich Saudi Arabia wastes astounding $35 million in food every day. *Int. Bus. Times* (2016).
74. Mariyam, S., Cochrane, L., Al-Ansari, T. & McKay, G. A framework to support localized solid waste management decision making: Evidence from Qatar. *Environ. Dev.* **50** 100986. (2024).
75. Minghua, Z. et al. Municipal solid waste management in Pudong new area, China. *Waste Manag.* **29**(3), 1227–1233 (2009).
76. Bui, T. D., Tseng, J. W., Tseng, M. L. & Lim, M. K. Opportunities and challenges for solid waste reuse and recycling in emerging economies: A hybrid analysis. *Resour. Conserv. Recycl.* **177**, 105968 (2022).
77. AlQaraleh, L., Hajar, H. A. A. & Matarneh, S. Multi-criteria sustainability assessment of solid waste management in Jordan. *J. Environ. Manag.* **366**, 121929 (2024).
78. Qaderi, P., Muradi, M. A. & Haqiqat, S. A. Q. Assessment of public awareness level regarding solid waste management: A case study of pol-e-khumri, Afghanistan. *Int. J. Innovative Res. Sci. Stud.* **4**(4), 200–204 (2021).
79. Bin Sadan, R. Impact of National and Municipal Environmental Standards on the Development of Effective Solid Waste Management Systems in Jeddah, Kingdom of Saudi Arabia (2021).
80. Kaya, D. Sustainable domestic solid waste management in Jeddah, Saudi Arabia. *J. Int. Environ. Application Sci.* **14**(4), 193–198 (2019).
81. Aleisa, E. & Al-Jarallah, R. Characterization of municipal solid waste in Kuwait: Sector-specific composition analysis and implications. *J. Air Waste Manag. Assoc.* **74**(9), 623–638 (2024).
82. Demirbas, A., Alamoudı, R. H., Ahmad, W. & Sheıkh, M. H. Optimization of municipal solid waste (MSW) disposal in Saudi Arabia. *Energy Sour. Part A Recover. Utilization Environ. Eff.* **38**(13), 1929–1937 (2016).
83. Ali, I. H. et al. Contamination and human health risk assessment of heavy metals in soil of a municipal solid waste dumpsite in Khamees-Mushait, Saudi Arabia. *Toxin Reviews*. **40**(1), 102–115 (2021).
84. Cudjoe, D., Wang, H. & Zhu, B. Assessment of the potential energy and environmental benefits of solid waste recycling in China. *J. Environ. Manag.* **295**, 113072 (2021).
85. Vaverková, M. D. et al. Municipal solid waste management under COVID-19: Challenges and recommendations. *Environ. Geotechnics*. **8**(3), 217–232 (2020).
86. Ouda, O. et al. A. A case study of sustainable construction waste management in Saudi Arabia. *Waste Biomass Valoriz.* **9**, 2541–2555 (2018).
87. Hadidi, L. A., Ghaithan, A., Mohammed, A. & Al-Ofi, K. Deploying municipal solid waste management 3R-WTE framework in Saudi Arabia: Challenges and future. *Sustainability* **12**(14), 5711 (2020).
88. Abdulaziz AlHumid, H. et al. Performance assessment model for municipal solid waste management systems: Development and implementation. *Environments* **6**(2), 19 (2019).

89. Hakami, B. A. Electronic waste management approaches, Saudi Arabia. *Am. J. Environ. Eng.* **8**, 4–10 (2018).
90. Soomro, Y. A. et al. What influences consumers to recycle solid waste? An application of the extended theory of planned behavior in the Kingdom of Saudi Arabia. *Sustainability* **14**(2), 998 (2022).
91. Do Valle, P. O., Reis, E., Menezes, J. & Rebelo, E. Behavioral determinants of household recycling participation: The Portuguese case. *Environ. Behav.* **36**(4), 505–540 (2004).
92. Oskamp, S. et al. Factors influencing household recycling behavior. *Environ. Behav.* **23**(4), 494–519 (1991).
93. Hansmann, R., Bernasconi, P., Smieszek, T., Loukopoulos, P. & Scholz, R. W. Justifications and self-organization as determinants of recycling behavior: The case of used batteries. *Resour. Conserv. Recycl.* **47**(2), 133–159 (2006).
94. Ojeda-Benítez, S., Armijo-de Vega, C. & Marquez-Montenegro, M. Y. Household solid waste characterization by family socioeconomic profile as unit of analysis. *Resour. Conserv. Recycl.* **52**(7), 992–999 (2008).
95. Al-Khraif, R., Abdul Salam, A. & Abdul Rashid, M. F. Family demographic transition in Saudi Arabia: Emerging issues and concerns. *Sage Open* **10**(1), 2158244020914556 (2020).
96. Umar, T. Sustainable energy production from municipal solid waste in Oman. In *Proceedings of the Institution of Civil Engineers-Engineering Sustainability*, Vol. 175, 3–11 (Thomas Telford Ltd, 2021).
97. Moustairas, I., Vardopoulos, I., Kavouras, S., Salvati, L. & Zorpas, A. Exploring factors that affect public acceptance of Establishing an urban environmental education and recycling center. *Sustainable Chem. Pharm.* **25**, 100605 (2022).

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Author contributions

Moahd Khaled Alghuson: Conceptualization, Methodology, Validation, Formal analysis, Writing—original draft, Writing—review & editing Abdullah Alghuried: Conceptualization, Methodology, Validation, Formal analysis, Su-pervision, Writing—original draft, Writing—review & editing.

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Correspondence and requests for materials should be addressed to M.K.A.

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