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Assessing public perception and parametric analysis of municipal solid waste management solutions in Tabuk City, Saudi Arabia

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Accelerated urbanization, population growth, and industrial revolution have resulted in significant environmental degradation and health issues for residents due to municipal solid waste. The effective management of solid waste is a significant issue, especially in developing economies, where improper waste disposal leads to economic losses and adverse impacts on environmental and public health. This study evaluates existing waste management procedures in Tabuk City in northern Saudi Arabia, finds significant challenges, and suggests possible solutions. For this purpose, this study administered a survey to assess public awareness regarding municipal solid waste recycling and management. Therefore, a two-stage analytic investigation was conducted that included a total of 228 respondents from Tabuk City, Saudi Arabia. Among them, 62.28% were male, and 37.72% were female, with the largest age group represented was 22–35 years, accounting for 42.10% of participants. The questionnaire responses were evaluated using SPSS V27, and relative scores were analyzed using SHapley Additive exPlanations and Partial Dependence Plots. Based on the study results, most respondents are knowledgeable and worried about the adverse environmental effects of solid waste. The Pearson correlation highlighted that lack of awareness with responsible authorities exhibited the highest positive correlations with recycling behavior improvement, with respective correlation values of +0.55. The results also revealed an absence of recycling systems since the majority of respondents were uninformed of existing practices and expressed a readiness to engage in recycling programs if established. Further, parametric modeling illustrates that most of the participants believe that lack of awareness along with authority responsibility is the most influential factor impacting poor waste management practice. The study concluded by highlighting the necessity for an organized municipal solid waste recycling system, enhanced community education, and more stringent governmental restrictions to mitigate environmental damage and foster sustainable waste management in Tabuk.

Keywords Municipal solid waste management, Recycling, Sustainability, Questionnaire, SHAP analysis, Partial dependency analysis

Municipal solid waste (MSW) comprises daily products discarded by households, including food leftovers, packaging, paper, glass, plastics, concrete, metals, and textiles. Urban regions generate substantial volumes of MSW because of rapid economic growth, increasing populations, and industrialization[1–6]. Thus, municipal solid waste management has been a necessity in all industrial countries. However, until today, it is still considered a type of extravagant in developed nations. This can be attributed to several factors, such as the community's financial, social, and cultural state[7,8]. Also, factors such as urbanization and modern lifestyle have caused a significant expansion in the amounts of waste material[9–12]. Furthermore, it has been established that MSW recycling significantly contributes to reducing the human carbon footprint[13,14]. This is especially applicable in emerging Middle Eastern countries such as Saudi Arabia[15]. Residential solid waste has a significant amount of organic material, which provides essential mineral nutrients and acts as a considerable carbon (C) source. Additionally, food waste is the biggest portion that can be found in the total volume of MSW. Statistics reveal that global food waste amounted to 931 million tons in 2019, with 17% of the entire production of food potentially being wasted[16]. However, the issue is prominent for countries with high and middle-income levels.

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Various initiatives have been established to recycle and classify this waste at the individual, community, and governmental levels. Nonetheless, substantial amounts of mixed industrial and residential garbage persist in being inappropriately disposed of. The administration of municipal solid waste profoundly influences the whole quality of life in communities, including aspects such as sanitation, health, and productivity[17,18]. Additionally, insufficient waste management is contaminating the environment, including oceans, rivers, and seas. The escalation of economic growth and rapid urbanization is significantly associated with a rise in per capita waste generation of any country[19]. The global yearly generation of solid waste from metropolitan regions is around 2.01 billion tons, with more than 33% inadequately managed in an environmentally safe manner[20,21]. Research by Farmanbordar, Amiri and Karimi[22] indicates that the worldwide waste generation rate ranges from 0.11 to 4.54 kg per person per day, with an ideal quantity of 0.74 kg per person per day. High-income countries, comprising just 16% of the global population, generate almost 683 million tons of trash, constituting 34% of the total waste generated globally[23,24]. A research by Hoque and Rahman[25], forecasts that global waste would rise to 3.4 billion tons by 2050. As a result, the financial burden of municipal waste management is much greater in urban areas. Waste management is the most significant segment of the budget in low-income countries, representing roughly 20% of the funds designated for municipal services. In middle-income nations, it constitutes over 10% of total spending, but in high-income countries, it accounts for around 4%[26]. Nevertheless, it still poses a challenge to application in developed countries.

Saudi Arabia is located in the southwestern part of Asia, bordered by the Arabian Gulf to the east and the Red Sea to the west. The country has a significant population of 34.8 million, as per the 2020 World Bank statistics[27,28]. Over the last four decades, a population growth rate of around 3.4% has been seen, with a 50–80% increase in urbanization from 1970 to the present[29]. The notable rise in population and urbanization in Saudi Arabia has led to a considerable amount of solid waste being generated. Consequently, certain challenges persist that need resolution concerning municipal solid waste recycling management in Saudi Arabia. The Saudi government faces difficulties in tracking the national recycling rate and must determine the optimal strategy for overseeing the recycling system to effectively engage local communities in creating a more organized and efficient recycling management framework[30]. The oversight of municipal solid waste management is conducted by the Local Affairs and Ministry of Municipalities, with implementation by local municipalities. The municipalities are accountable for the collection, transportation, and disposal of waste in landfills and dump sites without utilizing energy[31,32]. Unregulated waste is often eliminated by incineration and landfill disposal[33,34]. Composting facilities are used to transform organic waste into compost[35]. Improper waste disposal practices are causing considerable environmental damage, potentially contaminating surface water and soil, and producing foul odors[36,37].

Recent waste management techniques in some countries have concentrated on waste recovery, reuse, and proper disposal procedures, driven by environmental regulations aimed at enhancing MSW management[38]. A significant improvement in the private sector's involvement in the collection of organic, plastic, and metal waste for recycling and repurposing was seen. Sustainable waste management encompasses the recycling and repurposing of materials and energy to manufacture new goods while mitigating waste pollution[39,40]. Ultimately, public education is essential for the efficacy of municipal solid waste recycling and reuse initiatives[41]. Research conducted worldwide indicates that an individual's sociodemographic variables correlate with their waste generation[40,42]. Similarly, household attitudes on recycling, namely their inclination to sort and recycle, are significantly influenced by social factors. Key elements influencing people' intention to sort waste include their perspective, social influence, perceived behavioral control, economic incentives, regulatory support, and awareness[43]. In both low-income and wealthy communities, attitudes and willingness to sort and recycle waste were influenced by income and market incentives. The relationship between market incentives and the inclination to sort and recycle waste was influenced by the participants' gender[44,45].

Consequently, prior research in Saudi Arabia has mostly concentrated on examining the correlation between sociodemographic variables and the generation of MSW[46–48]. These studies have neglected the direct and indirect effects of a citizen's knowledge of garbage recycling and the specific reason for the lack of mismanagement in solid waste management and recycling. Furthermore, very few studies have been conducted that used parametric analyses to evaluate the association between behavioral factors and waste management system implementation. Considering these gaps of research, this study will conduct a questionnaire survey among the residents of Tabuk City, Saudi Arabia to evaluate the current solid waste management approaches, identify the main issues that hinder proper solid waste management practices, and investigate the opportunities that could be applied in the city. Further, the survey questionnaires will be distributed among a random sample of the local community, business owners, and University professors to analyze some of the critical issues facing the recycling application in the city. Analyses will be performed to identify the most relevant reasons for inadequate waste. The study also provides the respondents the freedom to relatively score the potential factors that hinder the implementation of a sustainable waste management system. Based on the responses, the data will be analyzed statistically to visualize public opinion and behavior toward waste management and recycling practices. Additionally, parametric management practices, as seen by the local residents. Finally, recommendations will be made to develop a user-friendly, sustainable solid waste recycling approach that will be introduced to fit the current circumstances.

Current practices and implementation for waste management in Tabuk City

The current situation of solid waste recycling in Saudi Arabia is still in the establishment phase. Moreover, in most cities, municipal solid waste was still collected in one bin. Separate recycling bins are still not applied in the system on a large scale. However, according to the city, some private sector companies collect bulk aluminum cans, steel, and plastic containers from the landfill. The general waste collection system in Saudi Arabia is accomplished through routine pickup by a private contractor, using trucks to collect the mixed MSW from the bins distributed evenly throughout the district streets, as shown in Fig. 1. Until now; there have been shy

Fig. 1. (**a**) Regular street municipal waste bin and (**b**) Municipal waste collection truck.
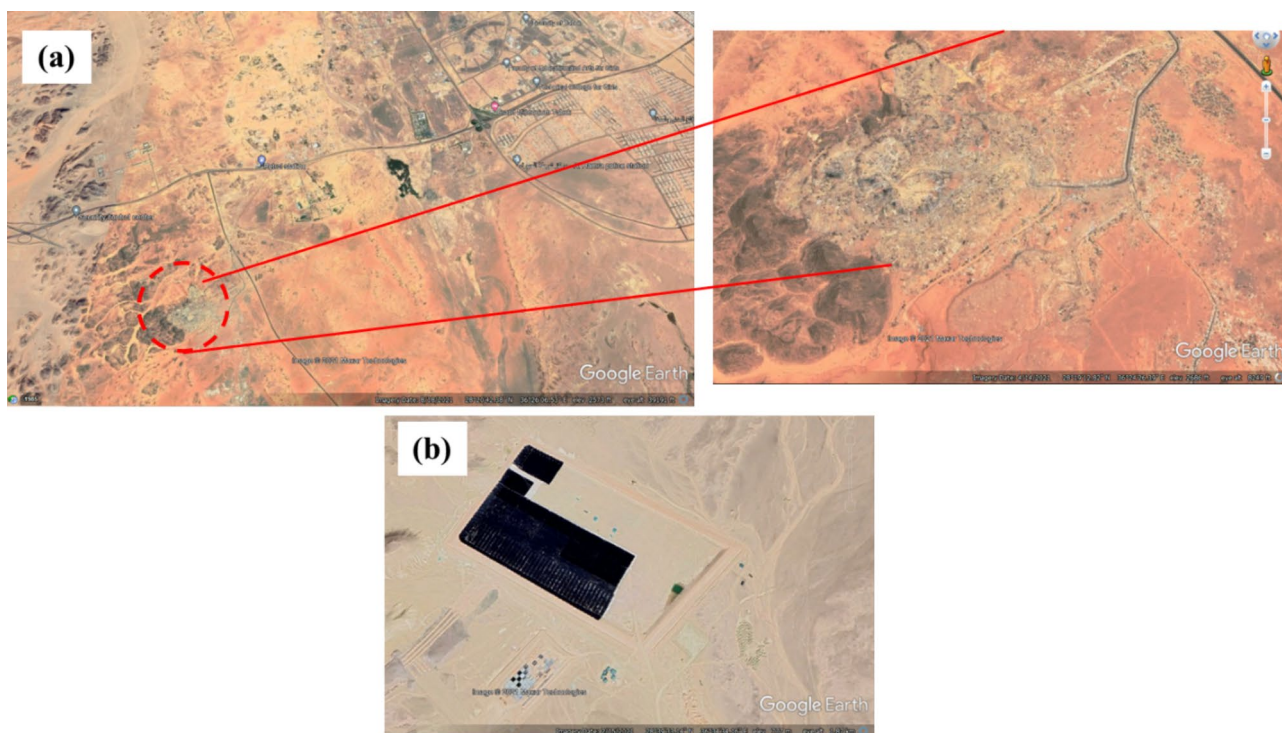
Fig. 2. (**a**) Old solid waste landfill and (**b**) New solid waste landfill (Google Earth Pro).

attempts to sort MSW. For example, there are separate bins to collect bread waste, which are used as a food source for livestock. The MSW completes its journey to be dumped in the city landfill.

Incinerators and landfills are considered the most used MSW disposal techniques in developed countries[49,50]. Following them, Saudi Arabia also used large landfills as their primary waste disposal and management component. The major landfill in Tabuk City has been used for the last 20 years and was not constructed on a sanitary basis. The contractor simply dumped the waste, spread it, and applied a ~ 20 cm soil cover. This landfill has no lining layers or leachate collection system and, nonetheless, a gas collection system; the location is shown in Fig. 2(a). Furthermore, this site has no environmental monitoring system; thus, it can be presumed that uncontrolled leachate seeps through the soil layers, contaminating the soil and the groundwater. Additionally, such a primitive landfill has resulted in random incineration caused by landfill scavenging, leading to serious air contamination. Another issue related to uncontrolled landfills is the growing number of stray dogs and rodents,

which have been associated with numerous diseases[51]. However, the municipality is currently constructing a sanitary landfill, including several lining layers and a leachate collection system, as shown in Fig. 2(b). This indicates how serious the government is about enforcing strong regulations towards any potential adverse environmental impact.

### Solid waste composition and generation rates

Rapid urbanization and population growth are the major factors affecting the high solid waste generation rate[51]. Tabuk City is considered a developed area with almost similar solid waste sources as any developed city worldwide. The sources include households, businesses, manufacturing, public areas, institutions, and local services[52]. The local average daily solid waste generated is estimated to be 2.31 kg/person; according to Tabuk municipality. The municipal solid waste is diverse, containing plastic, cartons, glass, used tires from the workshops, and food waste. The general composition of MSW in Saudi Arabia is illustrated in Fig. 3[53]. Furthermore, numerous factors justify the variation in the composition of the MSW generated in different districts. Examples of the factors are population, commercial events, level of urbanization, socio-economic status, local culture, illiteracy, seasonal conditions and consumption patterns[54,55].

Materials and methods

The author has 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. Informed consent was obtained from all subjects and/or their legal guardian(s) before participation in the questionnaire. 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.
– A statement to confirm that all experimental protocols were approved by a University of Tabuk, Saudi Arabia, research ethics approval committee.

Composition of MSW in Saudi Arabia

Food leftover
Papers
Waste glass
wooden material
Plastics
Cloth and textiles
Metals
Others
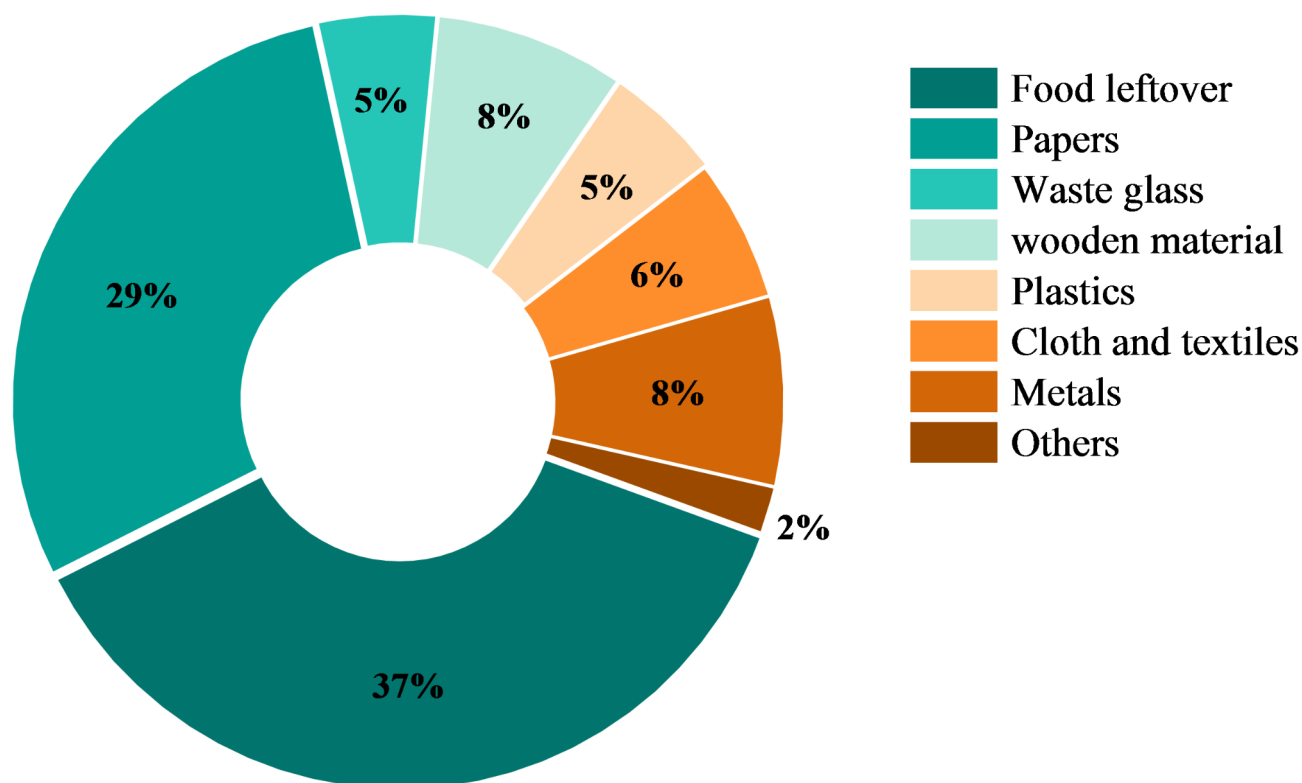
**Fig. 3**. A general composition of Saudi Arabia's MSW[53].

– It is confirmed that the above-mentioned consent was obtained for the civil engineering department, the University of Tabuk, Saudi Arabia and the university research ethics approval committee (see enclosed related file).

Survey location

The study area was in Tabuk city, located in the northern region of the Kingdom of Saudi Arabia between 28°23′50″N and 36°34′44″E, having a population of about 552,000 with an annual growth rate of 2.16% according to the Saudi General Authority for Statistics (2017). Tabuk City has an area of 65 km^2 at an altitude of 750 m. The local governmental municipality is responsible for all the MSW management in the city. This is accomplished through a private contractor, with the following responsibilities: collecting the domestic solid waste from houses and buildings all over the city up to the delivery to the dumpster located 7 km west of the city parameter. Figure 4 highlights the specific location of Tabuk City on the map of Saudi Arabia.

Questionnaire design and distribution

The main research instrument used in this study was a questionnaire having queries with multiple answer choices (refer to the Appendix). The questionnaire had three main sections: The first segment collected demographic information, including respondents' gender, age, marital status, educational background, and current employment. The second segment examined the extent of public knowledge and comprehension of MSW management. The final section collects a quantitative score out of 100, with which they identify the main reasons for waste management and recycling issues in Tabuk City. In accordance with the aforementioned segmentation, a total of 12 questionnaires were prepared and disseminated throughout the target population. Before executing the entire survey, a pilot survey was undertaken using online data exchange and gathering technologies. The questionnaire was later altered and enhanced in accordance with the input obtained from the pilot survey. The second segment survey questionnaires are listed in Table 1. The questionnaire was thereafter distributed
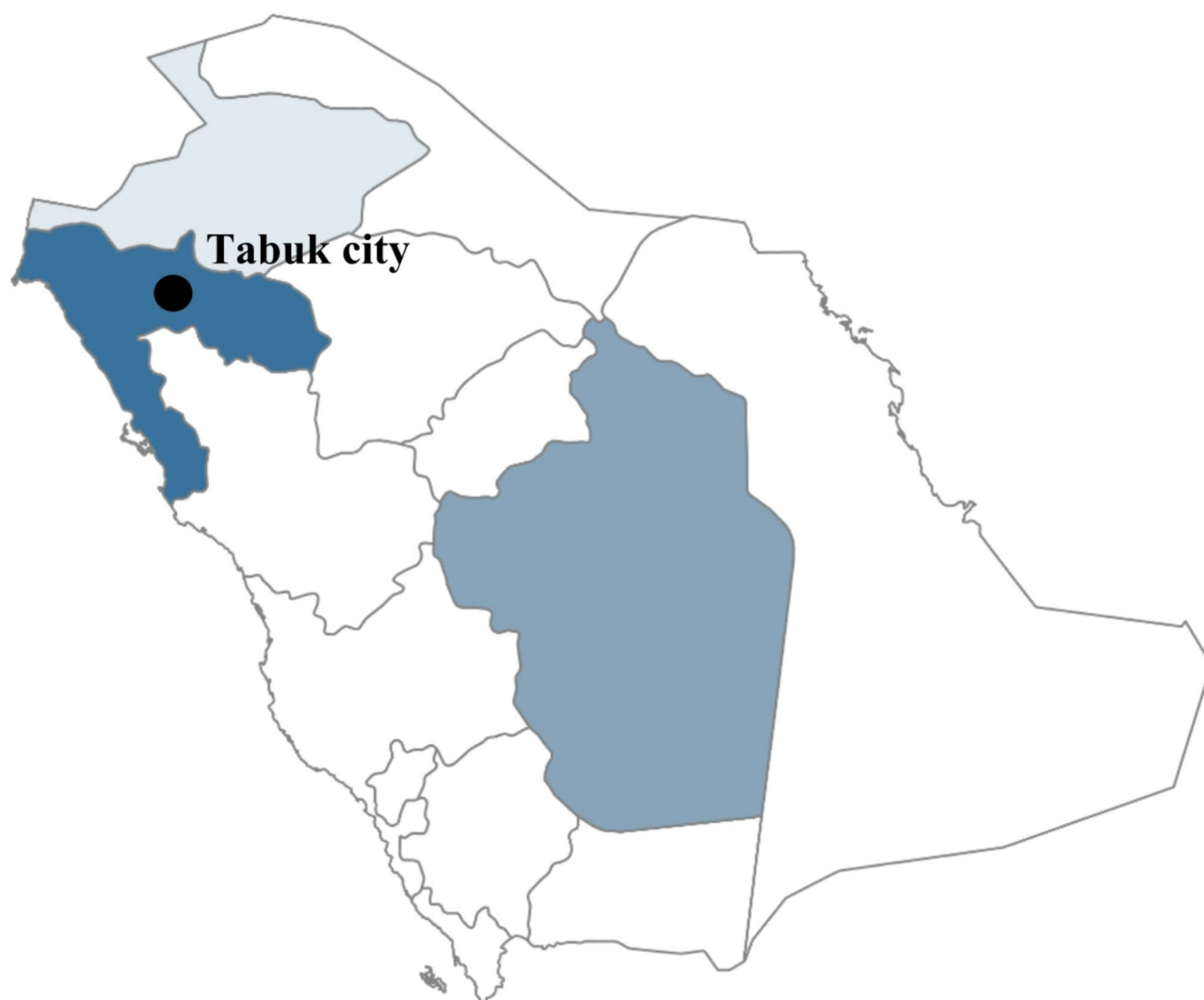
Fig. 4. Location of Tabuk City in the map of Saudi Arabia, where surveys were conducted.

Number	Opinion poll key questions
1	Do you find household waste an environmental hazard that needs to be addressed?
2	Do you recycle any waste in your household?
3	Do you have a background in any waste recycling methods?
4	Do you know the procedure used in your city to dispose of household waste?
5	Is the method used in your city to dispose of waste safe and environmentally friendly?
6	If the recycling system is implemented, will you contribute to sorting waste in your household?
7	In your opinion, what is the reason for not applying waste recycling in households?

Table 1. Key questions in the survey.
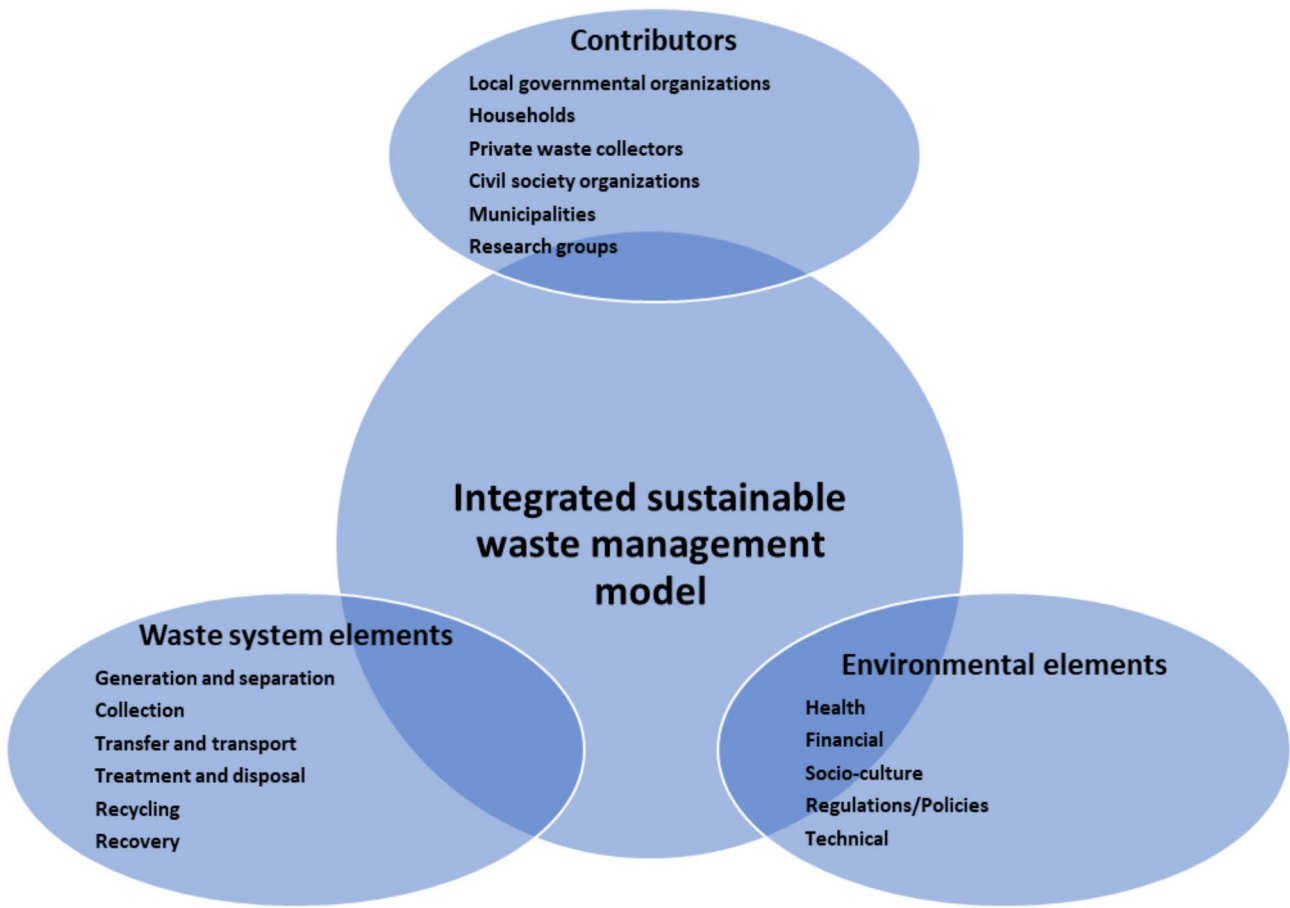
Fig. 5. Integrated Sustainable Waste Management model[56].

randomly using various channels, including online survey platforms and social media, face-to-face interactions, and direct inquiries. Some were also circulated as written content on vehicles and delivered to pedestrians on the streets. In addition, random and stratified sampling approaches were used to ensure randomness and representativeness in the distribution of the questionnaire. Furthermore, adapting both the online and offline methods for questionnaire distribution helps to mitigate selection bias and ensure participation from individuals with diverse technology backgrounds.

This study also inherently follows the Integrated Sustainable Waste Management (ISWM) model for assessing Tabuk City's current solid waste management system. The model identifies the significance of evaluating local conditions and requirements and proposing the best-fit resolutions. The model consists of three essential components: the contributors influenced by or involved in waste management, the waste system elements of the waste management system and a range of environmental elements that directly impact waste management, including political and cultural influences, as shown in Figure 5 [59]. Moreover, to understand the MSW management system in the field, the waste management activities were observed, from point source to the landfill.

Statistical and parametric analyses

The data obtained from the questionnaire survey were analyzed using IBM SPSS V27. This study endeavored to elucidate the sociodemographic variables (gender, age, married status, educational background and present employment) that impact public behavior, public awareness, and public desire to engage in MSW management and recycling. Additionally, the study examined the correlations between the influential factors and the improvement of the current waste management plan using parametric analysis. Artificial intelligence (AI) has become a crucial component in advanced problem-solving and optimization across various disciplines[57–59]. As a subset of AI, parametric optimization plays a significant role in addressing waste recycling and management challenges, similar to its applications in other areas of engineering[60].

The SPSS-based statistical analysis is mainly used to explore and visualize the key characteristics of the survey respondents. As the survey data collected in this study is descriptive type thus visualization using the percentage of total responses is the most effective to understand the relationship between sociodemographic characteristics and the public behavior, awareness, and willingness to participate in MSW management.

SHapley additive explanations (SHAP)
SHAP interprets a model's predictions by expressing them as a linear combination of input features, facilitating a clear insight into how each variable influences the final outcome[61,62]. This methodology is grounded in game theory, specifically the Shapley values, which assist in identifying the contribution of each participant in a collaborative setting[63]. In the realm of machine learning, the input features act as these participants, while the model's outputs represent the overall "game"[64]. SHAP determines the significance of each feature by observing variations in predictions when specific features are included or excluded from the input set, thereby providing a comprehensive scenario of how each feature affects the model's results.

$$z\left(t\prime\right) = \varphi_o + \sum_{j=1}^{M} \left(\varphi_j \, X_j'\right) \tag{1}$$

Here, the Shapley values φ_j function as the coefficients in this linear setup, where t' represents a generalized version of the original input vector t, and z stands as the interpretative model. These coefficients provide insights into the contributions of individual features to the overall prediction. In this study, SHAP analysis was conducted to quantify the contribution of each independent variable to the model's predictions. This method helps in understanding which factors have the most influence on recycling awareness and behavior. From the survey data, a total of five public opinions (i.e., lack of awareness & authority, lack of awareness, lack of initiative, lack of management, and society rejection) were identified that respondents thought could be the reason behind the implementation of an effective waste management system. The SHAP optimization will help to reveal the underlying pattern of which opinion has the highest importance on the outcome. By breaking down the model's predictions into individual contributions, SHAP allows us to assess the relative importance of different features, providing a more interpretable insight into the factors driving waste management engagement.

Partial dependence plots (PDP) method
PDP illustrates the relationship between the goal output and a certain set of input characteristics while taking into account the values of all other attributes of the input. The partial dependency 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, as shown by a specific survey question, and demographic characteristics. As a holistic tool, they analyze all instances to expose the broader link between a feature and the projected outcome[65]. These visualizations illustrate how individual input factors shape the predictions by showing the influence of varying their values on the machine-learning model[66].

Additionally, to evaluate the partial dependency of recycling awareness on demographic factors, one ensemble machine learning (ML) algorithms has been used here. The extreme gradient boosting (XGB) method is classified as a supervised ML technique. The XGB approach is unique among supervised learning algorithms in that it may be used for both regression and classification tasks. The primary reason for using XGB 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. The XGB often uses nonlinear activation functions, enabling the network to acquire intricate patterns in data. XGBs 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.

In this study, the partial dependency method was utilized to visualize the relationships between behavioral factors influencing public engagement in MSW management and recycling. PDP helps in visualizing how specific input variables, while holding all other factors constant, influence the target outcome—in this case, the "Waste Recycling Status." By doing so, it provides insights into the independent effect of each factor on recycling behavior. 2D-PDP plotting of these relationships will provide a clearer understanding of how individual factors contribute to the overall trend, making it easier to interpret the effects of each influential factor on the final decision.

Respondent's demographic information

Table 2 provides a comprehensive summary of the demographic characteristics of the participants involved in the study. Among the 228 respondents, 142 (62.28%) were male, and 86 (37.72%) were female. The largest age group represented was 22–35 years, accounting for 42.10% of participants, followed by 35–55 years at 29.80%. Conversely, individuals aged below 18 and above 65 were underrepresented, each constituting only 0.44% of the sample. In terms of marital status, the majority of participants were unmarried (71.1%, $n = 162$), while 28.9%

	No of respondents	Percentages
Gender		
Male	142	62.28
Female	86	37.72
Age		
< 18	1	0.44
18–22	54	23.72
22–35	96	42.10
35–55	68	29.80
55–65	8	3.50
> 65	1	0.44
Marital status		
Married	66	28.9
Unmarried	162	71.1
Educational level		
Below high school	14	6
High school	50	22
B.Sc.	130	57
Masters or Ph.D.	34	15
Job-status		
Employed	83	36.4
Unemployed	45	19.7
Retired	6	2.1
Student	87	38.5
Others	7	3.3

Table 2. Demographic information of participants.

($n = 66$) were married. Regarding educational attainment, most respondents had a bachelor's degree (57%, $n = 130$), with fewer individuals possessing a Master's or Ph.D. degree (15%, $n = 34$). High school graduates made up 22% ($n = 50$), and those with below high school education constituted only 6% ($n = 14$).

The employment status of respondents showed that 36.4% ($n = 83$) were employed, while a significant portion were students (38.5%, $n = 87$). Unemployed individuals accounted for 19.7% ($n = 45$), and retired respondents and those in other job categories formed the minority, with 2.1% ($n = 6$) and 3.3% ($n = 7$), respectively. These findings offer critical insights into the demographic distribution of participants, highlighting key trends in age, education, and employment within the study group. This is attributable to young people's greater inclination to acquire fast food, drinks, and other food items, many of which are later thrown away[67,68].

Results
Statistical analysis outcomes of questionnaire responses
Concern and willingness about solid waste recycling
The willingness and public concern regarding the solid waste recycling and management system was measured using two questions as stated below:

Q1: Do you find that household waste poses an environmental hazard that must be addressed?
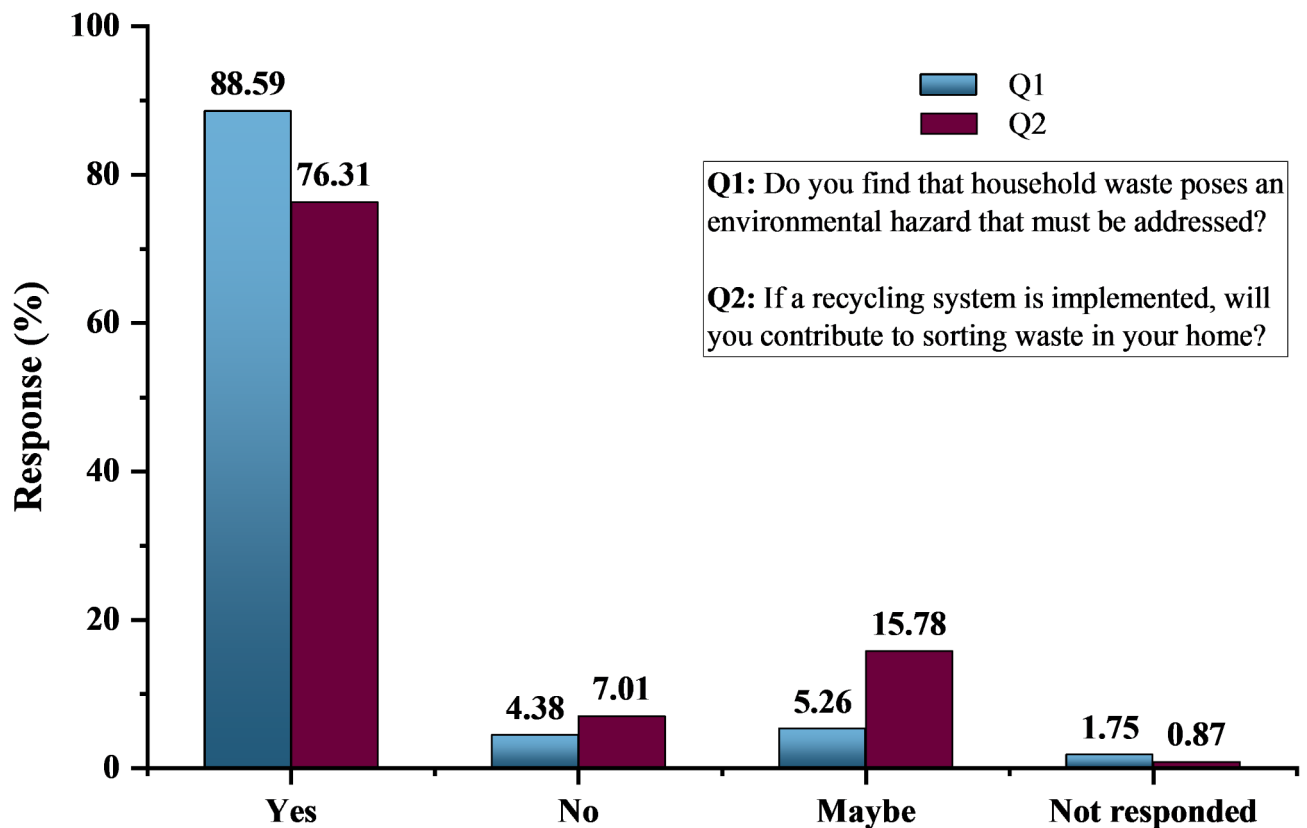
Q2: If a recycling system is implemented, will you contribute to sorting waste in your home?

Figure 6 depicts the beliefs and willingness of respondents to participate in the waste recycling system. When surveyed, around 88.59% of Tabuk residents admitted that household waste poses an environmental hazard that must be addressed. In contrast, barely 4.38% of participants refused to believe that household waste is one of the main causes of environmental hazards. Additionally, 5.26% expressed uncertainty ("Maybe"), and 1.75% did not respond. The high agreement percentage aligns with findings from relevant studies, which stated that public awareness of environmental hazards plays a critical role in adopting sustainable waste management practices[69].

Again, when the participants were asked about their response if a recycling system is implemented, they expressed a willingness to participate in sorting waste at home, provided that a recycling system is in place. However, 7.01% opposed this idea, while 15.78% remained uncertain. A small fraction (0.87%) chose not to respond. The lower percentage of positive responses for this survey question compared to first question indicates practical concerns or perceived barriers, such as the lack of infrastructure, convenience, or public incentives, which have been highlighted in prior research as critical factors influencing individual recycling behaviors[70].

The statistical comparison between these survey questionnaires suggests that while environmental awareness is relatively high, translating this awareness into actionable behavior like sorting waste requires addressing

Fig. 6. Beliefs and willingness of survey participants to support the waste recycling system.

logistical, motivational, and policy-related barriers. 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 the handling of waste, as well as the National Environmental Standards[71]. The waste disposal regulatory structure is established in accordance with 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 in a way that ensures the safeguarding of human health and the preservation of the environment[72].

Knowledge and self-practice about solid waste recycling
Figure 5 analyzes public awareness and engagement in waste recycling through a clustered bar chart. The analysis and interpretations are based on the responses to three key survey questions:

Q3: Do you have background in waste recycling methods?

Q4: Do you know what method is used in your city to dispose of household waste?

Q5: Do you do any recycling in your home?

As seen in Fig. 7, there's a notable disconnect between practical engagement and formal knowledge in the context of waste management. As can be seen, a substantial majority (71.92%) of participants reported negatively recycling at home, which ensures a low level of participation in source separation and awareness. However, considerably fewer demonstrated background in the science or methodology of recycling (39.47% for Q3) or possessed knowledge of their local waste disposal systems (44.73% for Q4). A significant proportion also responded negatively when they asked about recycling background (31.57%) and their city's waste disposal method (44.73%), which highlights a clear gap in understanding the broader context of waste management beyond individual household actions. These discrepancies suggest that public participation in recycling is encouraging, but a lack of comprehensive knowledge of recycling and waste management processes and local infrastructure could hinder the effectiveness of recycling programs.

Similar trends have been observed in other studies conducted in the same context. A study conducted by Almulhim[73] examining household waste management behaviors in Saudi Arabia found that although many households engaged in recycling, their understanding of the environmental impacts and the subsequent processing of recyclable materials was limited. The outcomes of their study align with the findings of our study,
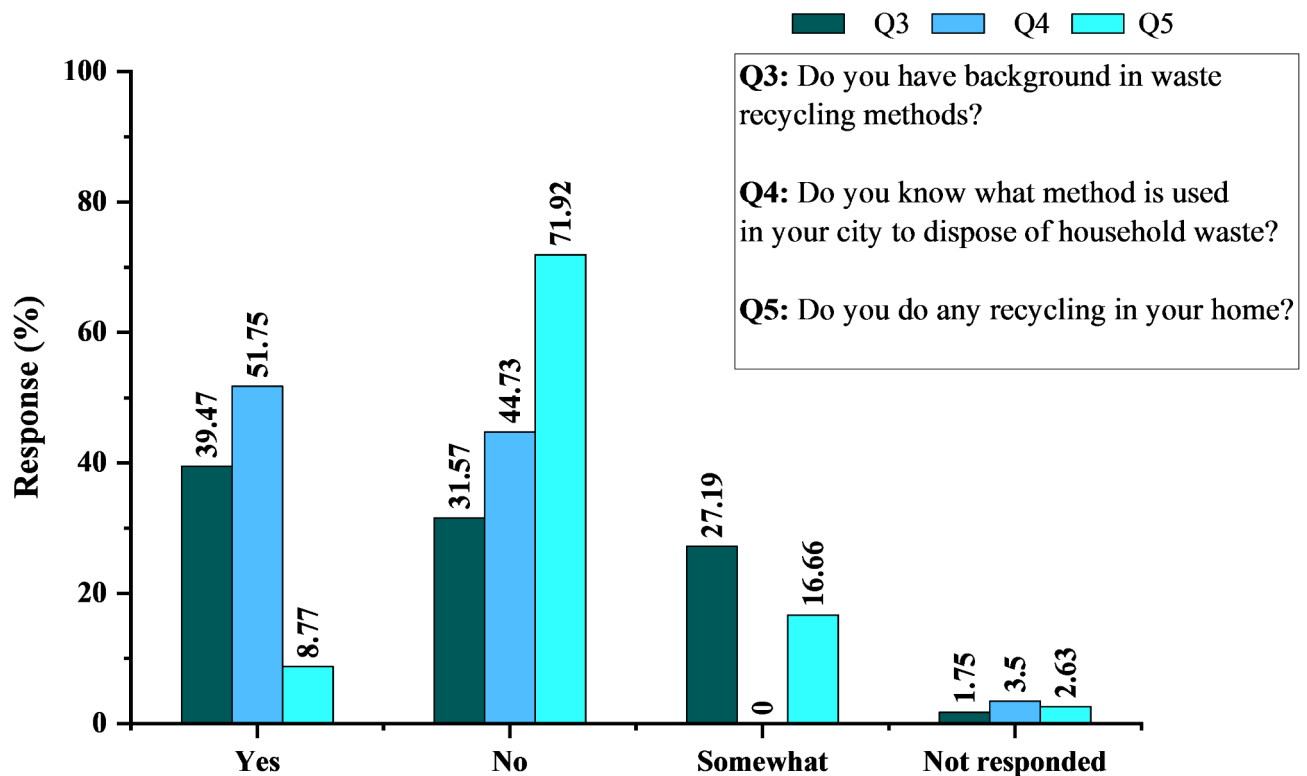
Fig. 7. Awareness and willingness of participants to waste recycling.

which suggests a common pattern of practical engagement that outpaces theoretical knowledge. Furthermore, a study conducted by Wang, Liu, Wang, Zhang, Wang, Zhang, Wang, Zheng and Matsushita[40] found that knowledge and awareness were significant predictors of recycling participation. However, perceived convenience and social norms also played a crucial role. Their outcomes highlight the importance of educating the public about recycling processes, creating convenient recycling infrastructure, and fostering a sense of social responsibility. Similarly, research by Debrah, Vidal and Dinis[32] emphasized the role of public education campaigns for enhancing recycling knowledge and promoting pro-environmental behavior. All these studies highlight the importance of targeted interventions to bridge the knowledge gap and support more informed and effective recycling practices.

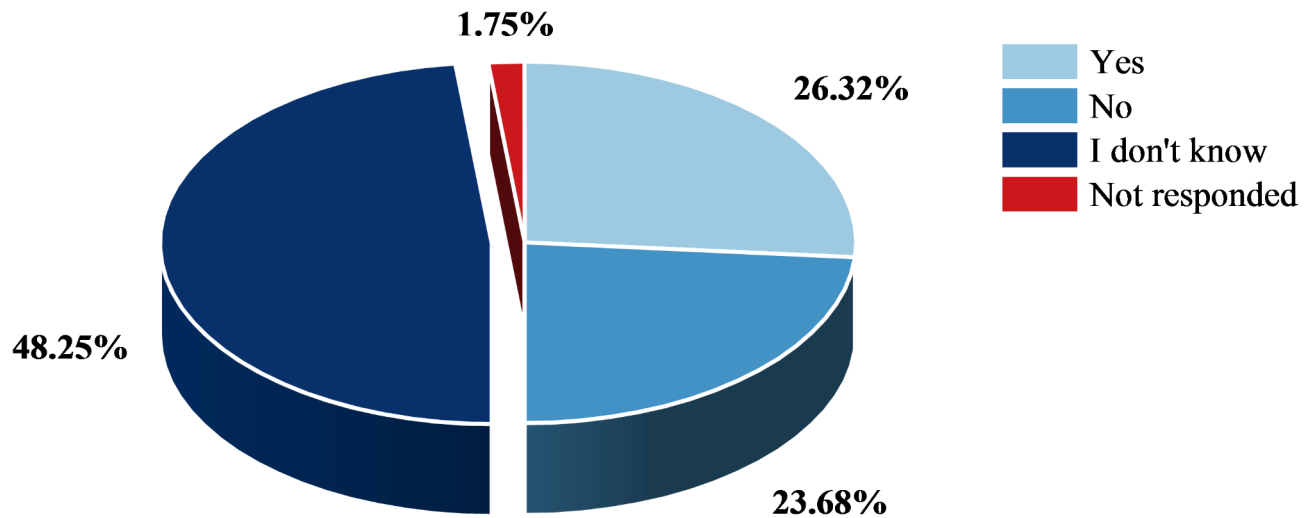*People's opinion about the current waste management system*
Figure 8 presents public perceptions about the safety and environmental friendliness of Tabuk City's waste disposal methods. The perceptions have been analyzed based on a particular survey question that can be stated as:

Q6: Is your city's waste disposal method safe and environmentally friendly?

As can be seen, the most prominent finding is the high proportion of respondents (48.25%) who indicated "I don't know" as a response to the safety and environmental impact of their city's waste disposal methods. This suggests a significant lack of public awareness and understanding of local waste management practices and their potential environmental consequences. Additionally, a smaller percentage (26.32%) believed that their city's waste disposal methods were safe and environmentally friendly, while a similar proportion (23.68%) expressed the opposite view, stating "No." The "Not responded" respondents appear to be a low percentage (1.75%), which indicates a high overall response rate to this particular survey question.

The analysis of this questionnaire highlights a critical need for improved communication and transparency from local authorities about their waste management strategies. The large proportion of "I don't know" responses suggests a lack of proper information and public engagement on this critical issue. Similar findings have been reported in other studies conducted by Kala and Bolia[74], where they stated that trust and communication shape public attitudes toward potentially complex technologies and waste management practices. Their study suggests that developing public trust through clear and accessible information about waste disposal methods could significantly increase support for sustainable waste management and recycling systems. Additionally, research by Adekola, Iyalomhe, Paczoski, Abebe, Pawłowska, Bąk and Cirella[75] suggested that public perception of environmental risk is influenced by factors such as knowledge, trust in authorities, and individual's experience. The study highlights the need for effective communication strategies between citizens and responsible authorities to address the knowledge gap about the waste management system.

Is your city's waste disposal method safe and environmentally friendly?

Fig. 8. Respondent's perceptions about the safety and environmental friendliness of Tabuk City's waste management system.

Public opinion behind the lack of an effective waste recycling system

This research further evaluates the public opinion on the reasons for the lack of implementation of waste recycling in homes. The evaluation was based on the last question of our questionnaire survey, which is stated as:

Q7: In your opinion, what is the reason for not implementing waste recycling in homes?

According to Fig. 9, the largest number of respondents (44.31%) think that a lack of responsible authorities combined with a lack of community awareness is the main reason for not implementing a sustainable waste recycling system. Lack of management is seen as the second most concerning reason (29.87%) behind the poor waste management system in Tabuk City. Further, the lack of initiative by the responsible party accounts for 14.24% of the responses, which emphasizes the inherent need for a stronger waste management plan and action from local authorities. Smaller percentages of survey participants attributed the lack of waste recycling implementation to a lack of awareness (6.68%) and society rejection (4.9%).

The outcomes suggest that optimized and user-friendly waste management plans and initiatives from responsible authorities are the primary needs to establish and enforce effective recycling programs. Similar outcomes can be found in a research conducted by Soomro, Hameed, Bhutto, Waris, Baeshen and Al Batati[76], where they highlight the role of intrinsic motivation and personal norms is very effective for raising public awareness in the context of greater adoption of recycling practices. Furthermore, studies by Knickmeyer[69] illustrate the importance of addressing factors, such as the availability of recycling infrastructure and convenient collection systems that are directly influenced by responsible authorities' actions. The outcomes of this study suggest a coordinated effort between authorities and the community to overcome the barriers to home recycling implementation.

Pearson correlation among current waste management status and influential factors

The correlation coefficient varies between -1 and 1, with values exceeding 0 indicating a positive relationship and negative values reflecting the opposite trend. A higher absolute coefficient value suggests a stronger connection. Figure 10 illustrates the correlation coefficients between input and output variables, which range from -0.51 to $+0.55$. The heat map indicates that among five influential factors, three input variables have a positive interaction with the waste recycling status of Tabuk City, with the exception of society rejection and lack of awareness. The relationship between suggestions for improvement of recycling status and lack of initiative is relatively weak but positive ($+0.20$), suggesting a moderate level of consistency. Lack of management and lack of awareness with responsible authorities exhibited higher positive correlations with recycling improvement, with respective R values of 0.48 and 0.55. These correlations suggest that monitoring these particular points and improving them can enhance the current recycling management system more sustainably. Conversely, a higher negative correlation exists between society rejection and recycling improvement, indicating that a higher rate of social rejection can be a primary reason for hindering the implementation of a sustainable waste management system.

In your opinion, what is the reason for not implementing waste recycling in homes?
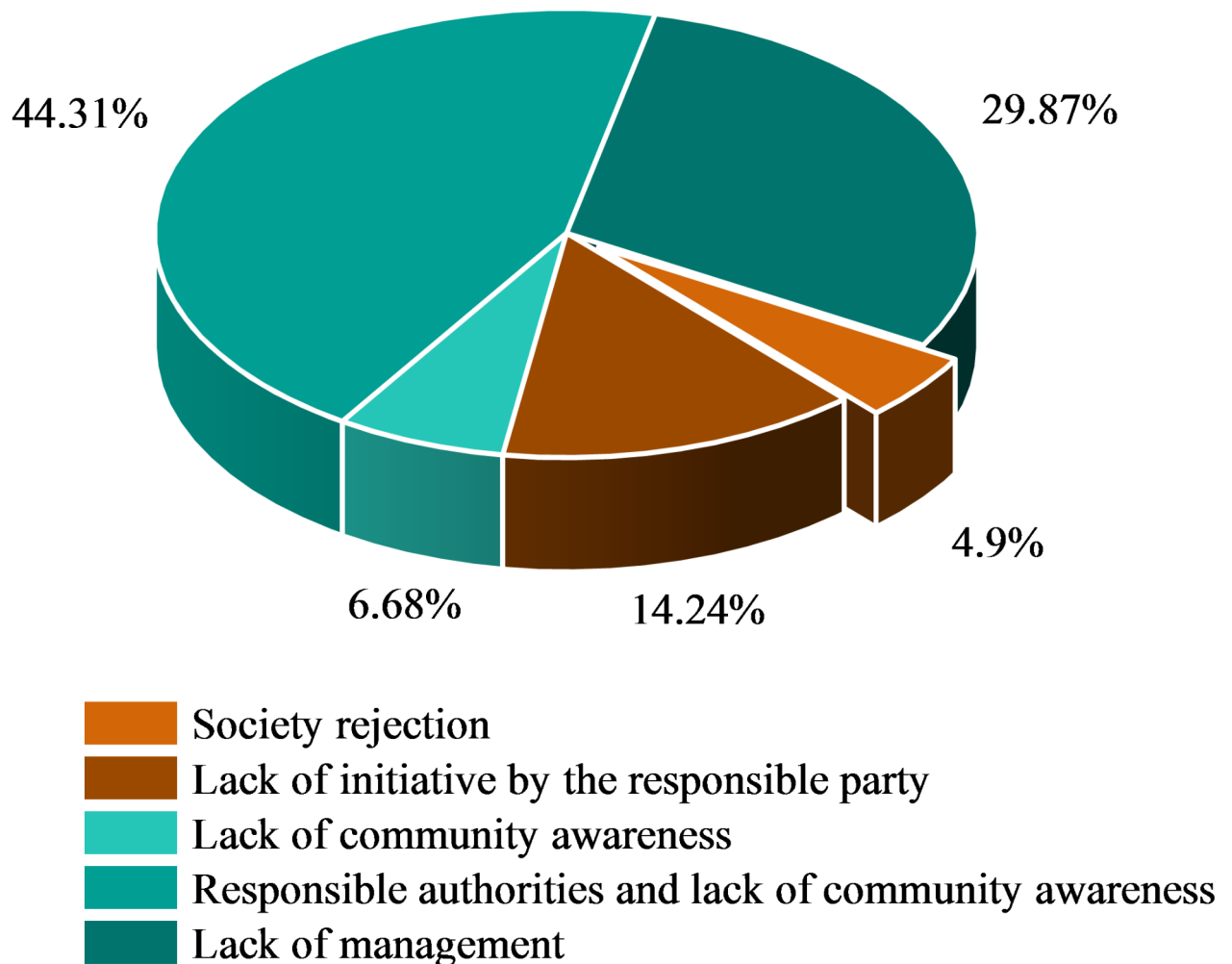
**Fig. 9**. Public opinion behind the reasons for not implementing effective waste recycling in homes.

## Parametric analysis

SHAP analysis

Identifying the essential elements for precise model predictions is essential. This study utilized mean SHAP values to assess the importance of each input variable. Figure 11 depicts the average SHAP values for the input features using extreme gradient boosting (XGBoost) as a base model for developing the algorithm. Lack of awareness and authority responsibility was found to have the most significant influence on the model's predictions, with a SHAP value of 2.15. Lack of management ranked as the second most important factor influencing recycling improvement. Society rejection will also play a significant role in optimizing the current waste recycling and management status. SHAP values reflect both the magnitude and direction of feature contributions, which amalgamate all predictions and thus provide a more reliable illustration of feature importance in non-linear contexts. The high SHAP importance of "society rejection" suggests that, despite its negative correlation with waste management improvement, it has a significant impact on model predictions through non-linear effects and interactions. This parametric analysis removes the limitations of relying solely on Pearson correlation in understanding feature relevance in machine learning models.

Effect metrics and heatmap

The application of SHAP game theory facilitated the ranking of the significance and predictive influence of all input variables. SHAP quantifies the average marginal effect of each variable over all possible combinations. The relative importance of each variable was computed and ranked in descending order to emphasize the
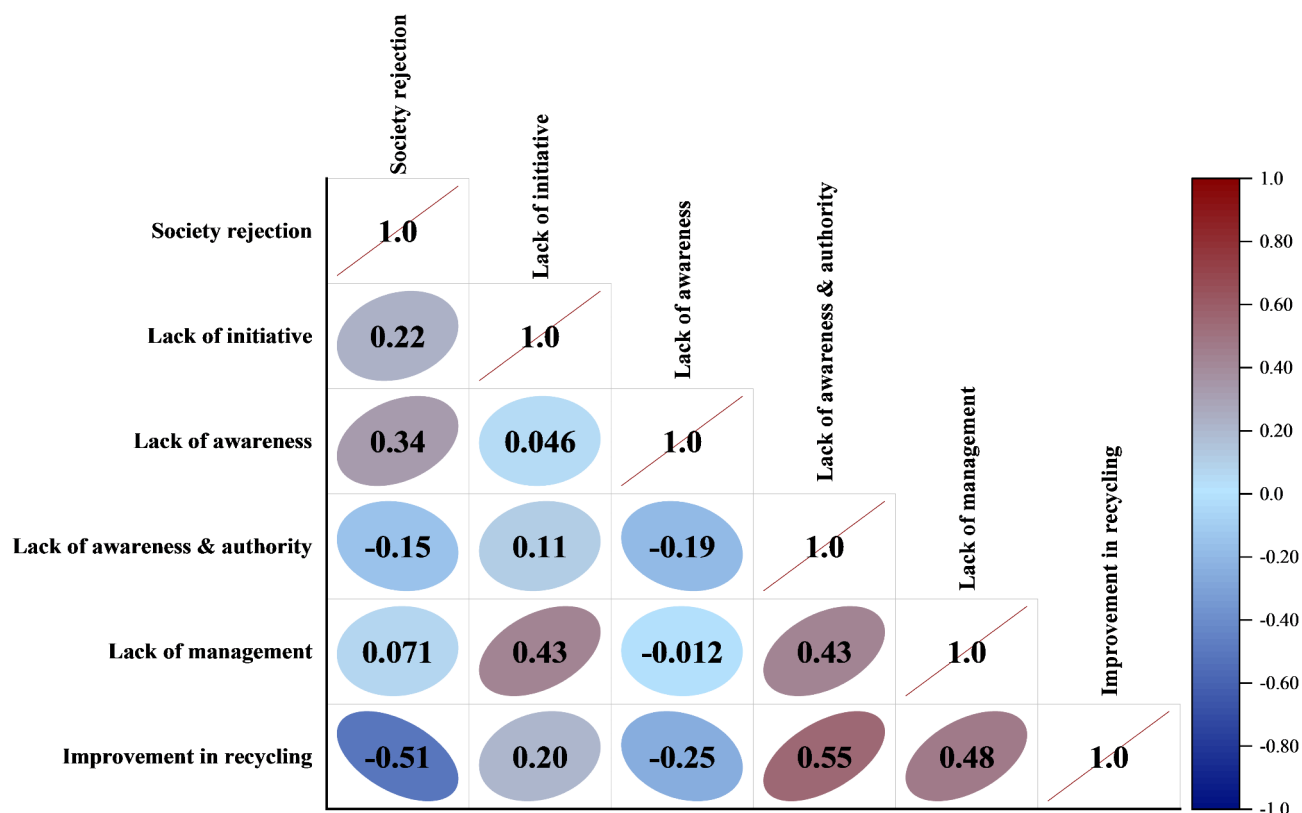
Fig. 10. Correlation shows the influence of factors for improvement in recycling and waste management status according to respondents.
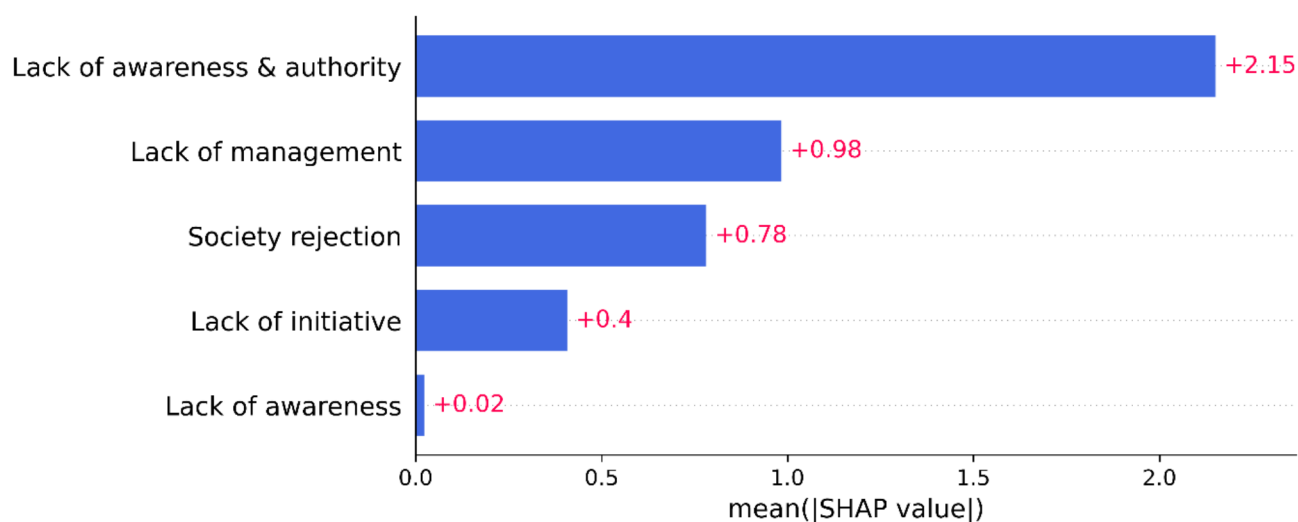

Fig. 11. Mean SHAP values.

overall feature relevance. Figure 12 illustrates the significance of each variable through a violin plot, with the Y-axis indicating feature importance and the X-axis representing SHAP values. This graph demonstrates the relationship between each input and its corresponding SHAP value. For example, lack of awareness and authority responsibility exhibited a notable SHAP value, signifying that the more this issue can be solved, the more the waste management system will be sustainable and user-friendly. Conversely, society rejection and lack of awareness displayed a negative correlation between its SHAP value and feature values. An expanded dataset would offer clearer insights into the patterns and effects of each input.
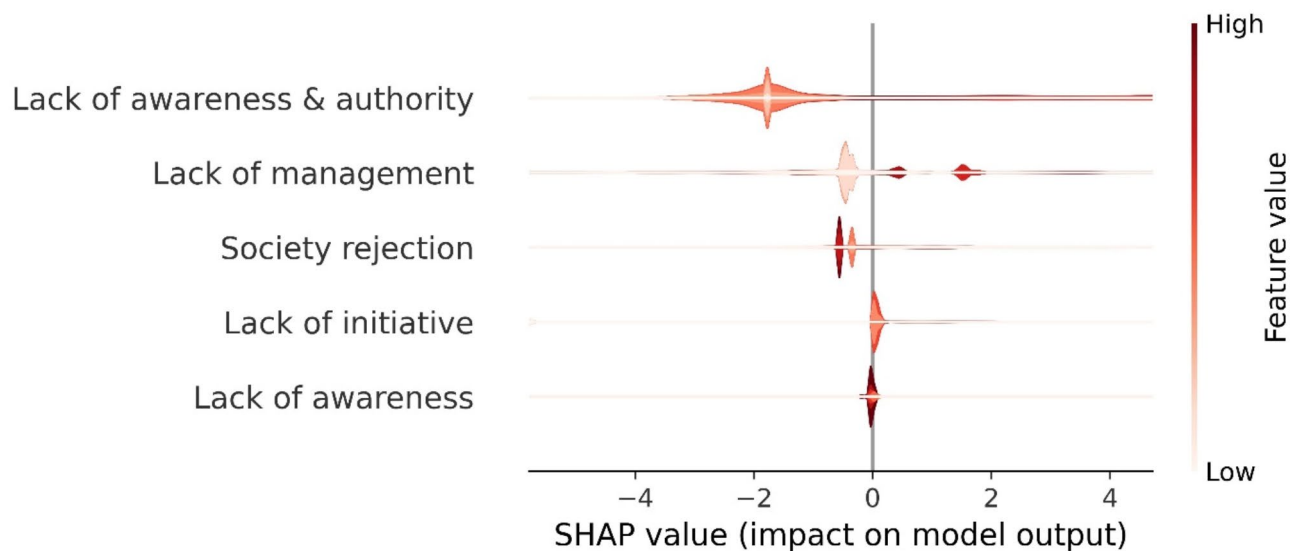
**Fig. 12.** Violin plot illustrating SHAP impact values.
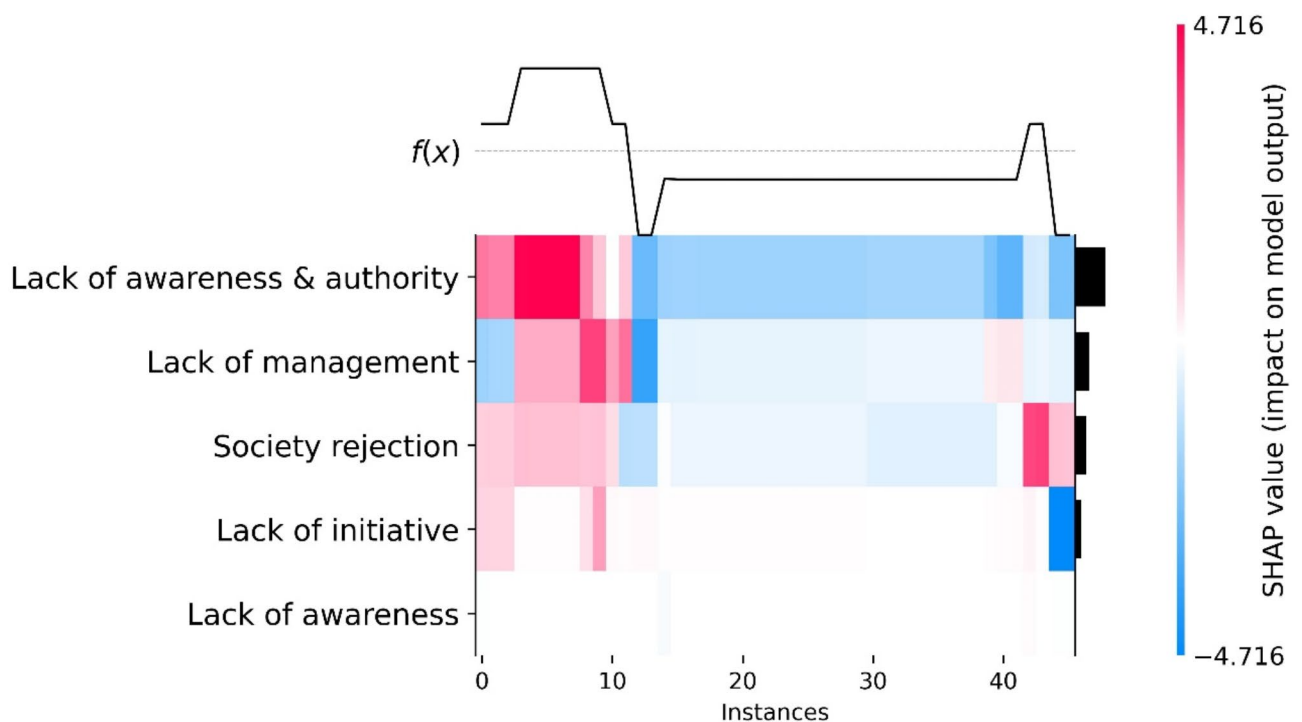
Fig. 13. SHAP heatmap (Generated using Python v3.12.6. Software URL: https://www.python.org/downloads/release/python-3126/).

Figure 13 displays a heat map depicting SHAP values for different features across individual data instances. Here, the shap.Explainer was used to create an explainer object. Then, the explainer was used to calculate SHAP values for the data. Finally, shap.summary_plot visualizes the outcome of the heatmap illustrated in Fig. 13. The f(x) graph showcases the fluctuations in SHAP values among data points with comparable f(x) scores. In the initial 10 instances, Lack of awareness & authority responsibility along with social rejection exhibit significant SHAP magnitudes; however, from instances 10 to 45, the SHAP values turn negative for lack of awareness & authority responsibility parameter. Society rejection displays a higher SHAP value in the last 5 cases, which declines for the remaining points. Other features consistently exhibit lower SHAP values, likely due to data limitations from the questionnaire survey responses.

SHAP interaction plots

Figure 14 illustrates the relationships among input variables and their impact on waste management system improvement. In Fig. 14(a), the relationship between lack of awareness & authority responsibility and lack of management. As can be seen, the first factor has a significant influence, although no significant relation can be visualized between lack of awareness & authority responsibility and lack of management. Figure 14(b) highlights that lack of management has a strong SHAP value, which highlights increased influence on the prediction of outcomes of the model. In Fig. 14(c), the interaction between society rejection and lack of awareness & authority
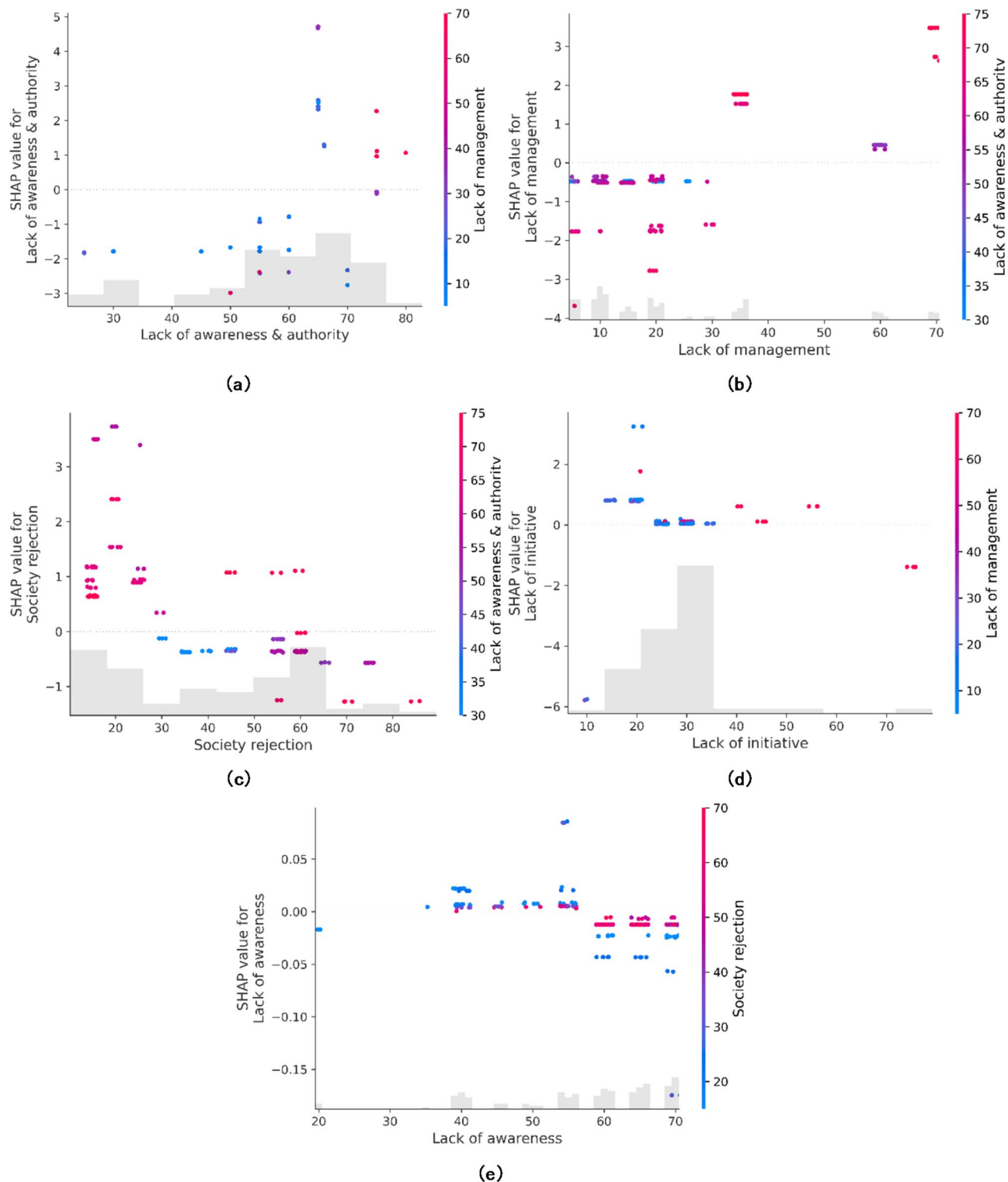
Fig. 14. Interaction plot for all influencing parameters.

(a)

(b)

(c)
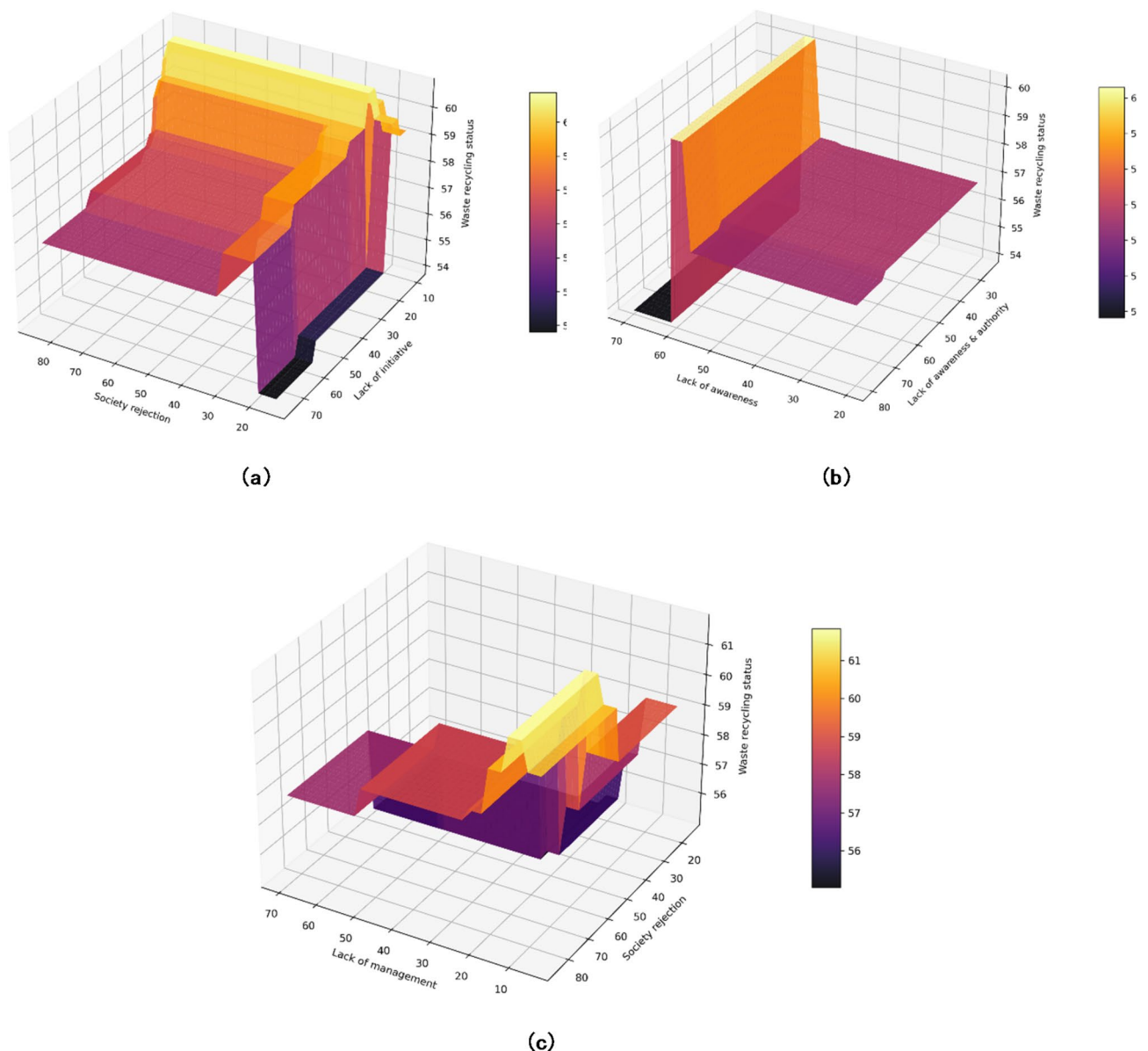
Fig. 15. 2D-PDP illustrating optimization of input features (Generated using Python v3.12.6. Software URL: https://www.python.org/downloads/release/python-3126/).

responsibility shows a strong correlation up to 30 scores; beyond this point, the influence gradually decreased. According to Fig. 14(d), a lack of initiatives almost neutrally affects the improvement of the waste management system, suggesting that keeping a score between 15 and 35 yields better optimization. In Fig. 14(e), lack of awareness showed negative value, which showcases the negative impact of predicting sustainable recycling practices.

Partial dependency analysis

Figure 15 illustrates the impact of various public opinions on the waste recycling and management of Tabuk City. The PDP plots generated in this study were primarily analyzed and visualized using open-source software Python v3.12.6. Additionally, it used Python's sci-kit-learn library, particularly the plot_partial_dependence() function from sklearn.inspection. The 2D-PDP plot in Fig. 15(a) illustrates a complex interaction between "Society rejection," "Lack of initiative," and "Waste recycling status". As seen in the figure, when lack of initiative increases, the waste recycling status shows a moderate increase, even if society's rejection remains low. However, the most significant improvement in waste recycling status occurs when society's rejection decreases with a moderate to high level of initiative. This suggests that addressing societal resistance to recycling is significant for achieving high recycling rates, even if initiatives are in place. Conversely, even with strong initiatives, significant societal rejection can hinder progress in waste recycling. Similarly, Fig. 15(b) visualized that when both "Lack of awareness" and "Lack of awareness & authority" are minimal, the "Waste recycling status" is also very low. This

summarizes that without both public understanding and effective action from authorities, recycling programs are likely to be ineffective. As "Lack of awareness" increases, regardless of the level of "Lack of awareness & authority," the "Waste recycling status" still remains low. This recommends that simply increasing authority intervention is not a guaranteed path to higher recycling rates; rather, it must be coupled with effective public awareness campaigns to be truly successful.

Similarly, Fig. 15(c) illustrates that when proper management is seen to be a downtrend, the waste recycling status is also a downtrend, highlighting the fundamental importance of effective management practices. Without proper infrastructure, efficient logistics, and adequate processing, even a highly supportive public cannot effectively recycle. Similarly, as society's rejection increases, the waste recycling status also tends to decrease, even with varying degrees of lack of management. This phenomenon emphasizes that if the public is apathetic or actively resistant, even the best-designed recycling programs will fall short of their potential. This parametric analysis summarizes that successful recycling outcomes are primarily concentrated in areas where both lack of management and society rejection are minimized.

Discussions and recommendations

The practical implication of the outcome of this study is crucial as the study highlights the important factors that primarily hinder the development of a sustainable waste management and recycling system (according to the opinion of users of Tabuk City). Responsible authorities and law practitioners can implement these opinions to understand the psychology of end users and further develop a user-friendly, convenient recycling plan that can enhance the waste recycling status of Saudi Arabia. By analyzing the outcomes of this study, it can be easily understood that most citizens are eager to engage in waste segregation and recycling programs at home; nevertheless, the absence of such activities or initiatives by local authorities renders the system unfeasible. As the production of solid waste increases rapidly by the Saudi populace, the government urgently requires the implementation of a stringent recycling program to manage these harmful waste contents and promote waste recycling for the enhancement of society. The local government must diligently develop a robust legislative framework for waste management based on this research findings.

Furthermore, it can be concluded that public engagement and effective governance are crucial for optimizing waste management systems. Based on the survey study and physical evaluation of the landfill and waste management system of Tabuk City, it is essential for the government to establish a recycling program with strict rules to tackle this detrimental waste and encourage waste recycling for the betterment of the community. In addition, the government should provide an education campaign and promote awareness about the adverse impacts of solid waste to the public in order to foster a widespread propensity towards recycling across every part of the population. Developed nations like China serve as exemplary examples of this situation. China considered the enhancement of access to recycling facilities essential for encouraging recycling practices[8]. For this, they provide readily available simple and practical methods for the segregation and storage of recyclable garbage, ideally on single floors inside residential complexes. Moreover, different containers with unique identifying colors were positioned in residential zones for source separation to reduce trash and enhance recycling efforts[8]. Conversely, the South Korean government, in partnership with nonprofit organizations, established educational initiatives designed to motivate residents to reduce food waste. Initiatives included the establishment of "The Day of No Food Waste," the acknowledgment of "Eco-Friendly Restaurants," and the initiation of a "Plates with No Food Left" campaign[77]. This comprehensive strategy effectively promoted a culture of waste reduction. The Saudi government could also initiate an educational effort to enhance awareness while promptly establishing user-friendly recycling facilities nationwide.

Conclusion and future studies

Solid Waste Management is a necessary routine function of modern cities. However, small cities still do not take advantage of MSW recycling, reusing, and proper disposal, which can cause various public health concerns and social and environmental complications. 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:

A significant proportion of participating Tabuk residents recognize the environmental hazards posed by household waste; however, there is a clear gap between awareness and actionable behavior. This gap is attributed to a lack of infrastructure, user-friendly recycling facilities, and public incentives. Furthermore, many participants displayed limited knowledge of recycling methods and their local waste management systems, which need extensive comprehensive education campaigns to foster informed participation. One of the most concerning outcomes is that the majority (71.92%) of participants are not involved in recycling at home, which ensures a low level of participation in source separation and awareness. Additionally, a significant proportion also responded negatively when they asked about recycling background (31.57%) and their city's waste disposal method (44.73%), which highlights a clear gap in understanding the broader context of waste management beyond individual household actions.

SHAP analysis revealed that lack of awareness along with authority responsibility was the most influential factor impacting waste management predictions. While "society rejection" showed a negative correlation, its non-linear effects and interactions significantly influenced the model. Partial dependency analysis further elaborates on the interplay between these factors and recommends the necessity of addressing societal resistance and promoting public awareness alongside effective management practices for successful waste recycling outcomes. Last of all, it can be said that the study's geographical priority, especially on Tabuk City, constrains the generalizability of the findings to the wider Saudi population or different cultural contexts. Further research could overcome this restriction by broadening the geographic reach of data collecting and using mixed-method

techniques, such as observational studies or experimental designs, to corroborate and enhance self-reported results.

Data availability
Dataset will be provided upon request. Please contact Wael S. Al-Rashed (email: walrashed@ut.edu.sa) if anyone needs the data for this study.

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Acknowledgements

Author contributions

Authors' contributionsWael S. Al-Rashed: Conceptualization, Methodology, Validation, Formal analysis, Writing - original draft, Writing - review & editing.

Declarations

Competing interests

The authors declare no competing interests.

Additional information

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1038/s41598-025-94525-w.

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