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VOL - XXV

SUSTAINABLE DEVELOPMENT

Edited by Nadeem Javed & Faheem Jehangir Khan

RASTA: LOCAL RESEARCH LOCAL SOLUTIONS

SUSTAINABLE DEVELOPMENT

(Volume XXV)

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Tel. +92 (51) 9248144, 9248026
Email: rasta@pide.org.pk
URL: rasta.pide.org.pk

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PART I

SUSTAINABLE DEVELOPMENT

Research Papers

A COMPREHENSIVE ASSESSMENT OF CONVENTIONAL PRACTICES AND SUSTAINABLE PATHWAYS FOR SOLID WASTE MANAGEMENT: INTEGRATING PERSPECTIVES, PRACTICES, AND THE ENVIRONMENTAL IMPACT

Shoaib Muhammad[1], Taimur Mazhar Sheikh[2], and Musharib Khan[3]

ABSTRACT

Solid waste generation is escalating globally due to population growth, urbanisation, and technological advancements, posing environmental, economic, and public health challenges. Developing nations, like Pakistan, face greater challenges due to limited resources. Solid waste management in Pakistan is characterised by inefficient collection and the lack of waste treatment, leading to unsustainable practices. This study comprehensively assessed the components of sustainable solid waste management, focusing on Wah Cantt City. Key objectives included waste characterisation, shortlisting treatment options based on waste composition, expert opinions, evaluating formal and informal sector integration, analysing public knowledge, attitudes, practices, and conducting a cost-benefit analysis, and environmental life cycle assessment of treatment options. Findings revealed: i) 55% organic waste composition, ii) composting and material recovery facilities as preferred treatment options, iii) minimal integration of formal and the informal sector, iv) public preference for Public-Private Partnership (PPP) operations, v) door-to-door collection as more effective, vi) good public knowledge (90%) but lower attitudes (73.3%) and practices (64.7%), and vii) nearly

[1] Lecturer, University of Wah, Wah Cantt. Rawalpindi.

[2] Assistant Professor, University of Wah, Wah Cantt. Rawalpindi.

[3] Assistant Professor, National University of Sciences and Technology (NUST), Islamabad.

self-sustaining operations despite no monthly fees. Policy recommendations include adopting (PPP) nationwide, transitioning to door-to-door collection, formalising informal sector access to waste, mandating composting and material recovery facilities, curriculum reforms to include SWM education, promoting awareness campaigns, and introducing gate fees at dumpsites. The findings apply to Pakistan and similar socioeconomic contexts, serving as a reference for researchers exploring solid waste management systems.

1. INTRODUCTION

Municipal solid waste[4] (MSW) is increasing at an alarming rate, with global production exceeding two billion tonnes annually. If current trends persist, this figure is expected to surpass four billion tonnes in the coming decades. To put this into perspective, if all the waste generated globally were packed into standard shipping containers and transported by truck, the line of vehicles would stretch the distance from Earth to the Moon and back (UNEP, 2024). The situation in developing countries is particularly critical, with Pakistan being a notable example. Although official data is lacking, estimates suggest that the country produces up to 32 million tonnes of solid waste each year, with an annual growth rate of 2.4% (Batool & Ch, 2009; Ejaz & Janjua, 2012; Majeed et al., 2018). Collection services are inefficient, covering less than half of the waste in major cities and virtually none in rural regions. Solid waste management is overly reliant on manual sweeping and collection, while sustainable treatment methods, such as incineration, composting, and anaerobic digestion, receive minimal attention. Furthermore, Pakistan lacks a single operational sanitary landfill, and most waste is disposed of through open dumping and burning, practices that pose serious environmental and health hazards (Iqbal et al., 2022; Devadoss et al., 2021; Nadeem et al., 2023).

Consequently, this mismanagement of solid waste is leading to accelerated pollution of the local environment and subsequently impacting the global climate, as observed by Misganaw (2023) in a case study of Ethiopia. A recent report by the United Nations Environment Programme (UNEP) linked solid waste to the triple planetary crisis of climate change, biodiversity loss, and pollution (UNEP, 2024). The primary reasons for the dilapidated state of solid waste management in Pakistan include political negligence, lack of resources, public awareness and behaviour, outdated regulatory framework, and administrative issues (Zia et al., 2020).

Considering the interconnection of waste management with the Sustainable Development Goals and the updated Nationally Determined Contributions[5] (NDCs), it is imperative to revisit the outdated national waste management policies urgently. The formulation of policies requires a comprehensive, holistic, reliable, and site-specific assessment of the baseline situation of the

[4] Municipal solid waste refers to the solid waste coming from residential and commercial sources but does not include industrial waste.

[5] Nationally Determined Contributions are the commitments/pledges made by the countries to reduce the green house emissions to mitigate the climate change.

various interconnected components of solid waste management (Muhammad et al., 2023). This research study undertakes a comprehensive assessment of solid waste management in Wah Cantt, Pakistan. It encompasses a detailed analysis of waste composition, evaluation of treatment options and their environmental impacts, an investigation into the role and significance of the informal sector, a cost-benefit analysis, and a public survey examining the knowledge, attitudes, and practices (KAP) related to solid waste management. Collectively, these components address the key pillars of sustainable solid waste management (SWM). The research study's findings will enable the relevant stakeholders, including the municipalities, cantonments, and waste management authorities, to make informed and data-driven decisions.

2. LITERATURE REVIEW

According to Seadon (2010), a sustainable SWM system refers to responsible and efficient generation, collection, transportation, and waste treatment, including recycling, anaerobic digestion, composting, and disposal of waste material, while considering the following:

- Environmental friendliness
- Economically feasible and self-reliant state of affairs
- Socially aware and inclusive communities
- The institutional capability of the management units

Thus, a sustainable SWM system comprises technical, institutional, social, environmental, and economic components, with comprehensive assessments incorporating all the sustainability components essential for successful planning and management (Muhammad et al., 2023). Multiple studies have been conducted in isolation on different aspects of the SWM. The subsequent section includes a critical analysis of the studies undertaken on the various aspects of solid waste management.

A waste audit or waste analysis and characterisation study (WACS) is essential to a reliable and effective SWM system. It involves determining and characterising the generated waste (Bilal et al., 2022). Amir et al. (2023) and Iqbal (2021) studied the composition of the waste generated in higher education institutes (HEIs). However, the nature of the waste generated in

HEIs is entirely different from municipal solid waste. Moreover, the installation of the waste treatment units for the HEIs is not economically feasible, considering the comparatively smaller amount of generated waste. Some waste audit studies conducted on municipal solid waste include Bilal et al. (2022), Nadeem et al. (2023), and Zia et al. (2017), among others. The methodology adopted in these studies included collecting waste samples from the households directly over one week. The issues with sample collection from the households included privacy concerns, sampling bias, labour intensiveness, and social desirability bias (SDB).[6] An alternate methodology to overcome the shortcomings of sample collection from households is based on the American Society for Testing and Materials (ASTM) D 5231-92, i.e., a standard method for determining the composition of municipal solid waste.

The increasing solid waste generation is resulting in detrimental effects on the environment and is a significant cause of climate change. Therefore, environmentally sustainable treatment of the generated solid waste is critical, and life cycle assessment is the most reliable and commonly used methodology to determine the environmental effects of different treatment technologies (Mulya et al., 2022). Batool & Chaudhry (2009) used the Integrated Waste Management-2, a life cycle inventory (LCI) model, to determine the environmental impacts of various treatment methods – material recovery facility (MRF), composting, biogasification, and landfilling – for Data Ganj Bakhsh Town in Lahore.

The literature recommends using SimaPro software, the most commonly used software for determining environmental impacts (Mulya et al., 2022). Ali et al. (2018) studied the environmental impacts of open dumping, sanitary landfill, composting, recycling, and incineration in Gujranwala City. Anaerobic digestion, which is a very relevant technology considering the predominantly organic nature of waste in Pakistan, was not considered. Also, the methodology used to determine the impacts included secondary sources, including data from other countries, which are more likely to generate less accurate and reliable results. Atta et al. (2020) used the SimaPro software to determine the environmental impacts, but they took into account only the existing practices of the Rawalpindi Waste Management Company, without considering other major waste treatment technologies.

Literature suggests that communities' knowledge, attitudes, and practices (KAP) significantly impact solid waste management (Eshete et al., 2023).

[6] Social Desirability Bias is a phenomenon where the people give responses based on their belief that they will be viewed favourably by others.

Although some studies, such as Haider et al. (2015), have conducted a KAP survey, the available studies have taken into account only limited KAP aspects, unlike some studies that have been published in renowned journals.

Another important stakeholder in the SWM system, particularly in the context of developing countries, is the informal sector. The determination of the role and significance of the informal is critical (Sigcha et al., 2024). Some studies on the informal sector in Pakistan include those conducted by Kamran et al. (2016) and Majeed et al. (2017). Since the various components of the SWM system do not remain static and evolve, studying the current situation is necessary (Muhammad et al., 2023). Moreover, the recent changes in the country's socioeconomic affairs make new studies necessary.

The existing approach focuses on breaking down a problem into smaller pieces and then visiting each problem in isolation. Although this approach provides a resolution of the problem being studied, the other issues remain unresolved due to the interconnected nature of the system. Therefore, approaching smaller issues in isolation is increasingly problematic. Moreover, multiple studies necessitate carrying out integrated studies (Joos et al., 1999; Marshall & Farahbakhsh, 2013; Merker et al., 2015; Seadon, 2010; Zarate et al., 2008).

3. RESEARCH METHODOLOGY

The methodological framework followed in this research study is presented in Figure 1. The adopted methodology encompassed five aspects, namely, technical, social, institutional, economic, and environmental, of sustainable SWM. Firstly, within the technical component of the study, the composition of solid waste generated in Wah Cantt was determined across two seasons through a WACS, conducted in accordance with the ASTM D5231-92 standard (ASTM, 2016). The WACS was conducted for both door-to-door collection of waste and waste collected from the roadside. The door-to-door collected waste is also referred to as household collection, and the roadside collection is referred to as the dumpsite collection in this study.

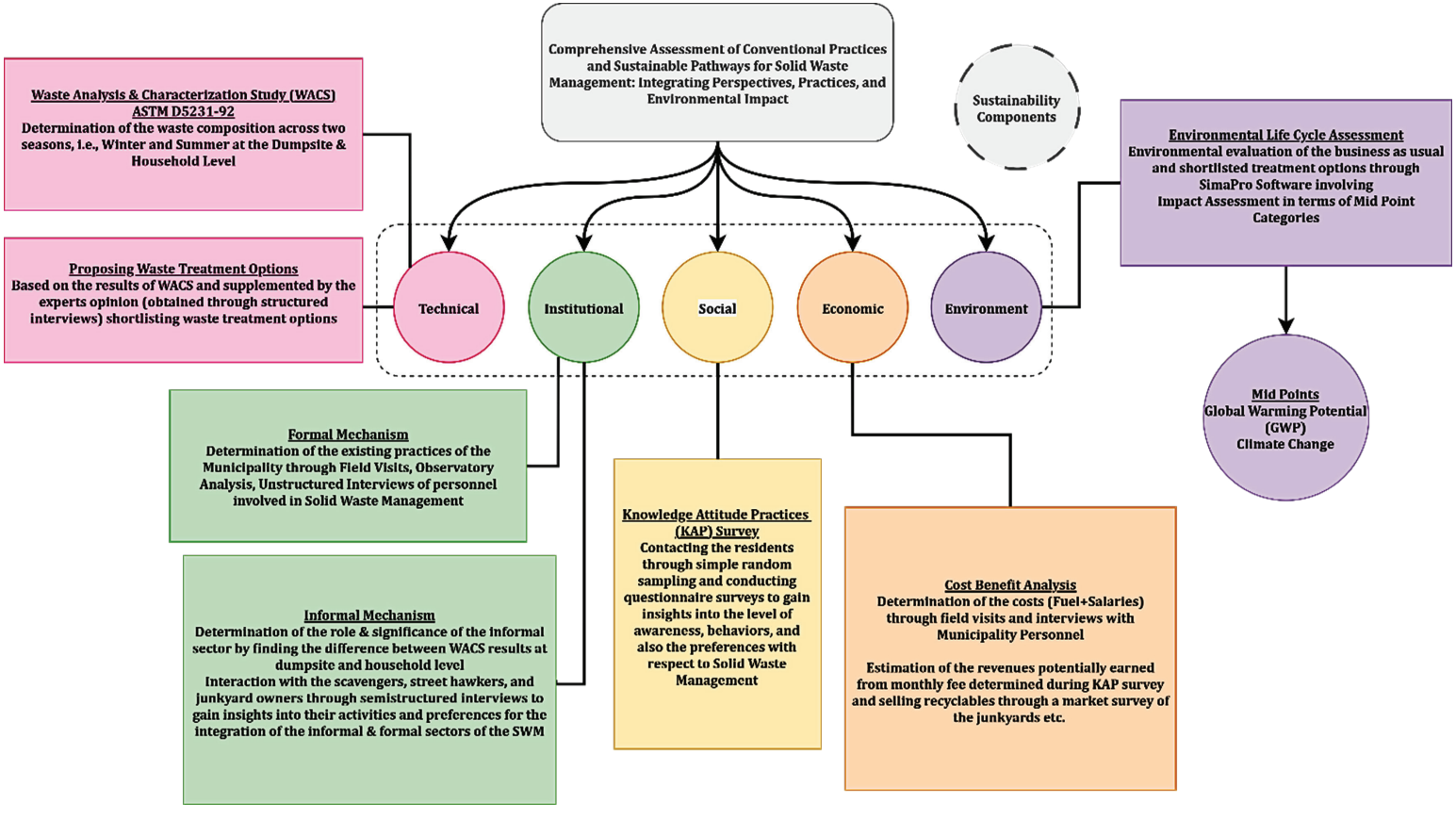
Wah Cantt City was selected as the study area due to its unique SWM structure. In Wah Cantt, waste management responsibilities are shared between two entities, namely, the Pakistan Ordnance Factories (POF), which has partnered with a private sector company to provide door-to-door waste collection in addition to the conventional roadside collection, and the

Cantonment Board Wah, which follows the conventional practice of collecting waste from roadside skips and tubs. This dual management system offered a valuable opportunity to examine the role of multiple stakeholders in enhancing the efficiency of solid waste management.

The door-to-door collected waste arrives at the waste management facility located near the dumpsite, while the roadside collected waste is directly transferred to the dumpsite. A representative sample from the trucks arriving at the facility and dumpsite was taken. The composition of the collected solid waste was then determined using the coning and quartering method, as represented in Figures 2 and 3. The composition of the solid waste provided vital insights into the consumption behaviour of the public and, more importantly, informed the selection of the treatment processes. The procurement of samples directly at the waste management facility and the dumpsite ensured an accurate representation of solid waste for management. Additionally, multiple experts' opinions were sought via Google Forms and emails to finalise the selected treatment options.

The institutional component included (i) the determination of existing practices regarding the collection, transportation, and management of solid waste through site visits, (ii) unstructured interviews of the personnel involved in the SWMS, and (iii) an investigation of the role and significance of the informal sector in SWM via semi-structured interviews and waste audit result analysis. The role and significance of the informal sector were first explored by quantifying the activity of the informal sector through the difference in the WACS results (recyclables only) of door-to-door collected waste and roadside collected waste. The role of the informal sector covered in the research study was also investigated to determine how the informal sector can be integrated with the formal sector of solid waste management. The said objective was achieved by following the framework proposed by Velis et al. (2012). The data for the framework were collected through semi-structured interviews with the key stakeholders of the informal sector, including scavengers, street hawkers, and junkyard owners (as presented in Figure 4). The sampling method adopted was the snowball technique, as recommended in the literature for the informal sector due to the lack of official records (Gall et al., 2020; Sigcha et al., 2024; Yıldız-Geyhan et al., 2017).

Figure 1: Methodological Framework



Source: Authors' illustration.

Figure 2: Arrival and Offloading of the Municipal Solid Waste from the Trucks

Source: Pictures by the authors.

Figure 3: Coning and Quartering of the Municipal Solid Waste

Source: Pictures by the authors.

The social component of the sustainable SWM system was assessed by determining the KAP survey of the Wah Cantt residents based on the simple random sampling method and using structured questionnaires. The questionnaire was developed after a rigorous literature review.[7] After

[7] Some of the studies that provided vital design guidelines included Aryal & Adhikary (2024); Baawain et al. (2019); Baba-Nalikant et al. (2023); Debrah et al. (2021); Desa et al. (2011); Desa et al. (2012); Eshete et al.(2023); Ferronato et al. (2022); Haider et al. (2015); Hamzah et al. (2022); Kiran et al. (2015); Laor et al. (2018); Lema et al. (2019); Limon & Villarino (2020); Wang et al. (2020).

developing an initial draft of the survey, it was sent to experts (via email and LinkedIn) who were requested to review the questionnaire. The experts included social scientists and environmental experts. The questionnaire was then revised in light of the reviews received. The comments received by each reviewer and the finalised questionnaire (English and Urdu versions) are provided in the appendices. The questionnaire was also translated into Urdu, keeping in view the local language preferences.

The economic component of sustainable SWM was assessed through a basic cost-benefit analysis (CBA) of the waste management entities' operations, in which the costs determined were limited to the operational and management (O&M) expenses, whereas the benefits included the potential earnings through recyclables and the monthly fee (if any). Finally, the environmental aspect of the sustainable SWM system was assessed by conducting an environmental LCA of the business as usual, i.e., open dumping and the shortlisted treatment options via SimaPro software analysis, to determine the environmental impacts in terms of midpoint categories.

Figure 4: The Informal Sector Survey

Source: Picture by the authors.

4. FINDINGS AND DISCUSSION

The findings of this study are listed in the same order as outlined in the research methodology.

Technical Components

Waste Analysis and Characterisation Study (WACS)

The ASTM-D5231 was performed on household and dumpsite waste across the winter and summer periods to develop a baseline assessment of the various wastes produced in Wah Cantt. Solid waste was categorised into 14 types following ASTM (2016), Bilal et al. (2022), and Nadeem et al. (2023). The statistical descriptives of the tests are summarised in Figure 5. These values are also tabulated in the Appendix as Appendix Tab. 1.

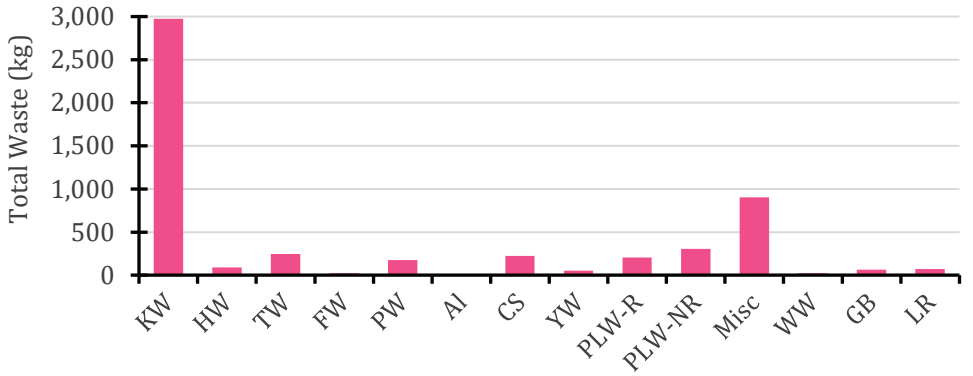
Each waste category type is assigned a label, as these labels are used in analysing the main findings in this section. Figure 5 shows the overall distribution of waste across seasons and collection types. Figure 5(a) shows the total amount of waste in each category in kilograms. Kitchen waste (KW) and miscellaneous (Misc) dominate the categories, with approximately 2,950 kg and 900 kg, respectively. These are followed by plastic waste non-recyclable (PLW-NR), textile waste (TW), ceramics and stones (CS), recyclable plastic waste (PLW-R), and paper waste (PW), respectively. The least waste was found for aluminium (Al), ferrous waste (FW), and wood waste (WW), in the ascending order.

A more helpful term, instead of total waste (kg), is average daily waste (ADW), collected in kg or as a percentage of the average waste collected daily for each waste category. The latter is denoted as "% of total average daily waste (%TADW)", and both ADW and %TADW are illustrated in Figure 5(b). The distribution is like that of Total Waste collected in Figure 5(a), with KW and Misc being collected the most daily at roughly 55 %TADW and 17 %TADW of the total waste composition. All remaining waste categories contribute less than 10% TADW each. Finally, Figure 5 (c) breaks down the 100 %TADW composition, better visualising the proportions of each waste category. Al is almost indiscernible in the total waste. This composition of waste is also corroborated by the literature.

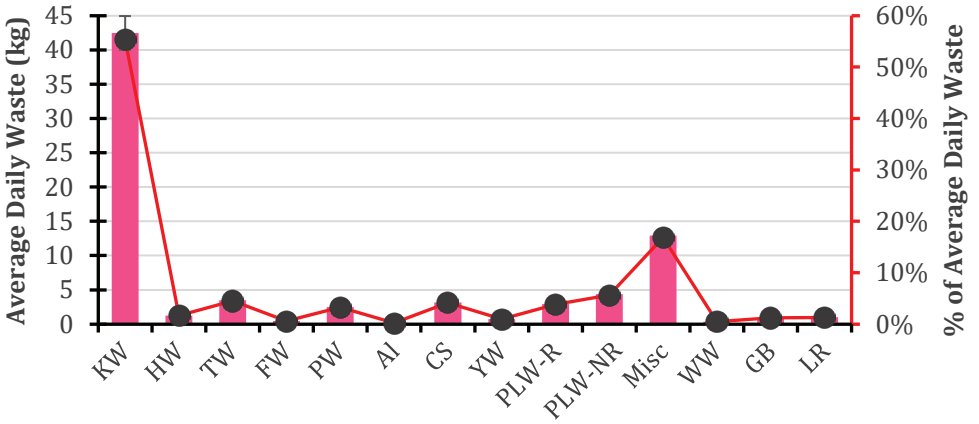
Figure 5a shows the total amount of waste recorded in kg, Figure 5b gives the average daily waste collected in kg and percentage, and Figure 5c gives the breakdown of the different waste categories in the total waste collected as percentage (% TADW).

Figure 5: Summary of WACS

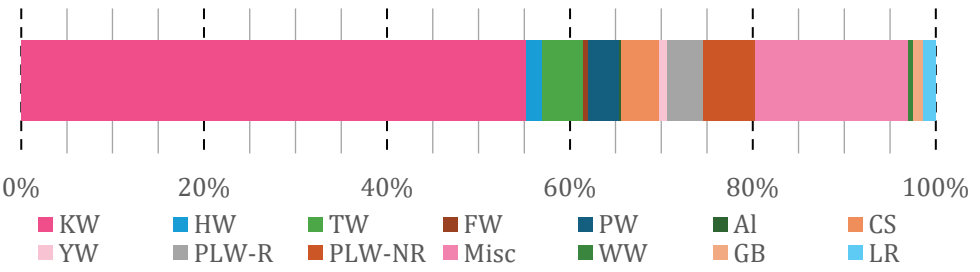
(a)



(b)



(c)



Source: Authors' computations.

The following sections further segregate the waste categories according to the waste collected during the summer and the winter, and the waste collected from a dumpsite and households.

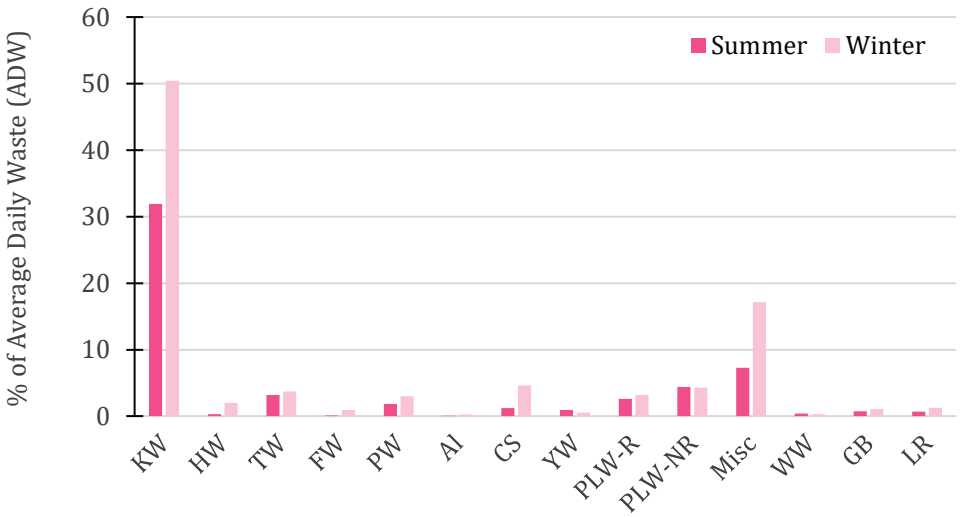
WACS during the Summers and Winters

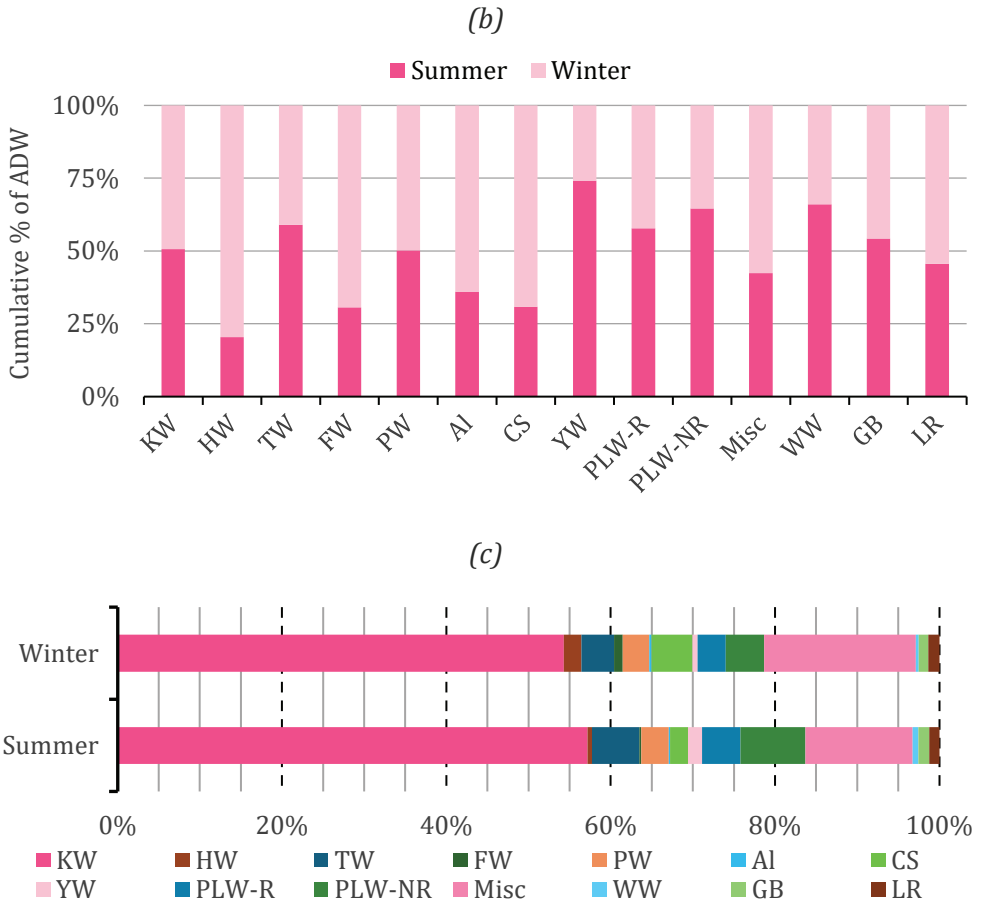
Figure 6 presents a visualisation of the difference in waste compositions during the summer and the winter periods. Notable differences in waste compositions can be observed in Figure 6(a). TW, PLW-R, PLW-NR, and glass and bottles (GB) show higher % TADW in the summer, while hazardous waste (HW), CS, and Misc show higher collections in the winter. Figures 6(b) and 6(c) further illustrate the difference in % TADW across the waste categories. HW and yard waste (YW) are the most visibly different distributions, with about 75% of %TADW collected in the summer for the latter. Also of note, KW, PW, GB and leather and rubber (LR) show similar %TADW for both summer and winter periods.

Figure 6a shows the %TADW for all waste categories of both periods, while Figure 6b shows the relative %TADW between the periods for each waste category. Finally, Figure 6c gives the breakdown composition of the different waste categories for winter and summer periods.

Figure 6: Waste Characterisation across the Summer and Winter Periods

(a)





Source: Authors' computations.

WACS of Household and Dumpsite Waste Collection

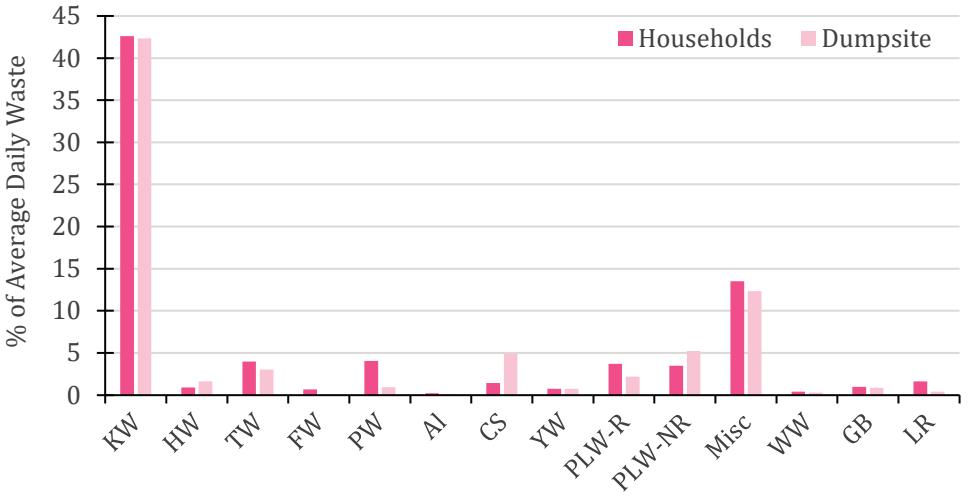
Figure 7 visualises the difference in waste compositions across household and dumpsite waste collections. Notable differences in waste compositions can be observed in Figure 7(a). A relatively higher %TADW can be seen for dumpsite collections of CS and PLW-NR, while higher amounts of PW, TW, PLW-R, and LR can be observed for household collections. As dumpsite waste is collected from large containers such as skips and bins, a higher number of fines is expected, and it is also difficult to separate it from the organic waste, so it is reflected partly in the organic waste of the dumpsite waste audit. Figure 8 shows the distribution of waste categories across the weekdays (Monday to Friday). A buildup of CS can be seen as the week progresses. Moreover, dumpsite collection occurs around commercial areas, where higher amounts of PLW-NR, such as plastic bags, are likely to be found. Conversely, households

do not tend to throw plastic bags often, leading to fewer amounts observed in Figures 7(b) and 7(c). Surprisingly, KW is consistent across both waste collection types. CS and Misc show higher collections in the winter. Figure 7(b) further illustrates that over 90% of FW comes from household collections. KW, YW, Wood Waste (WW) and Misc show approximately the same amount of %TADW for both waste collection types.

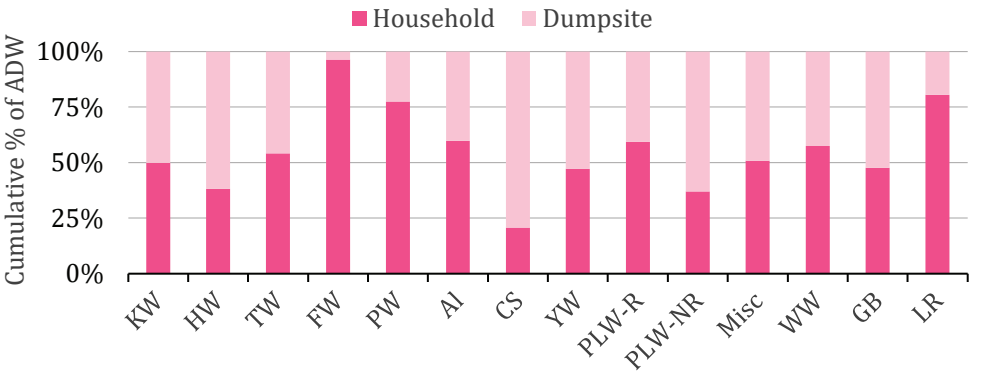
Figure 7a shows the %TADW for all waste categories of both collection types, while Figure 7b shows the relative %TADW between the collection types for each waste category. Finally, Figure 7c gives the breakdown composition of the different waste categories for household and dumpsite waste collections.

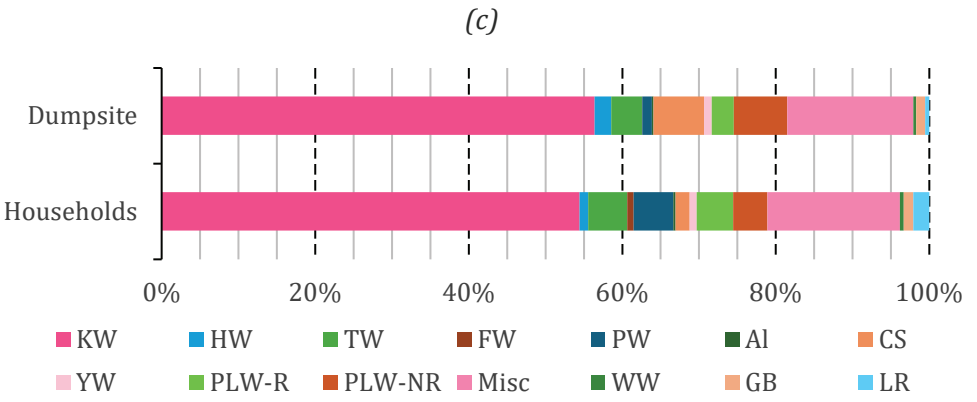
Figure 7: Waste Characterisation across Households and Dumpsite Collection

(a)



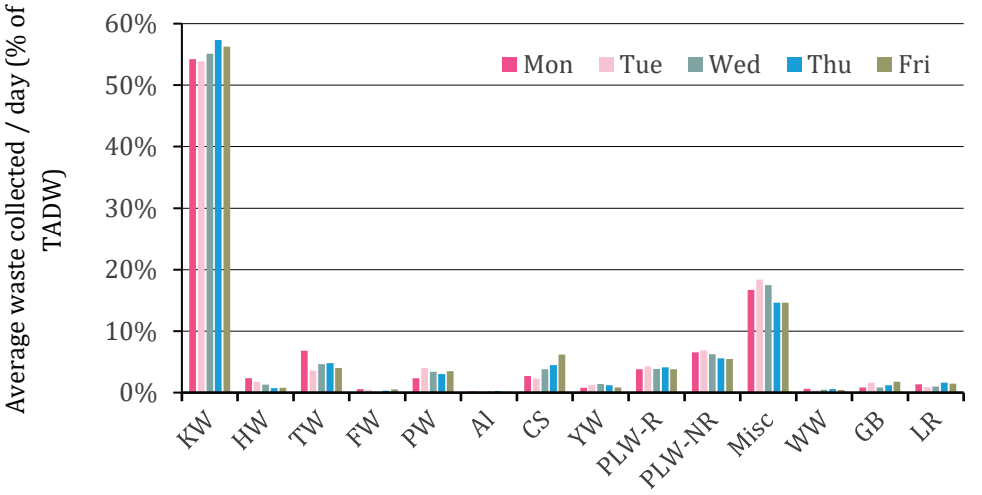
(b)





Source: Authors' computations.

Figure 8: Distribution of Each Waste Category across the Weekdays (Monday to Friday)



Source: Authors' computations.

Experts' Opinion on the Waste Treatment Options

As mentioned earlier, experts' opinions were sought to finalise the waste treatment options. A Google form[8] was created and shared (via email) with field experts who were primarily environmental engineers with relevant field experience. In-person meetings with the municipality experts were also conducted to obtain perspectives on the waste treatment options. A total of 30 experts were contacted, and the results of WACS were shared with them.

[8] The online Google form can be accessed at the following link: https://forms.gle/RT1fWNsAGK72Ag2j7

Moreover, relevant evidence from the literature was presented to obtain their perspectives. It is pertinent to mention here that the WACS results, coupled with the literature review, had already provided enough information about the suitable waste treatment options in the context of Pakistan. However, it was deemed important to contact local experts to ensure that no recent development is left out.

According to the expert's opinion, the following waste treatment options have been shortlisted, which will be assessed in the latter part of the study for the environmental impacts:

- Open dumping (existing practice)
- Sanitary landfill
- Recycling/material recovery facility
- Composting
- Anaerobic digestion
- Incineration

One specific observation shared about the treatment of organic matter was the preference for composting over anaerobic digestion due to the advanced technologies required for the latter, which is pertinent for developing economies like Pakistan.

Institutional Components

Formal Mechanism – Existing Practices by WMEs

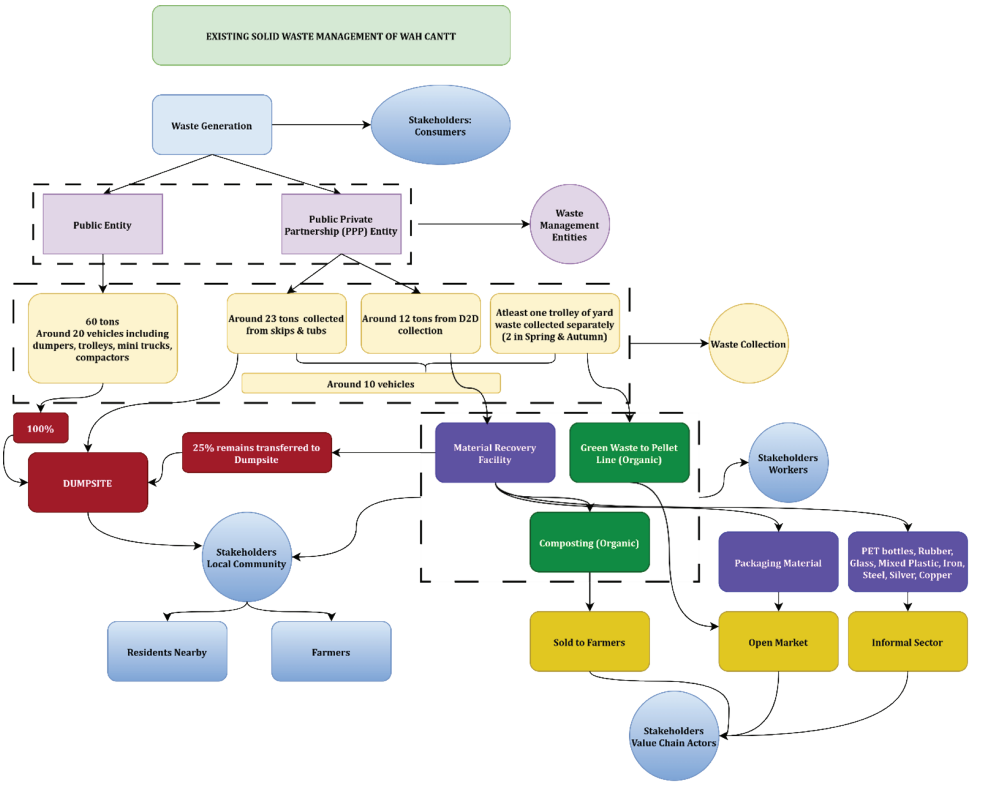
Wah Cantt is a small city situated in the province of Punjab, 30 km to the northwest of Islamabad. It is one of Pakistan's most literate, developed, and industrialised cities. The rapid urbanisation and industrialisation of the city result in the production of a larger amount of solid waste. The area is known to have a waste collection system (outlined in Figure 9), and the presence of diverse management entities offers a unique exploration venue and an authentic set for analysis. The POF and CBW manage the solid waste generated in the Wah Cantt. The POF functions under the Public-Private Partnership (PPP) model, and the CBW is a public entity. The city is divided into two areas, i.e., the state area and the private area. The state area has the highest population density, and the area is mainly inhabited by the employees of the POF. The private area is inhabited by people with private jobs and businesses. The state area is managed under the PPP, while the private area is managed by the public entity (Zia et al., 2020).

The following insights were obtained based on information gathered with the help of field visits and unstructured interviews with the officials of the waste management entities. The PPP offers door-to-door collection to 12,000 households within the state area. According to the officials, the waste is collected on alternate days only during weekdays. In addition to the door-to-door collection, the PPP collects waste from the skips and tubs placed near residential areas, commercial areas, and hospitals, in addition to cleaning streets and separately collecting yard waste. On the other hand, the public entity collects waste only from the skips and tubs placed within the private area. In the private area as well, per the officials' claim, the waste is collected on alternate days only during weekdays. The collection process starts early in the morning, and the collected waste by both entities is transported to a common venue on the city's outskirts, located in the village of Budho. The PPP has set up a waste treatment facility with the options of composting kitchen waste, a material recovery facility (MRF) for recovering recyclables, and a pellet line for yard waste. The public entity, on the other hand, transports all the waste directly to a dumpsite, which is located a little further from the waste treatment facility of the PPP.

The PPP has also set up a weighing bridge, which both the PPP and the public entity's vehicles use. However, the weighing bridge is used only to record the incoming weights, and there is no limitation on the weights or any concept of a tipping fee/gate fee, which is essential for promoting management initiatives. The vehicles start arriving at the facility from 9 a.m. with regular intervals until 1 p.m. in winter. In summer, the vehicles under PPP follow the same schedule, whereas the public entity's vehicles' arrival at the site continues until 5 p.m.–6 p.m.

The primary reason for the difference in the operations of both entities (related to the collection mode, the number of operating days in a week, and adherence to specific times throughout the year) is the presence of the treatment facility, due to which the PPP has a vested interest in the quality and quantity of collected waste. Since the public entity dumps all the waste into the dumpsite, they have no concern for the quality and quantity of waste collected, leading to a variable waste collection schedule. Through the MRF, the PPP recovers the recyclables and sells them to various value chain actors, as shown in Figure 9. Moreover, the PPP also has the option of composting. However, the PPP faces some challenges in getting high-quality compost due to the prevalent public practice of disposing of mixed waste despite the provision of separate bins for collection.

Figure 9: An Overview of the Existing Solid Waste Management of the City



Source: Authors' illustration.

The PPP officials stressed the need to educate the public and ensure strict implementation of waste segregation, for which the public's role is paramount. The PPP also sells pellets from the pellet line to nearby companies. The PPP also showed strong interest in accessing the waste collected by the public entity, so that instead of dumping all the waste into the dumpsite, some waste, especially the waste from commercial areas with recyclables and comparatively better quality, could be processed at the facility. Moreover, the PPP officials stressed the need for a complete shift to door-to-door waste collection as opposed to collection from skips and tubs due to the following two reasons. First, the collection from home means that there is no informal activity and thus offers maximum recyclables, which are essential for the sustainability of the PPP's operations. Second, the door-to-door collected waste is comparatively fresh and is thus more suitable for various treatment options, such as composting and anaerobic digestion. A diagrammatic overview of the existing practices is represented in Figure 8.

The main components of the treatment facility, such as the weighing bridge, MRF, composting, and pellet line, are shown in Figure 10.

Picture a in Figure 10 shows a truck being weighed at the weighing bridge, Picture b shows the pellet Line, Picture 10c shows the MRF, d shows the process of composting, e shows recovered recyclables (plastic bottles, rubber, glass, etc.) storage place, and Picture f shows packaging material storage.

Figure 10: Treatment Facility Components

Source: Pictures by authors.

During the site visits, indiscriminate disposal and open burning were observed in various parts of the city, specifically in the private area. The provision of skips and tubs was also more prevalent in high-income areas than in low-income areas. Many tubs were damaged, and the waste was dumped around the tubs instead of in them. The informal sector was also more prevalent in the private area than in the state area, with PPP allowing controlled access at the facility and actively discouraging uncontrolled access. Moreover, waste management of the observed indiscriminate disposal and open dumping was better in areas served by the PPP than by the public entity. Indiscriminate disposal and open burning significantly worsen the environment and ultimately aggravate climate change. The key observations from the field visit are shown in Figure 11.

Picture a: Open Burning, Picture b & c: Non-existent waste collection points in low-income areas, Picture d: Indiscriminate disposal, Picture e: Waste Dumping around the tub, and Picture f: the informal sector Activity.

Figure 11: Observations from Field Visits

Source: Pictures by authors.

Informal Mechanism

Role & Significance of the Informal Sector

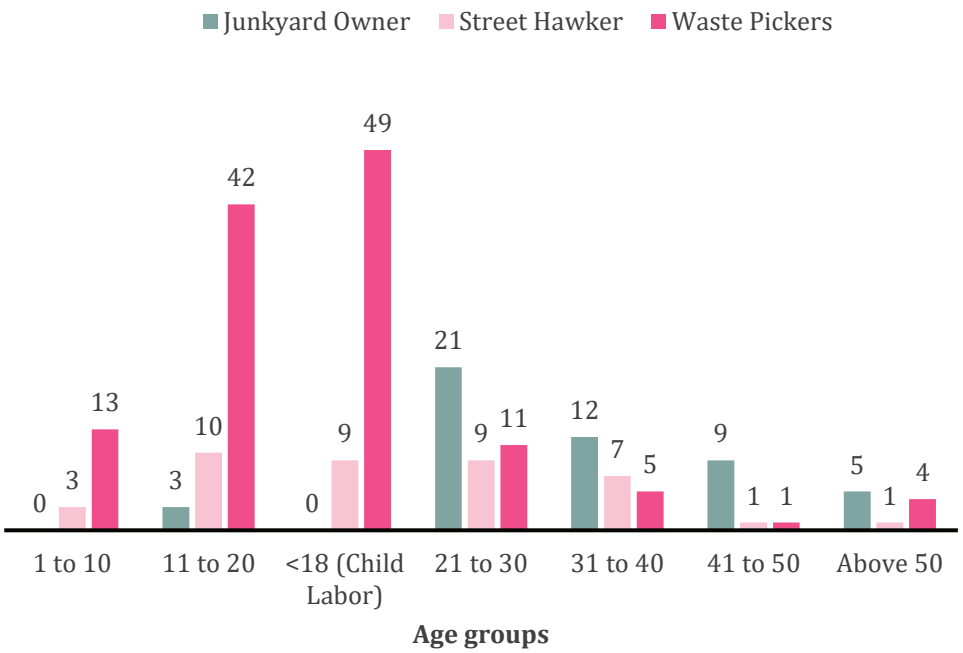
As evident from Figure 7, the number of recyclables in the dumpsite audited waste is considerably less than household audit waste, which shows an active role of the scavengers at various skips and tubs. This was also verified during the informal sector survey in which scavengers were found recovering the recyclables from the collection points, i.e., tubs and skips. Thus, the informal sector was further investigated to see if its role can be better integrated with the formal sector.

Integration of the informal sector with the Formal Sector

The informal sector, one of the important stakeholders in developing countries, is often unrecognised, and its contributions are not valued. In this regard, integrating the informal sector with the formal sector is an underresearched area in the context of developing countries, in general, and Pakistan, in particular. This subject is one of the main objectives of this research study, and to fulfil this objective, the framework suggested by Velis et al. (2012) was adopted. This framework is comprehensive and covers all the essential interfaces of the informal sector with the formal SWM sector, materials & value chain, and society. In addition to these three interfaces, the framework also covers the interface related to the empowering actions or the enabling factor, which can assist in better integrating the informal sector with the formal sector. The details of how each interface was adopted in the present study are tabulated in the Appendix (Appendix Tab. 2 Interface A- Between the Informal and the Formal SWM Sector (based on Velis et al., 2012).

A survey, using a semi-structured questionnaire, was conducted to gather data on the interfaces. A total of 157 respondents were contacted, comprising 76 waste pickers/scavengers, 31 street hawkers, and 50 junkyard owners. The age-wise distribution of the respondents is shown in Figure 12.

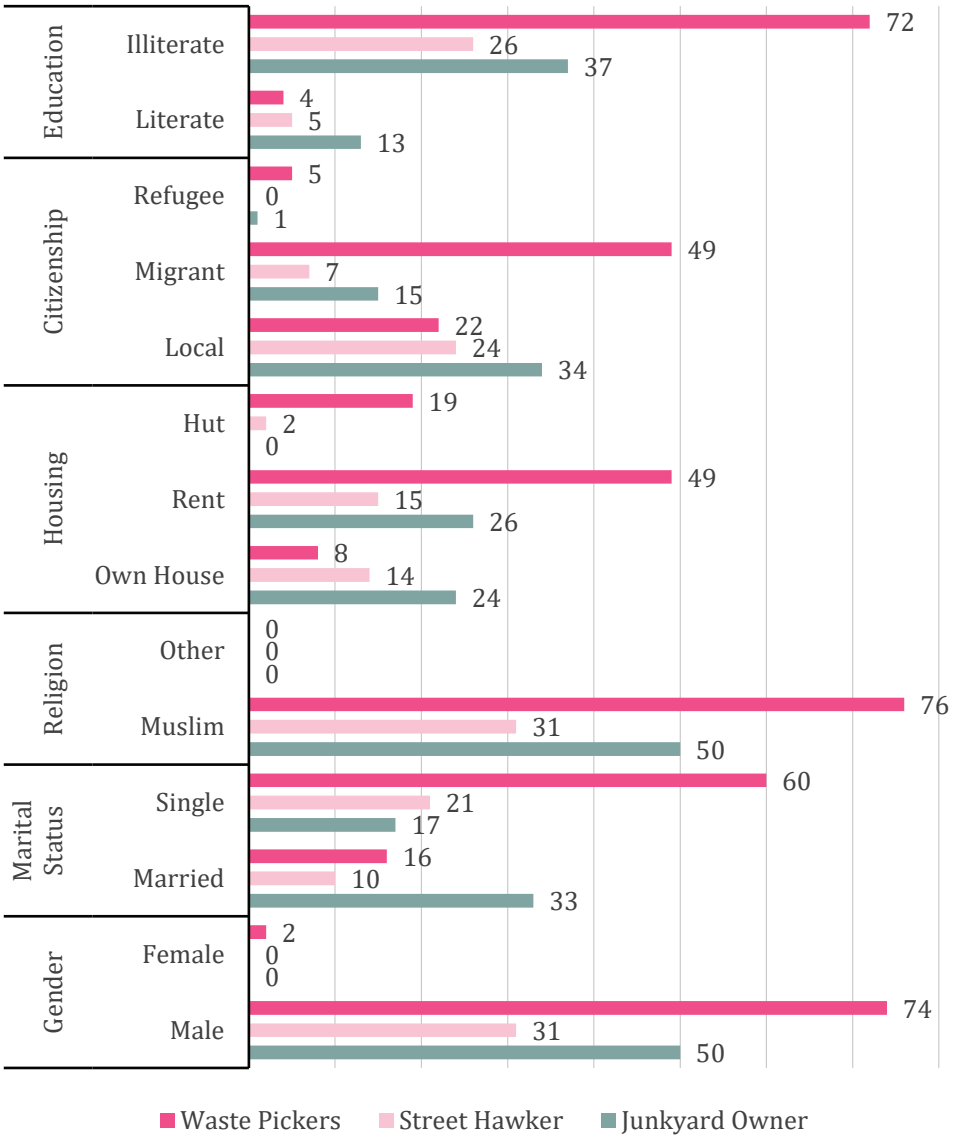
Figure 12: Age-wise Distribution of Respondents



Source: Authors' computations.

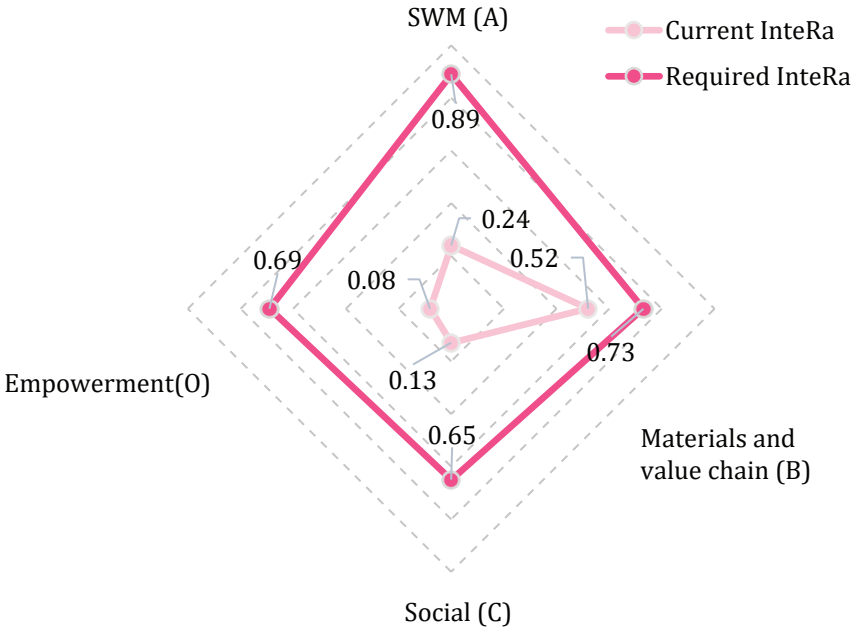
The intervention points mentioned in Appendix Tab. 2-5 were assessed based on the semi-structured interviews and field visits, and the detailed scoring may be seen in Appendix Tab. 6 Current & Required Assessments of the Informal Sector Interface with the Formal SWM Sector. In the scoring framework, an intervention that was fully implemented was assigned the value K=1. An intervention with a medium level of application was assigned the value C=0.5, while an intervention that was ignored or for which data were unavailable was assigned the value I=0. Beyond the situational assessment, a parallel assessment was conducted to capture the desired state of affairs—namely, improved integration of the informal and formal sectors, in line with the socioeconomic characteristics of Pakistan. The resulting scores are presented through a radar diagram, known as InteRa, which visually illustrates and communicates the findings (Figure 14).

Figure 13: Distribution of Respondents' Characteristics



Source: Authors' computations.

Figure 14: Current and Required InteRa



Source: Authors' computations.

Currently, there is a significant lack of SWM, empowerment and social interfaces for integration. However, the material and value chain interface shows a higher score, which underscores the role that the informal sector plays in the SWM in the region. A summary of the justification for the scores is provided in Table 1 below, while a detailed justification for these scores is included in the Appendix tables.

Table 1: Summary of Current and Required State Justifications for the Informal Sector SWM Integration

		Current State and Observations	Required State and Actions
1	SWM Interface	• No controlled access to waste • No acknowledgement of the informal sector services • Repression, neglect, and collusion of the informal sector • Informal sector not consulted at all on planned initiatives or the imposition of fines • Uncontrolled access of the informal sector to hazardous waste at the dumpsite • Limited waste management services in the residential areas of the informal sector • No policies to promote recycling	• Provision of controlled access at the transfer station/ dumpsite/ treatment facility, as follows by PPP, per the research study findings • Acknowledging and commending the positive role played by the informal sector by publishing their positive contributions from an environmental perspective • Accepting the role of the informal sector and commending and facilitating them to the maximum level instead of repressing them • Inclusion of junkyard owners in the planning phase of key initiatives • Curbing the uncontrolled activity of the informal sector at the dumpsite through strict fines and penalties • Provision of equal waste management services in all areas of the city • Introduction of a gate fee after installing the weighing bridge at the dumpsite, as done by PPP, per the research study findings
2	Material and Value Chain Interface	• Improving the quality of waste by taking active measures to promote waste segregation at the household level	• Replacing the three bins with two bins, i.e., dry and wet waste, is more user-friendly and will improve the quality of recyclable and organic waste.

		Current State and Observations	Required State and Actions
		• No facilitation for the informal sector members in terms of large containers • No washing of recyclables by the informal sector members • No primary recycling industry in small cities, and the materials have to be transported to Lahore, incurring major costs.	• Provision of large containers to registered informal sector members • Encouraging and educating the informal sector members to wash the recyclables for better recyclable quality • Facilitating the establishment of recycling industries in small cities by offering tax reliefs and other incentives
3	Social Interface	• Issue of illegal Afghan nationals in the informal sector • No ID cards or uniforms (vests) provided to the informal sector members • No consultation with the public representatives in planning various initiatives • Prevalent child labour • No use of PPEs by the informal sector • Limited access to healthcare facilities	• Crackdown against illegal Afghan nationals to facilitate the registration process of the informal sector • Provision of ID cards and uniforms to the informal sector • Inclusion of public representatives, such as Counsellors, in planning key initiatives that could ultimately affect the formal and informal sectors equally • Crackdown against child labour and offering incentives to the parents, such as exclusive access to waste, subject to admitting their children to school • Mandating the wearing of masks by first educating and informing them, followed by the imposition of fines for noncompliance

		Current State and Observations	Required State and Actions
			• Provision of easily accessible and affordable healthcare facilities to the informal sector stakeholders
4	Empower-ment Interface	• No unions or associations • No NGOs • No financial assistance provided to the informal sector in terms of accessible and affordable loans. • No regulation of recyclable prices resulting in the exploitation of the informal sector • No training or awareness sessions for the informal sector • No database of waste pickers and street hawkers, only junkyard owners recorded	• Facilitating and encouraging the union formation • Inviting and facilitating NGOs • Provision of affordable financial assistance to registered informal sector members • Regulation of prices with the consultation of all stakeholders • Training and educating the registered informal sector members on key environmental issues and how to augment the utility • Registering the waste pickers and street hawkers by mandating the already documented junkyard owners to buy from documented waste pickers and street hawkers

Source: Author's computations.

Social Component

Knowledge, Attitude, and Practices (KAP) Survey

A KAP survey was conducted to determine the residents' awareness of and behaviours toward SWM. This covers the social component of this study. The simple random sampling technique was employed to survey the Wah Cantt residents using a structured questionnaire. An initial survey draft was prepared with the help of the literature, which was sent to experts as part of

the pretesting to ensure that the survey design encompassed all the relevant aspects. The experts' responses and the finalised questionnaire (English and Urdu versions) are included in the appendices. The questionnaire was divided into the following five sections:

- Demographic Information
- Existing Situation Assessment
- Public Knowledge
- Public Attitudes
- Public Practices.

The sample size was calculated based on the Wah Cantt population according to the 2023 Population Census results, with a 95% confidence level and 5% margin of error. The sample size came out to be 405. The following equation was used for the determination of sample size (Almasi et al., 2019) :

$$n=\frac{N.Z^2_{1-\frac{\alpha}{2}}.\sigma^2}{(N-1)e^2+Z^2_{1-\frac{\alpha}{2}}.\sigma^2} \qquad (1)$$

The survey team collected 504 responses. The chi-square test was used to check the statistically significant association between the questions. Moreover, the Cramer V test was used to quantify the strength of the association between the variables. This association test was used because many questions in the questionnaire were nominal (non-ordinal). The survey results are detailed in the subsequent sections.

Demographic Information

The demographics of the respondents are shown in Table 2. Most respondents (73.5%) were male despite the efforts to include maximum female representation. Moreover, 56% of the respondents were in the 18-30 age group, which could probably be due to the younger generation being more familiar with the concept of SWM. Furthermore, most respondents (56.3%) had a bachelor's degree or higher. There was an almost equal representation of respondents according to their employment category. The household income was categorised into low income (below the 25th percentile), lower-middle income (between 25th and 50th percentile), upper-middle

income (between 50th and 75th percentile), and high income (above 75th percentile). 55% of households had between 4 and 6 members, which is comparatively lower than the mentioned value of 6.3 in the 2023 Census. Most respondents had been residing in Wah Cantt for more than 10 years (49%) and had owned homes (60%).

Table 2: Demographic Information

ID	Section 1: Demographic Information	Count	%
A1	**Gender**		
	Male	369	73.5%
	Female	133	26.5%
A2	**Age**		
	18-30	277	55.4%
	31-45	150	30.0%
	46-60	60	12.0%
	> 60 years	13	2.6%
A3	**Education**		
	No education	23	4.6%
	Diploma	74	14.8%
	Primary education	62	12.4%
	Secondary education	60	12.0%
	Bachelor's degree or higher	282	56.3%
A4	**Employment**		
	Self employed	116	23.4%
	Government employed	109	22.0%
	Private organisation	106	21.4%
	Other	165	33.3%
A5	**Household Income Category**		
	Low income (less than PKR 50,000)	125	25.5%
	Lower-middle income (between PKR 50,000 and PKR 90,000)	133	27.1%
	Upper-middle income (between PKR 90,000 and PKR 150,000)	111	22.6%
	High income (higher than PKR 150,000)	122	24.8%
A6	**No. of Household Members**		
	Less than 10	29	5.8%
	1-3	85	16.9%
	4-6	277	55.1%
	7-9	112	22.3%

ID	Section 1: Demographic Information	Count	%
A7	**Number of Household Members With a Job**		
	0	0	0.0%
	1	212	23.6%
	2	314	35.0%
	3	204	22.7%
	4	92	10.3%
	5	45	5.0%
	More than 5	30	6.0%
A8	**Living in the Region For**		
	Less than 2 years	43	8.6%
	2-5 years	99	19.8%
	6-10 years	113	22.6%
	More than 10 years	246	49.1%
A9	**Own House or Rented House**		
	Own house	301	60.6%
	Rented house	196	39.4%

Source: Author's computations.

Existing Situation Assessment

The existing situation assessment was conducted to determine the current waste collection methods, waste management entities involved, waste collection frequency, waste collection on weekends, satisfaction with the waste management services, problems faced by the residents due to improper waste collection, willingness to pay, and the preferred media type by the residents. The results of the existing situation assessment are shown in Table 3. The majority of respondents have access to the door-to-door collection (54.2%). However, among the formal waste management entities, the POF, which operates under the PPP model, mostly provides door-to-door waste collection services. The waste management entities are the POF (providing services to 30.7% of respondents) and the CBW, a public entity providing services to 32.6% of the residents. Of note, the informal sector is actively engaged in waste management and provides services to 36.7% of the respondents, reinforcing the need to integrate with the formal sector.

Moreover, most respondents said that waste was collected either daily or on alternate days. Waste collection services were offered on weekends to 47.1% of the respondents. Furthermore, 55.7% of respondents had waste dumping points near their homes. Regarding satisfaction with waste management services, 52.6% of respondents expressed satisfaction. A total of 51.2% of respondents did not pay for the services, which was due to the provision of free collection under the PPP model, as the PPP met its expenditures from recyclables recovered from door-to-door collection. The public entity and the informal sector were charging for waste management services.

The public entity charges between PKR 200 and PKR 500 for waste management services and other services, such as street lighting. The charges of the informal sector are variable depending on the frequency of services. Regarding the willingness to pay, the majority expressed willingness to pay for the services. A significant percentage of respondents (69.2%) used plastic bags for waste disposal. The major issues faced by the respondents due to improper collection were odour (46.4%) and mosquitoes (35.7%). Social media was the preferred media type by most respondents (70.56%), followed by TV (25.81%).

Table 3: Existing Situation Assessment

ID	Section II: Existing Situation Assessment	Count	%
B1	**Waste Collection Method**		
	Door-to-door collection	271	54.2%
	No access to waste collection services	90	18.0%
	Roadside/kerbside collection from skips & tubs	139	27.8%
B2	**Waste Collection Entity**		
	Cantonment Board Wah	159	32.6%
	Informal sector (scavengers)	179	36.7%
	POF	150	30.7%
B3	**Waste Collection Frequency**		
	Daily	158	31.5%
	Alternate days	200	39.8%
	Once a week	98	19.5%
	No collection	46	9.2%
B4	**Is waste collected on weekends?**		
	Yes	234	47.1%
	No	263	52.9%
B5	**Are there waste dumping points near your home?**		
	Yes	277	55.7%
	No	220	44.3%

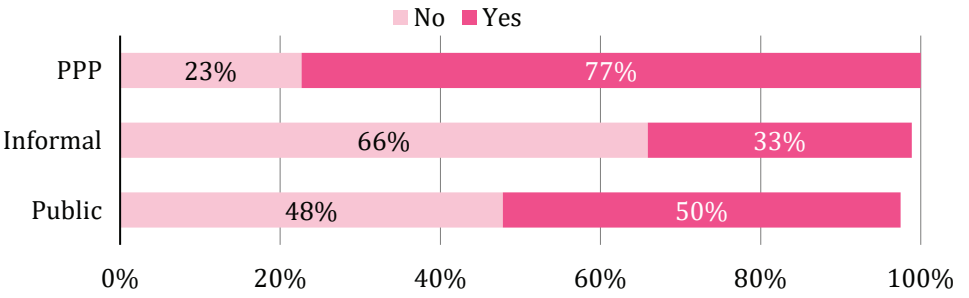
ID	Section II: Existing Situation Assessment	Count	%
B6	**Are you satisfied with your current SWMS?**		
	Yes	261	52.6%
	No	235	47.4%
B7	**Do you use garbage (plastic) bags for your waste?**		
	Yes	346	69.2%
	No	154	30.8%
B8	**Any problems encountered due to improper SW collection?**		
	Aesthetics	51	10.2%
	Mosquitoes/flies	178	35.7%
	Odour/smell	231	46.4%
	Rodents	38	7.6%
B9	**How much do you pay for existing SWMS? (PKR)**		
	0	243	51.2%
	1-200	36	7.6%
	201-400	96	20.2%
	401-600	49	10.3%
	More than 600	51	10.7%
B10	**Willingness to pay**		
	No, I can't afford it	72	14.5%
	No, it's the duty of the governing authority	158	31.9%
	Yes	265	53.5%
B11	**Choice of media type**		
	Newspaper	11	2.22%
	Radio	07	1.41%
	Social media	350	70.56%
	TV	128	25.81%

Source: Author's computations.

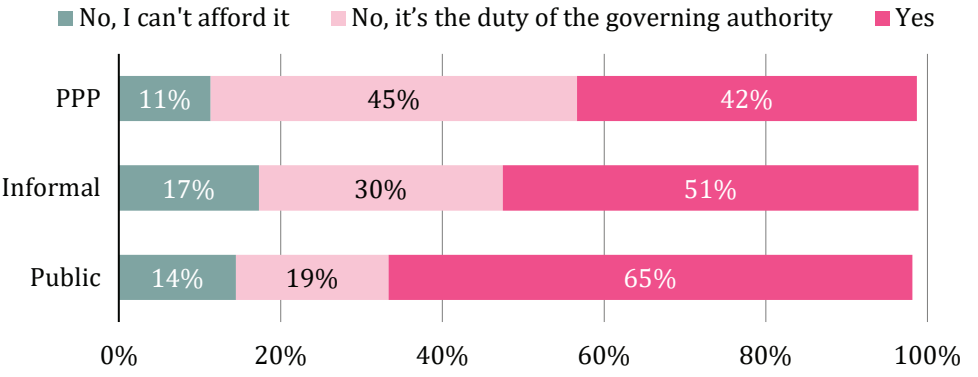
The satisfaction with the services and willingness to pay for waste management entities were analysed, the results of which are shown in Figure 15. The respondents served by the PPP expressed maximum willingness owing to the comparatively frequent waste collection reported by most respondents. However, these respondents were comparatively less willing to pay and considered it the duty of the government.

Figure 15: Satisfaction & Willingness vs Responsible Entity

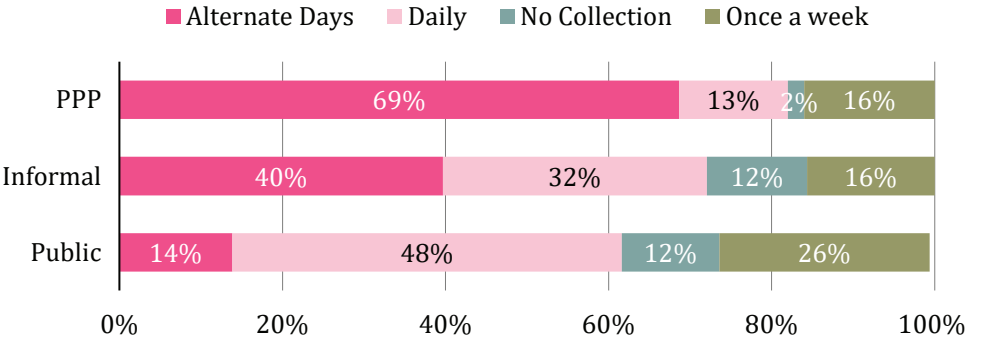
(a) Satisfaction with existing WMS



(b) Willingness to pay for SWM services



(c) Waste Collection Frequency



Source: Author's computations.

Public Knowledge

The respondents were asked about the important aspects/factors of the SWM. The responses were classified into poor (less than 50%), medium (50% to 75%), and good (more than 75%), as done by Almasi et al. (2019). The same criteria were also applied to the sections on attitudes and practices. The results of public knowledge are shown in Table 4. Public Knowledge.

Table 4: Public Knowledge

ID	SECTION III: PUBLIC KNOWLEDGE	Count	%
C1	**Is solid waste a source of pollution for the environment?**		
	No	23	4.6%
	Yes	476	95.4%
C2	**Have you ever heard about the 3Rs (Reduce, Reuse, and Recycle)?**		
	No	180	36.1%
	Yes	319	63.9%
C3	**Burning solid waste can lead to respiratory health issues.**		
	No	33	6.6%
	Yes	466	93.4%
C4	**Open dumping of waste can cause health-related problems such as diarrhoea, typhoid, and cholera.**		
	No	30	6.0%
	Yes	471	94.0%
C5	**Paper waste, plastic bottles, and metal are recyclable.**		
	No	66	13.2%
	Yes	434	86.8%
C6	**Compost or organic fertilisers can be prepared from solid waste.**		
	No	118	24.0%
	Yes	374	76.0%
C7	**The amount of solid waste can be reduced by reusing it at the household level.**		
	No	179	36.0%
	Yes	318	64.0%
C8	**Sorting of solid waste at home can help the SWM Authorities by turning waste into something of value.**		
	No	104	21.1%
	Yes	388	78.9%

ID	SECTION III: PUBLIC KNOWLEDGE	Count	%
C9	**Plastic bags (shoppers) are a threat to the environment.**		
	No	59	11.9%
	Yes	437	88.1%
C10	**Electronic waste and chemical waste (batteries, paints, etc.) are considered hazardous waste.**		
	No	60	12.1%
	Yes	436	87.9%

Source: Author's computations.

The results show that the respondents had an overall good knowledge of the SWM, which is evident from high scores on C1, C3, C4, C5, C6, C8, C9, and C10. However, the respondents showed a medium level of knowledge of the 3Rs and the reduction in the generated solid waste by reuse at home (see C2 and C7 in Table 4 above).

Public Attitudes

The respondents' attitudes towards the SWM were also evaluated. The results are shown in Table 5. Contrary to the results for public knowledge, where most respondents showed good knowledge of most questions, the scores for public attitudes were comparatively low.

Table 5: Public Attitudes

ID	Section IV: Public Attitudes	Count	%
D1	**Solid waste is anything without value.**		
	Strongly disagree	88	17.7%
	Disagree	103	20.8%
	Neutral	69	13.9%
	Agree	194	39.1%
	Strongly Agree	42	8.5%
D2	**Considering the health and environmental effects of household solid waste is important in the disposal of waste.**		
	Strongly disagree	41	8.2%
	Disagree	30	6.0%
	Neutral	44	8.9%
	Agree	286	57.5%
	Strongly agree	96	19.3%

ID	Section IV: Public Attitudes	Count	%
D3	**Solid waste is one of the environmental problems that needs immediate attention.**		
	Strongly disagree	43	8.7%
	Disagree	23	4.6%
	Neutral	26	5.2%
	Agree	243	48.9%
	Strongly agree	162	32.6%
D4	**Waste segregation is the job of sweepers only nd not the households.**		
	Strongly disagree	85	17.1%
	Disagree	163	32.7%
	Neutral	57	11.4%
	Agree	149	29.9%
	Strongly agree	44	8.8%
D5	**The role of the media is important in understanding the management of household solid waste and its importance.**		
	Strongly disagree	34	6.9%
	Disagree	50	10.1%
	Neutral	48	9.7%
	Agree	255	51.5%
	Strongly agree	108	21.8%
D6	**Cleanliness drives and campaigns on the importance of SWM arranged by the city authorities can prove beneficial for spreading awareness among the residents.**		
	Strongly disagree	45	9.0%
	Disagree	29	5.8%
	Neutral	43	8.6%
	Agree	276	55.3%
	Strongly agree	106	21.2%
D7	**Will you be willing to pay for biodegradable bags, an amount of PKR 10 –15, for carrying groceries?**		
	Strongly disagree	53	10.6%
	Disagree	64	12.9%
	Neutral	53	10.6%
	Agree	243	48.8%
	Strongly agree	85	17.1%

ID	Section IV: Public Attitudes	Count	%
D9	**Do you approve of people paying for the services provided for the management of solid waste?**		
	Strongly disagree	44	8.9%
	Disagree	80	16.1%
	Neutral	72	14.5%
	Agree	240	48.3%
	Strongly agree	61	12.3%
D10	**Do you approve of measures such as the container deposit scheme, i.e., an extra amount is paid by customers on the purchase of beverages, which is returned on the return of the bottle?**		
	Strongly disagree	39	7.8%
	Disagree	60	12.1%
	Neutral	84	16.9%
	Agree	241	48.5%
	Strongly agree	73	14.7%
D11	**Will you be willing to keep a cloth bag for carrying groceries instead of plastic bags, considering that cloth bags are environmentally friendly?**		
	Strongly disagree	30	6.0%
	Disagree	36	7.2%
	Neutral	38	7.6%
	Agree	284	57.0%
	Strongly agree	110	22.1%
D12	**The city government should conduct regular supervision and control of illegal dumping of solid waste in the town.**		
	Strongly disagree	33	6.6%
	Disagree	29	5.8%
	Neutral	25	5.0%
	Agree	243	48.9%
	Strongly agree	168	33.8%

Source: Authors' computations.

The respondents showed a strong attitude towards D2, D3, D6, D11, and D12, as more than 75% respondents selected the environmentally-friendly option. The aspects towards which the respondents had a positive, but not very strong, attitude were D5, D7, D8, D9, and D10. Finally, the queries to which the respondents recorded weak attitudes were D1 and D4. These responses validate the observation of Olukoju (2018) and Marshall & Farahbakhsh (2013) regarding the negative attribution to waste.

Public Practices

The respondents scored comparatively low on the practices aspect than on knowledge and attitudes. The scores for different questions on public practices are shown in Table 6.

Table 6: Public Practices

ID	SECTION V: PUBLIC PRACTICES	Count	%
E1	**Do you separate/sort solid wastes before disposal?**		
	No	342	71%
	Yes	141	29%
E2	**How do you get rid of solid waste from home?**		
	Dumped along roadsides/gullies	94	20%
	Dumped in the backyard with sacks	71	15%
	Dumped in the collection points designated by the authorities	310	65%
E3	**How often do you dispose of waste from your home?**		
	Every alternate day	199	40%
	Everyday	216	44%
	Once a week	81	16%
E4	**What specific solid waste item is present in the greatest amount in your household's generated solid waste?**		
	Kitchen waste	330	67%
	Others (pampers, dirt, debris)	76	15%
	Paper waste	21	4%
	Plastic waste	67	14%

ID	SECTION V: PUBLIC PRACTICES	Count	%
E5	**Do you make any deliberate effort to keep your house surroundings clean?**		
	No	80	16%
	Yes	414	84%
E6	**What do you prefer for carrying purchased items during grocery shopping?**		
	Cloth bag	241	48%
	Plastic bag	51	10%
	Whichever is available (no preference)	205	41%
E7	**Do you separately collect and sell recyclable items of solid waste to junkyards or street hawkers?**		
	No	239	48%
	Yes	257	52%
E8	**Do you reuse plastic bottles and glass bottles in your house?**		
	No	195	39%
	Yes	301	61%
E9	**Do you burn solid waste?**		
	No	351	70%
	Yes	148	30%

Source: Author's computations.

The respondents showed good knowledge of suitable practices to deal with solid waste, which is evident from their scores on the aspects summarised in E3 (daily or alternate waste disposal from homes, considering the utility of fresh waste) and E5 (making deliberate efforts to keep house surroundings clean). The respondents had reasonable knowledge of E1, E2, E7, E8, and E9. However, there was a stark difference between the knowledge of public practices and implementing that knowledge, as the people, despite having good knowledge of the harmful effects of open burning and indiscriminate disposal of waste, were still engaging in such practices. The respondents had a low score on E6 (regarding their preference for carrying groceries). The same was also observed during the situation assessment, which points towards an alarming situation, especially given that Pakistan has been declared as one of the eight hotspots for poor SWM. The statistically significant associations using the Chi-Square test and Cramer's V are shown in Table 7.

Table 7: Statistical Test Results of KAP Associations

Sr. No	Question	Demographic and Existing Situation Factors	Result	Chi-Square Value	Cramer's V
1	Knowledge about 3Rs (C2)	Age (A2)	Age groups vs (C2) 18-30 (72% aware) 31-45 (58% aware) 46-60 (38% aware)	27.18	0.234
2	Willingness to pay for the services (B10)	Education (A3)	Education vs (B10) Bachelor's degree & above (60% willing) Diploma (50%) Primary & Secondary Education (44%) No Education (40%)	39.85	0.201
3	Choice of media type (B11)	Education (A3)	Education vs (B11) Bachelor's degree & above (83% prefer social media) Diploma (65% prefer social media) Secondary Education (65% prefer social media) Primary Education (52% prefer TV & 43% social media) No Education (74% prefer TV)	80.48	0.233
4	Knowledge about 3Rs (C2)	Education (A3)	Education vs (C2) Bachelor's degree & above (78% aware) Diploma (50% aware) Secondary Education (54% aware) Primary Education or No Education (33% aware)	64.83	0.361
5	Knowledge about compost preparation(C6)	Education (A3)	Education vs (C6) Bachelor's degree and above (84% aware) Diploma & Secondary (72% aware) Primary Education (61% aware) No Education (45% aware)	28.38	0.241

Sr. No	Question	Demographic and Existing Situation Factors	Result	Chi-Square Value	Cramer's V
6	Waste collection method (B1)	Household Income (A5)	Household Income vs (B1) High Income (64% with Door-to-Door collection) Upper Middle Income (56% with Door-to-Door collection) Lower Middle Income (58% with Door-to-Door collection) Low Income (39% with Door to Door collection & 34% with no services)	158.17	0.398
7	Waste Collection frequency (B3)	Household Income (A5)	Household Income vs (B3) High Income (83% with daily/alternate day collection) Upper Middle Income (72% with daily/alternate day collection) Lower Middle Income (67% with daily/alternate day collection; 24% with once-a-week collection) Low Income (60% with daily/alternate day collection; 25% with once-a-week collection, and 15% with no collection)	217.59	0.380
8	Willingness to pay for the services (B10)	Household Income (A5)	Household Income vs (B10) High Income (64% willing) Upper Middle Income (60% willing) Lower Middle Income (50% willing) Low Income (39% willing)	162.08	0.405

Sr. No	Question	Demographic and Existing Situation Factors	Result	Chi-Square Value	Cramer's V
9	Knowledge about 3Rs (C2)	Household Income (A5)	Household Income vs (C2) High Income (79% aware) Upper and Lower Middle Income (67% aware) Low Income (44% aware)	90.28	0.425
10	Knowledge about compost preparation(C6)	Household Income (A5)	Household Income vs (C6) High Income (87% aware) Upper and Lower Middle Income (78% aware) Lower Income (56% aware)	84.77	0.415
11	Solid waste is anything without value (D1)	Household Income (A5)	Household Income vs (D1) High Income (50% disagreeing) Upper Middle Income (42% disagreeing) Lower Middle Income (38% disagreeing) Low Income (24% disagreeing)	296.72	0.387
12	Knowledge about compost preparation(C6)	Employed Household Members (A7)	Employed Household Members vs (C6) Respondents with two household members employed were most aware (85%); however, no clear trend	22.40	0.213
13	Amount currently paid for services (B9)	SWM Entity (B2)	SWM Entity vs (B9) Max respondents served by Private Entity were not paying (71%)	98.28	0.430

Sr. No	Question	Demographic and Existing Situation Factors	Result	Chi-Square Value	Cramer's V
14	Knowledge about compost preparation(C6)	SWM Entity (B2)	SWM Entity vs (C6) Private Company (78% aware) Public Company (76% aware) Informal (75% aware)	113.48	0.544
15	Waste sorting at home: Useful (C8)	SWM Entity (B2)	SWM Entity vs (C8) Private Company (74% aware) Public Company (81% aware) Informal (80% aware)	117.46	0.550
16	Do you sort waste before disposal (E2)	SWM Entity (B2)	SWM Entity vs (E2) Private Company (29% sorting) Public Company (35% sorting) Informal (25% sorting)	103.26	0.469
17	Method of waste removal from home (E3)	SWM Entity (B2)	SWM Entity vs (E3) Private Company (78% aware) Public Company (76% aware) Informal (75% aware)	104.99	0.358
18	Willingness to pay for the services (B10)	Satisfaction with the services (B6)	Satisfaction with Services vs Willingness to Pay 56% satisfied respondents were willing to pay 50% unsatisfied respondents were willing to pay	13.41	0.165
19	Knowledge about 3Rs (C2)	Willingness to Pay (B10)	Willingness to Pay vs (C2) 56% willing to pay, 48% unwilling to pay, and were aware	24.18	0.222

Note: Only associations with Cramer V > 0.15 are included.
Source: Authors' computations.

Although the public knowledge scores were good, the same was not evident from the attitudes and practices scores. Moreover, the scores of the respondents in the higher age groups were lower compared to the scores of the respondents in the younger age groups. A negative perception of waste was observed in the attitudes. There is a strong need to include SWM topics in curricula at all levels of education. Furthermore, there is a strong need for awareness campaigns through social media and TV, as evidenced by the media choices of the respondents. Considering the performance of waste management entities, it is evident that the PPP mode of operations is more socially acceptable, and the government should facilitate public entities in this regard. Considering the level of threat Pakistan is facing, it is paramount that the importance of SWM is realised, and measures are undertaken to reduce waste from a public perspective, such as awareness and knowledge about the 3Rs, harmful impacts of open burning and dumping are taken on a war footing.

Economic Component

Cost-Benefit Analysis

The CBA was initially planned for both the waste management entities (PPP and the public entity) of the Wah Cantt. However, due to the delays in obtaining the permissions required for getting the desired data from the public entity, the CBA was limited to the PPP, which facilitated access to the facility and permission to conduct interviews with the personnel. However, the CBA of the PPP gave a fair idea of the system's overall health, where investment has been made for the waste treatment facility, and the potential of solid waste through recyclables.

The O&M costs were considered only when calculating the costs. A market survey was conducted to estimate the monetary worth of recyclables to determine the revenue. Certain assumptions were made for the analysis when the exact data were unavailable.

The PPP runs a waste treatment facility named “Zero Waste Recycling Facility,” in which the primary treatment options are a material recovery facility and pellet line. The composting option is available, but it is in the developing stage and is facing challenges due to the absence of waste segregation, which leads to low-quality compost. The MRF starts functioning once the door-to-door collected waste is transported to the facility by 2:00 p.m.. After that, it typically runs for 5 hours until 7:00 p.m. The pellet line, however, typically runs during

the day. Moreover, the PPP offers door-to-door waste collection to 12,000 households and also collects waste from skips and tubs. In addition to those mentioned above, the PPP separately collects the city's yard waste and carries out street cleaning.

The PPP employs a total of 80 people for their complete operations. A fixed salary of PKR 30,000 is given, with free meals and residence offered to those who belong to far-flung areas. The PPP own ten garbage trucks, consisting of trolleys, dumper trucks, compactors, and mini trucks. All of these vehicles are diesel-engined. Four garbage trucks are used for door-to-door waste collection, while 6 are used for collection from skips and tubs. During the site visits, it was observed that one garbage truck conducts two trips per day, whereas the rest of the garbage trucks conduct one trip per day. The average fuel consumption of a garbage collection truck is 1.8 L/km (Nguyen & Wilson, 2010). Garbage/waste trucks consume much more fuel than regular trucks as they halt at appointed stops on the collection routes, leading to increased fuel consumption. The selected value from the literature was compared with the insights obtained from discussions with the garbage truck drivers, according to whom they refill the tank almost every third day, which is approximately in line with the value cited in the literature. The average trip distance for each garbage collection truck is around 15 km. Moreover, the MRF and pellet line are electrically operated. The MRF requires 5 kWh. The pellet line comprises four units, i.e., shredding, hammering, mixing, and pelleting, with each unit requiring 50 kWh. Additionally, the pellet line requires approximately 1,000 kg of molasses per month. The cost calculation based on these facts and figures is shown in Table 8.

Table 8: Cost Calculation

Sr. No	Item Description	Calculation	Cost/Month (PKR)
1	Salaries	30,000/worker/month x 80 workers	2,400,000
2	Fuel Expenditure	1.8 Litre/km x 15 km x 10 trucks x 30 days x 255.38*	2,068,578
3	Electricity Expenses **	4 rooms at the facility with one ceiling and one tubelight in each room = 4 ceiling fans and 4 tubelights Each ceiling fan (80 watts), each tubelight (50 watts) Ceiling fans and tubelights are assumed to run for the whole month with 24 hours and 12 hours, respectively. *4 Ceiling fans x 80 watts/fan x 26 working days/ month x 24 hours/day = 199.68 kwh / month* *4 tubelights x 50 watts/ tubelight x 26 working days/ month x 12 hours/day = 62.4 kwh/ month* *MRF requires 5 kWh and is functional from 2:00 p.m. to 7:00 p.m.* *5 kWh x 5 hours/day x 26 working days/ month = 650 kWh/month* The pellet line is typically operated in such a way that 2 components of the setup run at a time, i.e., shredding and hammering or mixing and pelleting, with each component requiring 50 kWh. *100 kWh x 2 hours/day x 26 working days/ month = 5200 kWh/ month* Total kWh consumed in a month = 199.68 + 62.4 + 650 + 5200 = 6112.08 kWh / month x 35.22 PKR / kWh	215,267
Total Costs		**4,683,845**	

**Diesel rate in Pakistan as on 16th December 2024. ** Electricity rates are calculated using the Electricity Consumption Calculator of the National Energy Efficiency & Conservation Authority: Ministry of Energy (Power Division). Source: Authors 'computations.*

The revenue collected from the waste audit and the quantity of waste that arrived at the MRF and pellet line was calculated. The compost prepared at the facility is usually given away free of cost due to substandard quality, so it does not contribute to revenue generation. However, if waste segregation is practised and the existing 3-bin system is replaced with a 2-bin system, it could result in the production of quality compost that could be sold to increase

revenues. The monetary worth of recyclables was obtained from the PPP officials, and a market survey of junkyards was conducted to validate the information. Currently, the PPP does not charge anything to the public for the services it provides. Thus, the calculations were made for the existing conditions where no fee is charged and also for an assumed scenario where a nominal fee of PKR 100 is charged after educating the public on the importance of efficient SWM. The detailed calculations for the revenue are shown in Table 9.

Table 9: Revenue Calculation

Sr. No	Item Description	Percentage	Rate (PKR/kg)	Calculations	Revenue/ Month (PKR)
	Ferrous Waste	0.55	135	0.55/100 x 12000* x 135 x 30	267,300
1.	Paper waste	4.26	60	4.26/100 x 12000 x 60 x 30	920,160
2.	Aluminium	0.22	150	0.22/100 x 12000 x 150 x 30	118,800
3.	Recyclable plastic waste	4.65	95	4.65/100 x 12000 x 95 x 30	1,590,300
4.	Glass & bottles	1.06	5	1.06/100 x 12000 x 5 x 30	19,080
5.	Leather & rubber	2.30	50	2.30/100 x 12000 x 50 x 30	414,000
6.	Pellets*	-	70	340** x 70 x 30	714,000
7.	Monthly fee	-	100	(20/100 x 479,000 x 100)***	9,580,000
Total Revenue 4,043,340 (Without a monthly fee) 13,623,340 (With a monthly fee)					

**16 tons of waste arrive at the MRF, 25% of which is diverted to the dumpsite. Therefore, the remaining waste is 12 tons, or 12,000 kg. **The pellet production depends on the weight of leaves and the moisture. One ton of yard waste typically produces 200 kg of pellets, as the weight of yard waste that arrives at the site is 1.7 tons, so pellet production is assumed to be 340 kg. ***The state area's population is roughly 20% of the Wah Cantt population.*
Source: Authors'computations.

Thus, the revenue generated is approximately PKR 680,000, less than the O&M costs. However, it is pertinent to mention that it does not include the price of compost, which can generate significant revenue if produced and sold to nearby farmers. Also, currently, the system is not running at its full capacity due to the limited waste in the state area and no access to the waste in the public area. Granting access to the public entity's collected waste to PPP is expected to increase revenue. Moreover, a nominal monthly fee – currently not charged – can significantly improve the economic health of the municipalities and aid them in setting up more sophisticated/advanced treatment options that require higher capital costs. Even if the municipality charges the households based on economic classification, i.e., low-income households are offered free services and middle-income and high-income households are charged the suggested amount, the revenue generated will be much more than the O&M costs. It is also evident that if the municipalities make the initial investment, the setup could recover the investment quickly.

Environmental Component

Environmental Life Cycle Assessment

Pakistan has been identified as one of the eight countries where more than half of the projected increase in global population up to 2050 will be concentrated (UNEP, 2024). Consequently, municipal waste generation will also increase significantly, thus requiring sustainable management. Currently, the waste generated is either open-dumped or burnt, which harms the environment and public health. As a result, there is a strong need for the implementation of environmentally friendly waste treatment options (Ayub et al., 2024). The environmental life cycle assessment (E-LCA) has been recognised as a suitable and reliable approach for evaluating the potential environmental impacts of the various waste management/treatment options, such as landfilling, recycling, and refuse-derived fuel (RDF) (Mulya et al., 2022). The E-LCA results can assist the relevant stakeholders, such as policymakers and municipal authorities, in the selection of environmentally friendly waste management options.

In view of the importance of the adoption of environmentally sustainable waste treatment options, a software-based analysis of the shortlisted waste management/treatment options was carried out using SimaPro software. The waste treatment options shortlisted based on the WACS result and experts' opinions are provided below:

- Open dumping (existing practice)
- Sanitary landfill
- Incineration
- Recycling/material recovery facility
- Composting
- Anaerobic digestion

Different scenarios were assumed based on the waste composition determined from the WACS, which have already been discussed at length in the results of Objective 1. The scenarios selected for the software simulation are provided below, along with their brief description:

- S0_Open dumping: 100% of waste diverted to the dumpsite.
- S1_Recycling + open dumping: 12.19% of the recyclables are transferred to recycling, and 87.81% to the dumpsite.
- S2_Recycling + sanitary landfill: 12.19% of the recyclables are transferred to recycling and 87.81% to the sanitary landfill.
- S3_anaerobic digestion + recycling + sanitary landfill: 53.1% of the organic fraction is sent to anaerobic digestion, 12.19% of the recyclables to recycling, and 34.71% to the sanitary landfill.
- S4_composting + recycling + sanitary landfill: 53.1% of the organic fraction is sent to composting, 12.19% of the recyclables to recycling, and 34.71% is sent to the sanitary landfill.
- S5_recycling + incineration: 12.19% of the recyclables are recovered, and the remaining 87.81% are transferred to incineration.

The E-LCA process is guided by ISO 14040 and 14044, and the assessment framework includes Goal and Scope definition, Inventory Analysis, Impact Assessment, and Interpretation of the obtained results.

Goal and Scope

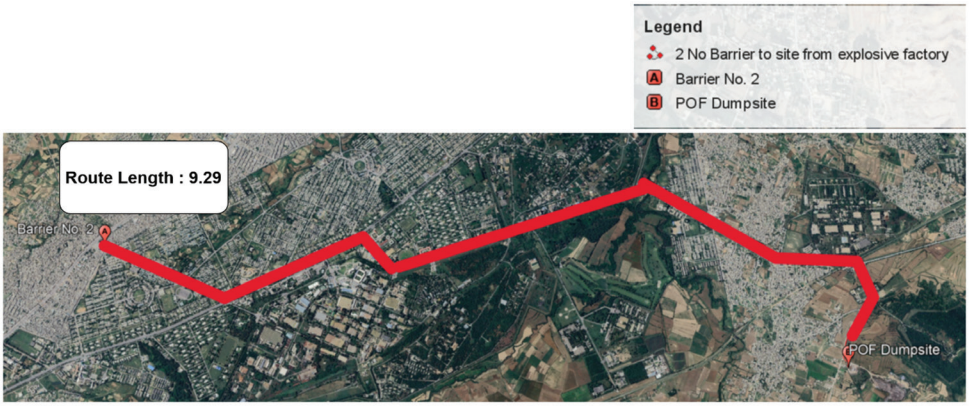
The goal of the study was to carry out a comparative evaluation of the environmental impacts of different scenarios based on various combinations of the shortlisted waste treatment options. The system boundary under

consideration was "bin to grave" (Mulya et al., 2022). Moreover, the evaluation was conducted in terms of mid-point categories. The functional unit used for the study was "one ton of municipal solid waste (MSW)".

Life Cycle Inventory/Inventory Analysis

The data for the inventory stage came primarily from the waste compositions determined in the WACS, while the fuel expenses of the vehicles were determined by taking the average of the two routes currently used by the vehicles for transporting the waste to the dumpsite. The two current routes were tracked and are shown in Figures 16 and 17.

Figure 16: Route 1 (9.29 km)



Source: Authors' computations.

Figure 17: Route 2 (11.6 km)

Source: Authors' computations.

The other data related to the different treatment options, such as electricity and fuel requirements, were obtained from secondary sources, such as the published literature.

Life Cycle Impact Assessment

The scenarios were assessed using the ReCiPe Midpoint (H) method, and 13 midpoint categories were considered for the comparative evaluation of the different scenarios. The 13 midpoint categories are provided in Table 10. Mid-Point Categories Description.

Table 10: Mid-Point Categories Description

Sr. No.	Impact Category	Label	Unit
1	Global warming	GWP	Kg CO_2 eq.
2	Stratospheric ozone depletion	SOD	Kg CFC_{11} eq.
3	Ozone formation	OF	Kg NO_x eq.
4	Fine particulate matter formation	PM	Kg $PM_{2.5}$ eq.
5	Terrestrial acidification	TA	Kg SO_2 eq.
6	Freshwater eutrophication	FEn	Kg P eq.
7	Marine eutrophication	MEn	Kg N eq.
8	Freshwater ecotoxicity	FEy	Kg 1,4 - DCB
9	Marine ecotoxicity	MEy	Kg 1,4 - DCB
10	Human carcinogenic toxicity	HCT	Kg 1,4 - DCB
11	Human non-carcinogenic toxicity	HNCT	Kg 1,4 - DCB
12	Land use	LU	M^2a crop eq.
13	Water consumption	WC	M^3

Source: Authors' computations.

The results of the 13 mid-point categories for the different scenarios are shown in Table 11.

Table 11: Mid-Point Impact Category Results for Different Scenarios

Sr No.	Impact Category	Unit	S0	S1	S2	S3	S4	S5
1	GWP	Kg CO_2 eq.	963	1.20E+03	585	303	311	457
2	SOD	Kg CFC_{11} eq.	0	1.57E-06	8.06E-05	0.000231	0.000237	0.000456
3	OF	Kg NO_x eq.	0.000864	0.0486	0.0913	0.074	0.076	0.29
4	PM	Kg $PM_{2.5}$ eq.	0.00804	0.0175	0.0397	0.0468	0.0478	0.0559
5	TA	Kg SO_2 eq.	0.0277	0.0444	0.0943	0.118	0.123	0.145
6	FEn	Kg P eq.	2.82	2.48	2.48	0.989	0.992	0.11
7	MEn	Kg N eq.	0.896	0.787	0.855	0.34	0.43	0.00991
8	FEy	Kg 1,4 - DCB	480	422	422	167	174	250
9	MEy	Kg 1,4 - DCB	635	558	558	222	231	326
10	HCT	Kg 1,4 - DCB	9.69	12.4	12	10.9	11.4	75.7
11	HNCT	Kg 1,4 - DCB	1.11E+04	9.78E+03	9.83E+03	3.90E+03	3.98E+03	4.80E+03
12	LU	M^2a crop eq.	3.14	1.49	1.75	1.34	1.34	0.928
13	WC	M^3	0	0.004	0.004	-1.27	-1.19	0.961

Source: Authors' computations.

A diagrammatic description of the results is also presented in Figure 16.

Interpretation

The software analysis of the scenarios showed that Scenarios 3 and 4, i.e., anaerobic digestion + recycling + sanitary landfill and composting + recycling + sanitary landfill, are the top two environmentally friendly waste treatment options, respectively. A limited sensitivity analysis was performed by checking for both operating routes, but the results were still the same for environmentally friendly scenarios, i.e., S3 and S4 performed better. Further analysis can be performed by altering the percentages of the recyclable fractions and combustible fractions, but this was not performed due to the time constraint. Nevertheless, the findings are more or less in line with the literature. It is worth mentioning that although anaerobic digestion performed comparatively better than composting, the literature suggests that anaerobic digestion is a complicated process and requires more skill and

resources to install and operate. Therefore, scenario S4, which includes composting alongside recycling and sanitary landfill, should be preferred in developing countries like Pakistan.

6. CONCLUSIONS

The following conclusions are drawn after the investigation of the different components of the Municipal SWM (MSWM):

1. Organic fraction, comprising kitchen and yard waste, is the predominant component (55% of the total average daily waste) of the solid waste generated, consequently establishing a need and a potential venue for the respective treatment options such as composting and anaerobic digestion.

2. The number of recyclables in the door-to-door collected waste is significantly more than that collected from the skips and tubs, thus establishing an active role of the informal sector, signifying the need for and importance of the door-to-door waste collection.

3. Significant amounts of plastic bags are being used for waste disposal (5.68% of the total average daily waste), necessitating their discontinuation due to their harmful environmental effects.

4. According to the experts, the shortlisted waste treatment options are sanitary landfill, material recovery facility/recycling, composting, anaerobic digestion, and incineration. Moreover, composting is preferred over anaerobic digestion due to the required resources and user-friendliness.

5. Two waste management entities are currently functional in the city, i.e., the PPP and the public entity, with the PPP offering door-to-door waste collection, conventional collection of waste from the skips and tubs, and separate collection of yard waste from the city. Moreover, the PPP has also set up a treatment facility comprising a weighing bridge, MRF, compost line, and pellet line. In contrast, the public entity dumps all the waste into the dumpsite.

6. The weighing bridge is only used to record the incoming weights, and there is no limitation on the quantity of waste coming in or on the concept of a gate fee/ tipping fee.

7. Compared to the public entity, the PPP operates on a regular and uniform waste collection schedule throughout the year due to its requirement for fresh waste for the different parts of the treatment facility.

8. Compost quality is not of the desired quality due to the lack of waste segregation despite the provision of separate bins for waste components at the source, which shows that the existing practice of providing three bins is ineffective.

9. Despite being willing and interested in managing some of the waste (from commercial areas) collected and brought to the dumpsite – an environmentally friendly measure – the PPP is not allowed access to it, pointing to the bureaucratic barriers in the system.

10. Door-to-door waste collection is determined to be a better input material for the treatment options than waste collected from the skips and tubs, necessitating a maximum possible transition to door-to-door waste collection across the city, a point also stressed by the PPP.

11. The provision of waste collection bins was more prevalent in high-income areas than in low-income areas.

12. Open dumping, open burning, and informal sector activity are more prevalent in the areas managed by the public entity. Moreover, PPP waste management was significantly better than that of the public entity.

13. The informal sector is a reality and plays a crucial and positive role in the city's waste management, offering services to 37% of the residents. However, an almost non-existent level of integration was observed between the formal and the informal sector of the SWM. The key issues related to the integration were the following:

    i. Lack of controlled access of the informal sector to waste.
    ii. Repression/neglect/collusion of the informal sector.
    iii. No database of waste collectors and street hawkers.
    iv. Discrimination and lack of public acceptance of the informal sector.
    v. No facilitation of the informal sector by the authorities.
    vi. Prevalent child labour.

vii. Lack of informed initiatives.

viii. No fines for open burning of waste.

ix. The absence of recycling-friendly policies.

x. The absence of NGOs supporting the informal sector's rights.

xi. No usage of PPEs.

xii. Limited access to health-care facilities.

xiii. Exploitation of the informal sector by the recycling industry.

xiv. Lack of financial support for the informal sector.

14. The level of public knowledge (90%) is considerably higher than the public attitudes (73.3%) and practices (64.7%). Moreover, there is a negative perception of waste and less knowledge about waste management essentials like the 3Rs and waste segregation. Additionally, the younger respondents were more knowledgeable than the older age groups, and the respondents with higher qualifications are more willing to pay than those with lower levels of education. Social media and TV are the preferred media choices among higher education and lower education, respectively. The respondents reported a higher satisfaction level served by the PPP, also corroborated by a higher reported waste collection frequency of the PPP as compared to that of the public entity. However, the respondents served by PPP were comparatively less willing to pay than those served by the public entity. The level of practices regarding open burning and plastic usage was alarming, considering the environmental threat faced by Pakistan.

15. The CBA showed significant revenue-earning potential, with revenues only PKR 600,000 short of the O&M costs. Moreover, revenues could significantly increase if waste segregation is practised so that compost can also be sold to interested parties, if the treatment options are run at full potential by incorporating the public entity's managed waste as well.

16. Scenario 3 (anaerobic digestion + recycling + sanitary landfill) and Scenario 4 (composting + recycling + sanitary landfill) are the top two environmentally friendly treatment options. Considering the advanced technology setup required for anaerobic digestion, as highlighted by the survey of experts, the existing PPP setup is the best possible environmental waste management scenario for Pakistan.

7. RECOMMENDATIONS

The following is recommended, given the findings of the research study:

1. The PPP model, incorporating basic treatment options such as MRFs and composting, presents a viable path forward for effective solid waste management. This approach ensures regular and frequent waste collection, driven by the profit motive of the private sector in maintaining the quality of waste for processing, an incentive largely absent in conventional public-sector waste management systems, where waste is typically transported directly to dumpsites without segregation or treatment. Moreover, these treatment options are largely self-sustainable, beyond the initial capital investment, which can be recovered over time through revenue generation or a minimal monthly fee, and require limited ongoing government funding. Additionally, the environmental analysis confirms that these treatment methods are environmentally friendly, further reinforcing their overall utility and long-term viability.

2. The existing waste collection method from the skips and tubs needs to be replaced to the extent possible with door-to-door waste collection to limit the informal sector's uncontrolled access. Moreover, open burning incidents and the presence of plastic bags that residents use to dump their waste in nearby skips and tubs, which cause harmful environmental effects, can also be limited if timely door-to-door waste collection is ensured. Additionally, door-to-door waste collection benefits the PPP's interests, thus helping them to be self-sustainable.

3. The government must install the weighing bridge at the dumpsite and introduce a tipping or gate fee to encourage recycling initiatives. Schools, colleges, universities, hospitals, and commercial centres should be charged based on the waste they produce. It will compel them to produce less waste by opting for and promoting the reuse and recycling of waste.

4. The existing three-bin placement at the residences must be replaced with two bins for dry waste and wet waste, which is more user-friendly and is likely to yield better waste management results.

5. To reduce open burning incidents, the government must ensure better waste management facilities (placement of bins and frequent collection) for low-income areas where the less privileged, including the informal sector stakeholders, reside.

6. To facilitate the integration of the formal and informal sectors in the SWM, the following must be ensured by the government:

    a. Provision of controlled access to waste at the transfer or treatment facility.

    b. Registration of waste pickers and street hawkers by mandating the junkyard owners to buy only from registered waste pickers and street hawkers. Additionally, continuous quality improvement through strict oversight is essential on the part of the government to ensure that waste pickers and street hawkers are not exploited by junkyard owners as an unintended consequence of the proposed intervention.

    c. Provision of larger containers/ sacs, and bicycles to the registered informal sector members in order to encourage their registration and also facilitate them.

    d. The informal sector stakeholders, including the junkyard officials and staff, registered street hawkers, and registered waste pickers, should be given ID cards and vests for their identification.

    e. A crackdown against the unregistered waste pickers and street hawkers, and also those informal sector members, who are engaged in open burning and accessing waste other than the transfer stations, treatment facilities or dumpsite.

    f. The activities of the informal sector (except those engaged in open burning) should be commended, and regular figures about them and their positive role in the reduction of burden on dumpsites should be published on different media options to facilitate their recognition and mitigate the discrimination.

    g. The informal sector members, in particular, the junkyard owners, should be informed and consulted on key policy issues.

    h. Regulation of recyclable prices to limit the informal sector's exploitation at the hands of recycling industries.

    i. Mandating the wearing of masks for informal sector members.

    j. Affordable healthcare facilities for the informal sector.

    k. Encouraging the parents of underage children engaged in waste picking to enrol them in government schools by offering them exclusive controlled access to waste. The children should be taught religious education along with the basic school curriculum to control child labour.

l. Provision of affordable loan options to registered informal sector members.

m. Encourage the formation of unions at least for the junkyards.

7. SWM essentials should be included in the curriculum at every level of education, from primary to graduation, regardless of specialisation. Moreover, social media and TV (the most preferred media choices) should be used to spread awareness and communicate information. Awareness walks and campaigns should be regularly held. Furthermore, imposing heavy fines on indiscriminate waste disposal and open burning is paramount.

8. LIMITATIONS

The study was envisioned to holistically assess the existing technical, institutional, social, economic, and environmental components of the situation of the sustainable solid waste management system. The purpose was to collect as much information as possible by considering a diverse range of stakeholders, including the waste management entities' staff and officials, informal sector (waste pickers, street hawkers, and junkyard owners), residents, and experts from industry and academia. However, various limitations were identified during the project, which are elaborated in this section. It is pertinent to mention here that the limitations stemmed primarily from the non-cooperation of the public waste management entity, which was reluctant to provide access to the research team to its operations and records. Moreover, despite the research team's initial target to conduct an in-depth analysis of the collected data, some analyses had to be narrowed down in scope due to the limited time of the research project. The limitations of this research study are elaborated as follows:

1. For this research, the SWM components were clearly delineated into five components. Specifically, the institutional component considered in this research study was found to have deeper economic and political aspects, which could not be further explored due to the limited timeline of the project.

2. Two waste management entities were operational in the study area: the public entity (most common in major cities) and the PPP (first of its kind in Pakistan). The PPP cooperated with the research team by providing access to its operations and records. However, the public

entity provided limited access to its operations and no access to its records. Moreover, since the public entity did not provide access to its records, the scope of the Cost-Benefit Analysis initially envisioned by the research team was reduced. Consequently, the comparative analysis of the economic component was not possible.

3. The waste treatment options deemed suitable in the context of Pakistan were finalised primarily through WACS, as recommended by the literature. While a total of 30 experts' opinions were sought to validate the findings, the absence of any further location-specific data limited further exploration into more waste treatment options.

4. The formal mechanism within the institutional component comprised determining the existing practices of the waste management entities related to the collection, transportation, and management of the municipal solid waste. Although the practices on the waste management facility and dumpsite were observed and documented in detail, the practices in different wards of the city managed by the various waste management entities were not observed and reported in detail due to limited manpower and resources. Hence, only a general overview of some selective wards representing suburban and urban parts of the city was surveyed.

5. A detailed KAP survey was designed and conducted to gain insights about the level of awareness, behaviours, and preferences regarding solid waste management. The sample size of 504 comprised the residents served by PPP, the public entity, and the informal sector. However, a mixed-methods approach or iterative survey design may significantly improve the precision of the survey, leading to more reflective policy recommendations.

6. Finally, the environmental component of sustainable solid waste management comprised carrying out a software-based analysis of the shortlisted waste treatment options. The processes used in the analysis had to be simplified due to a lack of office records. Therefore, the environmental analysis results can be further refined by considering the primary data, which was not included in this study and is hence listed as a limitation of the study.

REFERENCES

Ali, M., Marvuglia, A., Geng, Y., Chaudhry, N., & Khokhar, S. (2018). Energy-based carbon footprinting of household SWM scenarios in Pakistan. *Resources, Conservation and Recycling, 131*(April), 283–296. https://doi.org/10.1016/j.resconrec.2017.10.011.

Almasi, A., Mohammadi, M., Azizi, A., Berizi, Z., Shamsi, K., Shahbazi, A., & Mosavi, S. A. (2019). Assessing the knowledge, attitude and practice of the Kermanshahi women towards reducing, recycling and reusing of municipal solid waste. *Resources, Conservation and Recycling, 141*(October 2018), 329–338. https://doi.org/10.1016/j.resconrec.2018.10.017.

Amir, S., Asghar, G. F., Batool, R., Nawaz, S., Zahid, A., and Kanwal, A. (2023). A comprehensive waste audit analysis for assessing recycling opportunities in the University of Simra Nawaz. *Journal of Xi'an Shiyou University, 66*(09), 09, 33–47. https://doi.org/10.5281/zenodo.8343484.

Aryal, M., & Adhikary, S. (2024). SWM practices and challenges in Besisahar Municipality, Nepal. *PLoS ONE, 19*(3 March), 1–23. https://doi.org/10.1371/journal.pone.0292758.

ASTM (American Society for Testing and Materials). (2016, June 06). *Standard test method for determination of the composition of unprocessed municipal solid waste.* https://www.astm.org/d5231-92r16.html

Atta, U., Hussain, M., & Malik, R. N. (2020). Environmental impact assessment of municipal SWM value chain: A case study from Pakistan. *Waste Management and Research, 38*(12), 1379–1388. https://doi.org/10.1177/0734242X20942595.

Ayub, F., Naqvi, S. L. H., Naqvi, S. H. Z., Yasar, A., Akram, R., & Niamat, J. (2024). Assessment of municipal SWM practices in urban centers of Pakistan: A comprehensive review. *Environmental Protection Research, 4*(1), 87–103. https://doi.org/10.37256/epr.4120244086.

Baawain, M. S., Al-Mamun, A., Omidvarborna, H., Al-Mujaini, F., & Choudri, B. S. (2019). Residents' concerns and attitudes towards municipal SWM: Opportunities for improved management. *International Journal of Environment and Waste Management, 24*(1), 93–106. https://doi.org/10.1504/IJEWM.2019.100663

Baba-Nalikant, M., Abdullah, N. A., Husin, M. H., Syed-Mohamad, S. M., Mohamad Saleh, M. S., & Rahim, A. A. (2023). The relationship between knowledge, attitudes, values, and technology in promoting zero-waste pro-environmental behaviour in a zero-waste campus framework. *Recycling, 8*(2). https://doi.org/10.3390/recycling8020040

Batool, S. A., & Ch, M. N. (2009). Municipal SWM in Lahore City District, *Pakistan. Waste Management, 29*(6), 1971–1981. https://doi.org/10.1016/j.wasman.2008.12.016

Batool, S. A., & Chuadhry, M. N. (2009). The impact of municipal solid waste treatment methods on greenhouse gas emissions in Lahore, Pakistan. *Waste Management, 29*(1), 63–69. https://doi.org/10.1016/j.wasman.2008.01.013

Bilal, S., Qasim, S., Rana, A., & Haseeb, Z. (2022). Waste amount characterization survey of municipal solid waste generated in Sahiwal, Punjab, Pakistan. *International Journal of Agriculture & Environmental Science, 9*(4), 12–20. https://doi.org/10.14445/23942568/ijaes-v9i4p103

Debrah, J. K., Vidal, D. G., & Dinis, M. A. P. (2021). Raising awareness on SWM through formal education for sustainability: A developing countries evidence review. *Recycling, 6*(1), 1–21. https://doi.org/10.3390/recycling6010006

Desa, A., Ba'yah Abd Kadir, N., & Yusooff, F. (2011). A study on the knowledge, attitudes, awareness status and behaviour concerning SWM. *Procedia - Social and Behavioral Sciences, 18,* 643–648. https://doi.org/10.1016/j.sbspro.2011.05.095

Desa, A., Kadir, N. B. A., & Yusooff, F. (2012). Waste education and awareness strategy: Towards SWM (SWM) program at UKM. *Procedia - Social and Behavioral Sciences, 59,* 47–50. https://doi.org/10.1016/j.sbspro.2012.09.244

Devadoss, P. S., Pariatamby, A., Bhatti, M. S., Chenayah, S., & Shahul Hamid, F. (2021). Strategies for reducing greenhouse gas emissions from municipal SWM in Pakistan. *Waste Management and Research, 39*(7), 914–927. https://doi.org/10.1177/0734242X20983927

Ejaz, N., & Janjua, N. S. (2012). SWM issues in small towns of the developing world: A case study of Taxila City. *International Journal of Environmental Science and Development, 3*(2), 167–171. https://doi.org/10.7763/ijesd.2012.v3.209

Eshete, H., Desalegn, A., & Tigu, F. (2023). Knowledge, attitudes and practices on household SWM and associated factors in Gelemso town, Ethiopia. *PLoS ONE, 18*(2 February), 1–13. https://doi.org/10.1371/journal.pone.0278181

Ferronato, N., Guisbert Lizarazu, E. G., Valencia Vargas, D. J., Pasinetti, R., & Torretta, V. (2022). Investigation on the solid waste recyclers' perspective in La Paz, Bolivia. *Habitat International, 123*(May 2021), 102542. https://doi.org/10.1016/j.habitatint.2022.102542

Gall, M., Wiener, M., Chagas de Oliveira, C., Lang, R. W., & Hansen, E. G. (2020). Building a circular plastics economy with informal waste pickers: Recyclate quality, business model, and societal impacts. *Resources, Conservation and Recycling, 156*(January), 104685. https://doi.org/10.1016/j.resconrec.2020.104685

Gunsilius, E., Spies, S., García-Cortes, S., Medina, M., Dias, S., Scheinberg, A., ... & Ruiz, S. (2011). Recovering resources, creating opportunities. *Integrating the informal sector into solid waste management.* The Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH.

Haider, A., Amber, A., Ammara, S., Saleem Mahrukh, K., & Aisha, B. (2015). Knowledge, perception and attitude of common people towards SWM: A case study of Lahore, Pakistan. *International Research Journal of Environment Sciences, 4*(3), 2319–1414.

Hamzah, N., Marzuki, N. S., Baharudin, F., Rahim, N. L., Mohd Kamil, N. A. F., Akbar, N. A., & Mohd Zin, N. S. (2022, January). Knowledge, attitudes, awareness and practices on household hazardous waste disposal among undergraduate students in Selangor, Malaysia. In *Proceedings of the 3rd International Conference on Green Environmental Engineering and Technology: IConGEET 2021, Penang, Malaysia* (pp. 103-113). Singapore: Springer Nature Singapore.

Iqbal, A., Abdullah, Y., Nizami, A. S., Sultan, I. A., & Sharif, F. (2022). Assessment of the SWM system in Pakistan and a sustainable model from an environmental and economic perspective. *Sustainability (Switzerland), 14*(19). https://doi.org/10.3390/su141912680

Iqbal, J. (2021). Best practices of solid waste management at the Institute of Business Management, Karachi, Pakistan. *Journal of Sustainability Perspectives, 1,* 193-199.

Joos, W., Carabias, V., Winistoerfer, H., & Stücheli, A. (1999). Social aspects of public waste management in Switzerland. *Waste management, 19*(6), 417-425.

Kamran, A., Chaudhry, M. N., & Batool, S. A. (2016). Role of the informal sector in recycling waste in Eastern Lahore. *Polish Journal of Environmental Studies, 24*(2), 537–543.

Kiran, K. G., Kini, S., & Kiran, N. U. (2015). KAP study of solid waste disposal of households in Kuttar & Manjanadi Panchayath covered under the gramaskhema programme of K.S. Hegde Medical Academy. *Journal of Health and Allied Sciences NU, 05*(03), 029–035. https://doi.org/10.1055/s-0040-1703908

Laor, P., Suma, Y., Keawdounglek, V., Hongtong, A., Apidechkul, T., & Pasukphun, N. (2018). Knowledge, attitude and practice of municipal SWM among highland residents in Northern Thailand. *Journal of Health Research, 32*(2), 123–131. https://doi.org/10.1108/JHR-01-2018-013

Lema, G., Mesfun, M. G., Eshete, A., & Abdeta, G. (2019). Assessment of the status of SWM in Asella Town, Ethiopia. *BMC Public Health, 19*(1), 1–7. https://doi.org/10.1186/s12889-019-7551-1

Limon, M. R., & Villarino, C. B. J. (2020). Knowledge, attitudes and practices on household food waste: Bases for formulation of a recycling system. *Global Journal of Environmental Science and Management, 6*(3), 323–340. https://doi.org/10.22034/gjesm.2020.03.04

Majeed, A., Batool, S. A., & Chaudhry, M. N. (2017). Informal waste management in the developing world: economic contribution through integration with the formal sector. *Waste and Biomass Valorization, 8*(3), 679–694. https://doi.org/10.1007/s12649-016-9648-4

Majeed, A., Batool, S. A., & Chaudhry, M. N. (2018). Environmental quantification of the existing waste management system in a developing world municipality using EaseTech: The case of Bahawalpur, Pakistan. *Sustainability (Switzerland), 10*(7). https://doi.org/10.3390/su10072424

Marshall, R. E., & Farahbakhsh, K. (2013). Systems approaches to integrated SWM in developing countries. *Waste Management, 33*(4), 988–1003. https://doi.org/10.1016/j.wasman.2012.12.023

Merker, R., Schwarz, W., Schreiber, H., & Zlateva, T. (2015). Thinking in systems. *AEU-International Journal of Electronics and Communications, 69*(1), 151-152.

Misganaw, A. (2023). Assessment of potential environmental impacts and sustainable management of municipal solid waste using the DPSIRO framework: A case study of Bahir Dar, Ethiopia. *Environmental Monitoring and Assessment, 195*(2). https://doi.org/10.1007/s10661-023-10929-z

Muhammad, S., Kauser, F., Raza, A., Hassan, I., Janjua, S., Peshawar, T., Kauser, F., Raza, A., Hassan, I., Janjua, S., & Author, C. (2023). Application of system dynamics for the sustainable management of solid waste. *International Journal of Environmental Issues, 22.*

Mulya, K. S., Zhou, J., Phuang, Z. X., Laner, D., & Woon, K. S. (2022). A systematic review of life cycle assessment of SWM: Methodological trends and prospects. *Science of the Total Environment, 831*(March), 154903. https://doi.org/10.1016/j.scitotenv.2022.154903

Nadeem, K., Shahzad, S., Hassan, A., Usman Younus, M., Asad Ali Gillani, S., & Farhan, K. (2023). Municipal solid waste generation and its compositional assessment for efficient and sustainable infrastructure planning in an intermediate city of Pakistan. *Environmental Technology (United Kingdom), 44*(21), 3196–3214. https://doi.org/10.1080/09593330.2022.2054370

Nguyen, T. T. T., & Wilson, B. G. (2010). Fuel consumption estimation for kerbside municipal solid waste (MSW) collection activities. *Waste Management and Research, 28*(4), 289–297. https://doi.org/10.1177/0734242X09337656

Olukoju, A. (2018). "Filthy rich" and "dirt poor:" social and cultural dimensions of SWM (SWM) in Lagos. *Social Dynamics, 44*(1), 88–106. https://doi.org/10.1080/02533952.2018.1430475

Seadon, J. K. (2010). Sustainable waste management systems. *Journal of Cleaner Production, 18*(16–17), 1639–1651. https://doi.org/10.1016/j.jclepro.2010.07.009

Sigcha, E., Sucozhañay, D., Cabrera, F., Pacheco, G., & Vanegas, P. (2024). Applying social life cycle assessment in the informal recycling sector: Understanding challenges and limitations. *Waste Management, 181*(September 2023), 20–33. https://doi.org/10.1016/j.wasman.2024.03.029

UNEP (United Nations Environment Programme). (2024). *Beyond an age of waste: Turning rubbish into a resource.* UNEP, Nairobi.

Velis, C. A., Wilson, D. C., Rocca, O., Smith, S. R., Mavropoulos, A., & Cheeseman, C. R. (2012). An analytical framework and tool ('InteRa') for integrating the informal recycling sector in waste and resource management systems in developing countries. *Waste Management and Research, 30*(9 SUPPL.1), 43–66. https://doi.org/10.1177/0734242X12454934

Wang, H., Liu, X., Wang, N., Zhang, K., Wang, F., Zhang, S., Wang, R., Zheng, P., & Matsushita, M. (2020). Key factors influencing public awareness of household solid waste recycling in urban areas of China: A case study. *Resources, Conservation and Recycling, 158*(October 2019), 104813. https://doi.org/10.1016/j.resconrec.2020.104813

Yıldız-Geyhan, E., Altun-Çiftçioğlu, G. A., & Kadırgan, M. A. N. (2017). Social life cycle assessment of different packaging waste collection systems. *Resources, Conservation and Recycling, 124*(April), 1–12. https://doi.org/10.1016/j.resconrec.2017.04.003

Zarate, M. A., Slotnick, J., & Ramos, M. (2008). Capacity building in rural Guatemala by implementing a SWM program. *Waste Management, 28*(12), 2542–2551. https://doi.org/10.1016/j.wasman.2007.10.016

Zia, A., Batool, S. A., Chaudhry, M. N., & Munir, S. (2017). Influence of income level and seasons on quantity and composition of municipal solid waste: A case study of the capital city of Pakistan. *Sustainability (Switzerland), 9*(9), 1–13. https://doi.org/10.3390/su9091568

Zia, U. U. R., Rashid, T. U., Ali, M., & Awan, W. N. (2020). Techno-economic assessment of energy generation through municipal solid waste: a case study for small/medium-sized districts in Pakistan. *Waste Disposal & Sustainable Energy, 2*(4), 337-350.

EMPOWERING SUSTAINABLE AQUACULTURE ENTERPRISES: HARNESSING THE POTENTIAL OF BIOFLOC TECHNOLOGY IN INVESTMENT, COMPLIANCE, AND GROWTH STRATEGIES

Aima Iram Batool[1], Muhammad Fayyaz Ur Rehman[2], Naima Huma Naveed[3], and Muhammad Mustaqeem[4]

ABSTRACT

Biofloc fish farming, an evolutionary approach and emerging trend of modern aquaculture, is gaining importance in recent times. Biofloc is a true game-changing invention in present-day aquaculture farming because it maximises productivity, preserves aquatic and terrestrial resources, and is responsible for higher financial returns. The main factors for the adoption of biofloc are examined in this project, along with the challenging factors farmers and other stakeholders encounter in the successful implementation of this technology. The findings of the current study revealed that through the adoption of biofloc farming, farmers may increase fish production by up to three times, drastically reduce the usage of water, as it is based on zero water exchange technology, reduce the feed cost, and decrease the mortality rate by enhancing fish health. By reducing waste discharge and intelligent resource use, biofloc farming not only maximises economic efficiency but also decreases environmental deterioration. Biofloc is an economically feasible and sustainable substitute for conventional aquaculture that satisfies the circular economy's principles and the urgent demand for environmentally friendly methods. But even with its obvious benefits, problems still exist.

[1] Associate Professor, University of Sargodha.

[2] Associate Professor, University of Sargodha.

[3] Assistant Professor, University of Sargodha.

[4] Lecturer, University of Sargodha.

Extensive adoption is fraught with high investment costs for set-up, feed quality issues related to crude protein level, a lack of technical know-how, higher electricity bills, and limited access to training. The study identified that financial incentives, easy loans for set-ups, subsidies on electricity bills, reliable monitoring systems, provision of good quality fish seed and fish feed are indispensable for the future success of biofloc farming in Pakistan. Currently, Pakistan's aquaculture sector is burdened by high operational costs, particularly due to feed expenses, which account for 60–70% of production costs. Additionally, a shortage in water resources and poor waste management are critical challenges that limit productivity and sustainability. In this scenario, the Biofloc technology (BFT) appears as a blue revolution and climate-smart technology to tackle these issues. BFT systems use microbial flocs to convert organic waste into protein-rich biomass, creating a self-sustaining ecosystem. To fully realise the potential of biofloc technology, however, major challenges still need to be addressed, including the lack of policies for biofloc farming, the lack of incentives and subsidies, and false beliefs about the technology.

1. INTRODUCTION

Aquaculture has been the fastest-growing segment of global food production for the past thirty years, now supplying over half of the fish consumed worldwide (Subasinghe, 2017). Asia accounts for 90% of aquaculture production, and the volume is predicted to double by 2050. This industry plays a vital role in ensuring food security, generating income, and supporting community economic development (Little et al., 2016). An estimated 58.5 million people are directly employed in the aquaculture industry, while associated industries and services contribute 100 million jobs globally. Therefore, sustainable aquaculture systems are crucial. The contribution of global aquaculture to world fish production has consistently increased, reaching 46.0%, with the production of farmed aquatic animals growing at an average rate of 5.3% per year from 2001 to 2018 (FAO, 2020). By 2030, it is expected that freshwater species, such as carp and catfish, will make up the majority (62%) of global aquaculture production (FAO, 2016 and 2020). The sector's rise to global significance has generated interest in its potential to drive economic growth and reduce poverty in developing countries (Little et al., 2012). Aquaculture provides greater income opportunities for small-scale commercial fish farming (Wuyep & Rampedi, 2018).

However, aquaculture's growth is hindered by certain challenges, including the unavailability of suitable and cost-effective feed, water shortage, decreasing water resources, excessive dependence on fish meals for aquatic feed preparation, prevalence of diseases, and pollutants arising from effluents emerging from cultivation farms. Researchers always keep on trying to find new ways to make aquaculture more sustainable and eco-friendlier (Fasolin et al., 2019). The Biofloc Technology (BFT), recirculatory aquaculture systems (RAS), raceway systems, integrated aquaponics, and integrated aquaculture are some of those ways recommended by researchers that can make aquaculture more sustainable (Zimmermann et al., 2023). Among these, biofloc technology really stands out for cutting down on water use, cleaning up waste efficiently, improving feed conversion ratios, boosting stocking density, and optimising overall system performance (Khanjani et al., 2023).

BFT resembles a micro-ecosystem. It is a problem-solving evolutionary technology for traditional aquaculture's difficult issues. Biofloc farming is based on a self-nutrition process as it converts the feed, waste and fish faecal material into edible accumulates with the help of microorganisms, which are known as bioflocs. Biofloc farming, along with decreasing the cost and dependency on large quantities of fish feed, also conserves the land and water,

making it economically feasible and environmentally friendly. One-acre Pond fish can be raised efficiently in a smaller tank having a diameter of 16-20, with almost zero water exchange (Das et al., 2022).

One of the most enduring challenges is nitrogen waste production from organic sources in traditional aquaculture, as improper management causes poor water quality and fish mortality (Rind et al., 2023). A straightforward yet efficient solution is provided by BFT to this issue by converting the nitrogenous waste into bacterial biomass (Minabi et al., 2020). 106 to 109 bacteria per centimetre cube of water may be present in a biofloc system, working like a mini biotechnological industry. Materials rich in carbon and poor in protein are added to the system to maintain a C/N ratio higher than 10, which will cause bacteria to use nitrogen present in the water. Bacteria that are a major contributor to this process are heterotrophic in nature, and this encourages their spread. These bacteria can transform nitrogen molecules into microbial protein, which is an excellent and sustainable substitute for conventional protein present in fish feed (Avnimelech, 2009).

Closed biofloc systems are becoming more and more popular all over the globe in terms of biosecurity and environmental impact. One of the major advantages of adopting biofloc technology is linked with improvement in water quality parameters (pH, DO, ammonia, nitrites, nitrate), thus making the water more productive for fish growth and health in aquaculture structures. BFT emphasises environmental sustainability by recycling waste and residual feed (Mordenti et al., 2014; Habib et al., 2023), reducing water exchange, and also enhancing overall yield per unit area. BioFloc is an innovative farming approach that satisfies the modern demands of aquaculture and resource efficiency (Deswati et al., 2022; Liu et al., 2019).

Unfortunately, Pakistan's aquaculture industry is relying on outdated and traditional practices (Laghari, 2018). Introduction of innovative technologies like biofloc in the traditional aquaculture industry can be a transformative force for developing nations like Pakistan (Habib et al., 2022), due to its potential to promote sustainable food production and economic growth (Kausar, 2017).

Pakistan is currently facing an alarming water crisis, with per capita water availability dropping drastically from 5,260 cubic meters in 1951 to less than 900 cubic meters in 2023. Given this water scarcity, the adoption of BFT provides a sustainable solution for the aquaculture sector by enabling efficient fish farming with minimal water usage. In conventional aquaculture, large water bodies are required to sustain fish, but BFT allows fish to be raised

in smaller tanks with a diameter of 16-20 feet and almost zero water exchange. This technology significantly reduces water consumption, as traditional freshwater aquaculture techniques require 16.9 cubic meters per kilogram of fish output, whereas BFT requires only 0.071 to 6.8 cubic meters per kilogram (Mordenti et al., 2014). The implementation of this system can help Pakistan overcome its water scarcity while promoting a more efficient and productive fish farming industry.

The current study explores how BFT is reshaping Pakistan's traditional aquaculture sector. It highlights BFT's role in attracting investors, ensuring regulatory compliance, and promoting growth opportunities. As a practical, innovative solution, BFT addresses critical challenges such as disease control, resource optimisation, and water scarcity, positioning it to significantly advance sustainable aquaculture in Pakistan."

With an emphasis on investments, regulatory compliance, and growth strategies, this study attempts to investigate how BFT might support sustainable aquaculture businesses in Pakistan. The particular goals consist of:

- Evaluating biofloc technology's economic feasibility as a potential investment for Pakistani aquaculture companies.
- Investigating the impact of compliance constraints and regulatory environments on the uptake of biofloc technology in various regions of Punjab, Pakistan.
- Providing recommendations and strategic insights for using biofloc technology in aquaculture growth plans to improve profitability, operational efficiency, and environmental sustainability.

2. LITERATURE REVIEW

Aquaculture, the fastest-growing food production sector, addresses the critical global challenges of food security, malnutrition, and sustainable resource management in an impressive manner. 49% of global fish consumption comes from the aquaculture sector, which has grown significantly from just 4% in the 1950s (FAO, 2022). This remarkable expansion highlights aquaculture's pivotal role in providing affordable, nutrient-rich food to a rapidly growing population. In regions like South Asia, where dietary protein deficiencies are common, aquaculture has become a cornerstone of rural livelihoods, economic growth, and nutrition.

In South Asia, aquaculture contributes significantly to the fisheries sector. Pakistan is sitting on a goldmine of aquatic resources with 1,120 kilometres of coastline along with an exclusive economic zone that extends 350 nautical miles into the sea (Jarwar, 2008; Wasim & Abbas, 2024). Despite this natural advantage, fish production in Pakistan still lags far behind regional aquaculture dynamos, like India and Bangladesh, due to a mix of social and economic factors. India leads with 9.4 million tonnes of aquaculture production (Table 1), making up 65.1% of its total fisheries output. Bangladesh follows with 2.6 million tonnes, representing 55.1% of its fisheries production. Pakistan lags with 817,000 tonnes, which accounts for only 24.8% of its total fisheries output (GOP, 2024).

Table 1: Comparison of Fisheries and Aquaculture Production

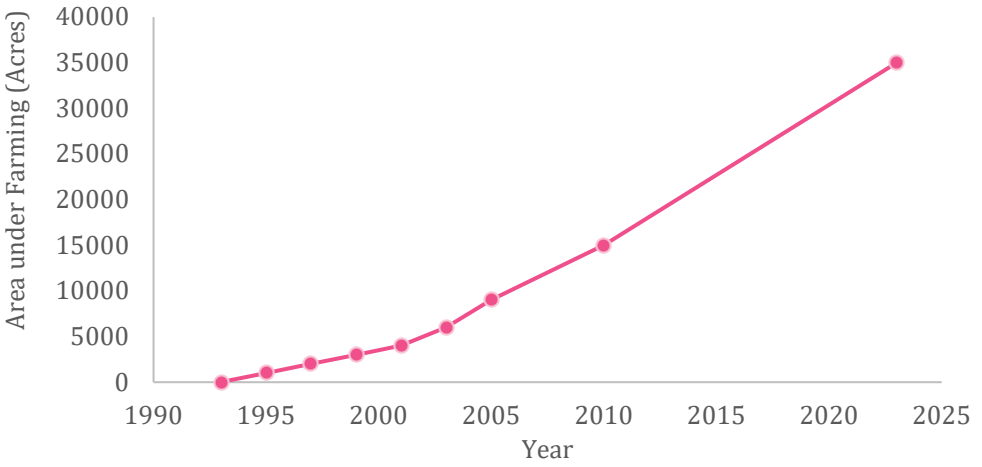
Country	Total Fisheries Production (Tonnes)	Aquaculture Production (Tonnes)	Aquaculture Contribution (%)	GDP Contribution (%)
India	15.72 million	9.4 million	65.1%	1.1%
Bangladesh	4.51 million	2.6 million	55.1%	3.57%
Pakistan	665,371	817,000	24.8%	<1%

Source: FAO (2024).

In the 1970s, Pakistan began focusing on developing its inland fishery and aquaculture sectors. Aquaculture production in Pakistan has experienced significant growth during the 21st century, becoming a substantial contributor to the country's economy. Over this period, the sector has expanded manifold, playing an increasingly vital role in national food security and economic stability. Semi-intensive aquaculture is widely practised in Pakistan, focusing on species like Catla catla, Labeo rohita, Cirrhinus mrigala,

Hypophthalmichthys nobilis, Ctenopharyngodon idellus, Cyprinus carpio, and Hypophthalmichthys molitrix. Among these, Cirrhinus mrigala, Catla catla, and Labeo rohita command higher market prices due to consumer demand. Nile tilapia, Catfishes, and Snakeheads are also being cultivated, with tilapia development initiatives introduced by the Fisheries Development Board in 2014 to enhance culture techniques and quality (Javed & Abbas, 2018). Species like Tor tor, Schizothorax richardsonii, Lates calcarifer, Tenualosa ilisha, Rita rita and Mystus seenghala also hold potential for aquaculture in Pakistan (Laghari, 2018). However, production levels are still insufficient for national supply or export.

Figure 1: Fish Farming Trend in South Punjab, Pakistan



Source: PakFishOnline (n.d.).

Major hurdles like power outages, poor feed quality, and high construction costs continue to hold back aquaculture progress. Most of the biofloc fish farmers do not have access to modern-day technologies, lack training related to the biofloc system, and lack investment and technical know-how of the system, which is the main reason for a reduction in fish yield (Ahmad & Farooq, 2010; Meeran, 2000).

Biofloc Technology: Transforming Aquaculture Practices

Biofloc technology is an innovative and transformative solution for most of the critical challenges of aquaculture, including higher food requirements and feed costs, negative impact on the environment and scarcity of aquatic resources. Biofloc setup acts as a mini biotechnological unit based on

microbial processes to convert organic waste into protein-rich bioflocs, which act as an alternative feed source for fish and shrimp. Biofloc technology significantly reduces the feed cost by about 20 to 30 times, enhancing the financial viability as feed accounts for 50 to 80 % of the total production cost of the system (Crab et al., 2012). Biofloc technology's working principle requires the continuous addition of carbon and nitrogen sources into the pond water, which acts as a stimulant for the growth of heterotrophic bacteria, which in turn fosters the production of microbial biomass. Maintenance of a carbon-to-nitrogen (C/N) ratio above 10 plays a central role in promoting vigorous bacterial growth and efficient nutrient cycling within the aquaculture environment (Avnimelech, 1999 and 2009). This ratio can be achieved by the addition of carbon-rich organic sources like molasses, wheat flour and starch. Alternatively, adjusting feed protein levels downward also promotes the growth of heterotrophic bacteria essential for biofloc formation (Rind et al., 2023).

Biofloc technology is attributed to water quality enhancement and reduction in water utilisation. The addition of carbon sources in water increases the proliferation of microbial biomass that utilises waste materials present in the water and efficiently converts them into protein-rich bioflocs. On the other hand, it is driven by the zero water exchange principle, eradicating the need for excessive water inclusion. These microbial conversions maintain the level of ammonia at a tolerable intake level, which eliminates the need for frequent water exchange. So biofloc not only lowers water intake requirements but is also cost-efficient to farmers and elevates biosecurity by reducing the entry of harmful pathogens into the water. This enhances overall efficiency and sustainability by providing a continuous supply of high-standard juveniles, a critical component in the aquaculture process (Khanjani & Sharifinia, 2020; Emerenciano et al., 2012).

Implementing biofloc setups for broad-scale aquaculture production has many environmental and economic advantages, specifically in coastal areas and marine environments (Khanjani & Sharifinia, 2020). If aquaculture wastewater poses various environmental threats, biofloc systems may serve as a substitute for conventional ingredients like soybean or fish meal in aquatic feed with floc compounds if managed effectively (Stockhausen et al., 2023). This not only eliminates the environmental challenges related to aquaculture but also increases the sustainability of the entire production process.

The adoption of BFT has resulted in impressive outcomes in countries like India and Bangladesh. In India, BFT has been broadly adopted in shrimp and tilapia farming, assisted by public-sector training programmes, which have enhanced productivity and exports (GOI, 2023 Likewise, Bangladesh has incorporated BFT into community aquaculture projects, especially in areas with restricted water availability. These initiatives have raised the productivity of high-value species like shrimp and carp, ensuring sustainable development and greater incomes for farmers. Pakistan, however, has only recently commenced implementing BFT. Pilot projects in Sindh and Punjab have resulted in better yields and reduced expenditure, but wide-scale adoption is still a challenge due to limited technical proficiency and high setup costs (GOP, 2024).

Tilapia, Carp and shrimp species are among the most cultured species in biofloc systems (Crab et al., 2012). Some of the shrimp species particularly adapted to biofloc systems include white leg shrimp (Litopenaeus vannamei) (Aguilera-Rivera et al., 2019; Xu & Pan, 2013), Kuruma shrimp (Marsupenaeus japonicas) (Duan et al., 2017), blue shrimp (Litopenaeus stylirostris) (Cardona et al., 2015; Emerenciano et al., 2012); white shrimp (Litopenaeus setiferus) (Khanjani et al., 2020), giant tiger shrimp (Penaeus monodon) (Anand et al., 2014), and pink shrimp (Farfantepenaeus duoradum).

Economic Considerations of Biofloc System

BFT has appeared as a blue revolution serving as a substitute for traditional aquaculture due to its considerable effect on the growth rate, feed conversion ratio, specific growth rate of individuals, enhanced rates of survival, efficient water management, minimisation of set-up cost and alignment with the circular economy principles. These factors are necessary in contouring the economics and managing the strategies of aquaculture (Khanjani & Sharifinia, 2020).

Elevated growth rate and reduced or nil mortality rate accomplished through the biofloc system are directly related to economic consequences. For example, enhanced survival growth rates can lead to considerable gains in profit margin. Browdy et al. (2001) reported that profitability can be boosted by 57% and 45%, due to a 20% increase in stocking density or growth rate. Moreover, the reduction of nutritional expenses by 20% can also have a significant progressive impact on overall profitability (Rind et al., 2023).

One of the noteworthy benefits of BFT systems is their ability to utilise bioflocs as a replacement for marketed feeds without jeopardising the growth or survival of aquatic species. These systems provide higher protein efficiency compared to traditional methods, which facilitates cost savings. For instance, producing one kilogram of tilapia or green tiger shrimp in BFT systems can lead to lower costs by10% and 33%, respectively. It depends on various factors, such as requirements that are species-specific, feed costs, biofloc consumption, and prices of carbohydrates (Megahed, 2010; de Schryver & Verstraete, 2009). BFT adoption also abolishes the need for natural and synthetic fertiliser inputs, eliminating the costs of these fertilisers. Water treatment expenses can be lowered by approximately 30% by maintaining a zero water exchange system. This efficiency not only reduces the cultivation time but also increases the survival and growth rates of aquatic species, comparable to conventional methods. Also, BFT systems are recognised as sustainable practices for aquaculture production (de Schryver et al., 2008; Khanjani & Sharifinia, 2020).

Avnimelech (2009) reported a 20% to 30% feed cost reduction in biofloc systems as compared to traditional systems. Its ability to lower water utilisation by up to 90% further reduces management expenses, making it a cost-efficient alternative to traditional aquaculture practices. Hossam et al. (2024) compared the economic results of traditional aquaculture and biofloc with respect to growth and efficiency of protein utilisation of Nile tilapia (Oreochromis niloticus). They found that they had a considerably elevated final body weight, specific growth rate, and feed conversion ratio of tilapia, which were cultivated under biofloc setups. They also reported higher net incomes under this system, particularly when provided with molasses and rice bran as the source of carbon. An 85% reduction in water usage was observed by them in this comparative study under biofloc ponds, as only 108 litres of water per kilogram of fish was required according to their reported study, while 1,166 litres of water per kilogram of fish was required under traditional aquaculture.

Arifin (2024) carried out investigations of the environmental and economic benefits of BFT. He reported BFTs' significance in terms of improvement in water quality parameters, reduction in use of feed, thus in feed costs, as well as the fastest growth rate of fish species. He added that this system acts as a biotransformer, converting the organic waste with the help of microbes into protein-rich bioflocs. BFT is economically viable as it reduces the use of commercial feed and has ecological advantages via lower water usage and waste output, making it a promising solution for sustainable freshwater fish cultivation.

Khanjani & Sharifinia (2020) considered biofloc technology as a promising solution to minimise the environmental impacts of traditional aquaculture. They reported that this technology operates on the principle of producing microbial protein from fish waste and residual feed, thus improving water quality. This technology is an effective and sustainable approach.

Khanjani et al. (2024) highlighted the benefits of the adoption of BFT in terms of reduction in feed costs by up to 33% for shrimp and 10% for tilapia, despite the higher initial investment and energy demands. Furthermore, they supported the adoption of BFT with the supporting comments that the long-term savings on feed and water management offset these upfront costs, making BFT an attractive option. Panigrahi et al. (2019) supported these findings, showcasing higher yields—up to 25 metric tons per hectare per crop—and improved feed conversion ratios (FCRs). Their cost analyses revealed that even under less favourable scenarios, the internal rate of return (IRR) remained substantial, confirming the economic viability of BFT.

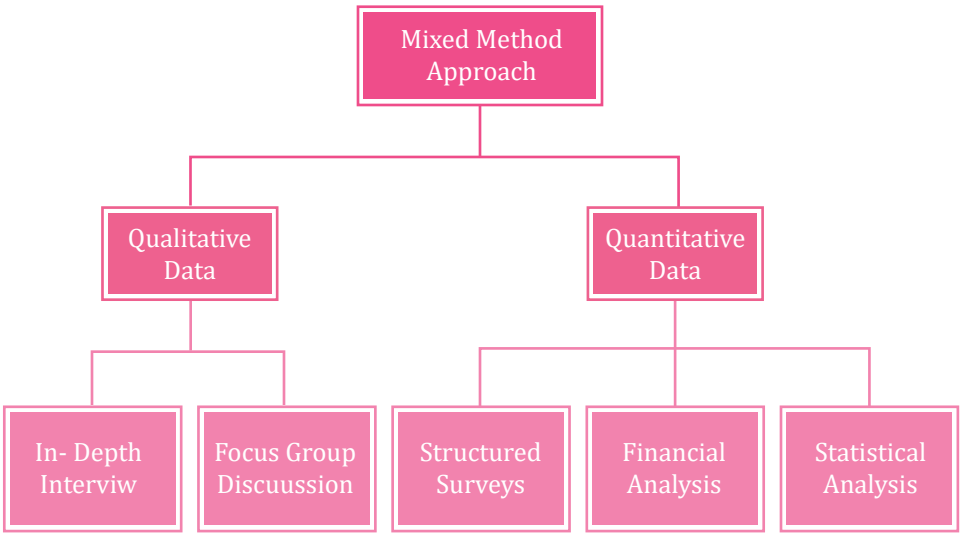
Studies focusing on nutrient efficiency also highlight BFT's economic value. da Silva et al. (2013) reported significant increases in nitrogen and phosphorus utilisation, reducing feed waste and lowering production costs. Jatobá & Lehmann (2021) demonstrated that biofloc systems consistently reduced FCR and increased survival rates, resulting in higher economic returns per crop cycle. Rani et al. (2017) further showed that microbial protein from bioflocs can replace up to 50% of fishmeal, significantly cutting feed expenses without compromising growth rates.

Other research has focused on the operational savings associated with BFT. Ray et al. (2010) observed that minimal water exchange in BFT systems greatly reduced pumping and treatment costs. Emerenciano et al. (2013) also emphasised that BFT's improved FCR and reduced water usage make it a financially sustainable choice. Megahed (2010) reported similar benefits, with shrimp yields increasing by 25–30% per hectare and overall operational costs decreasing due to nutrient recycling. Finally, Xu & Pan (2013) highlighted faster growth rates and better FCR among shrimp fed on bioflocs, which resulted in approximately 20% savings on feed costs. By reducing feed and water costs, improving growth performance, and minimising waste, BFT offers a cost-effective and sustainable solution for aquaculture operations.

3. RESEARCH METHODOLOGY

Large and small biofloc setups in almost all parts of Punjab, Pakistan, were part of the current project (Table 2). The Faisalabad region can be considered a hub of BFT, comprising hundreds of small and large private setups. Only 3 biofloc setups have been established under the Punjab Fisheries Department of Pakistan, which mainly rely on these setups for fish seed production. Out of all the biofloc setups, only one setup was running successfully by females, while all others were under the ownership of males. Both qualitative and quantitative data were collected using a semi-structured questionnaire. The questionnaire included sections on demographic information, farm characteristics, investment details, compliance with regulations, operational challenges, and growth strategies. Farmers were randomly selected from the study area. The selection criteria ensured a diverse representation of biofloc fish farms in terms of size and operational scale. Data were collected through in-person, individual interviews conducted at the biofloc fish farming sites, typically located in outdoor areas of the farmers' houses. All interviews were conducted by trained researchers to ensure data consistency and reliability. Data for an economic analysis were collected from biofloc setups located in Faisalabad, Sargodha, and Lahore.

Figure 2: Flow Chart of Research Methodology



Source: Authors' illustration.

Qualitative Analysis

The qualitative analysis took into account three key approaches to have comprehensive insights into BFT. In-depth interviews were conducted with industry experts, aquaculture professionals, researchers, and environmental specialists using a semi-structured questionnaire. The data was analysed using thematic analysis to identify common themes, benefits, challenges, and perspectives on sustainable practices. Focus group discussions (FGDs) were held with practitioners and stakeholders in aquaculture enterprises who are using BFT. They shared their experiences, challenges, and strategies. Additionally, case studies were done to focus on aquaculture enterprises that have successfully implemented BFT, examining their investment strategies, compliance strategies, and growth approaches.

Quantitative Analysis

Structured surveys were conducted of a broad range of biofloc farmers who are using BFT. These surveys included Likert scales and multiple-choice questions addressing investment patterns, cost-benefit analyses, and compliance. The collected data were analysed using descriptive and inferential statistics to identify patterns.

Financial data analysis was done on the financial records of the participating aquaculture enterprises. This involved examining investments, operational costs, and revenue streams. A comparative analysis was carried out to evaluate the economic impacts of BFT against traditional aquaculture methods.

Additionally, a statistical analysis of growth metrics was conducted using data such as production volume, feed conversion ratios, and market share.

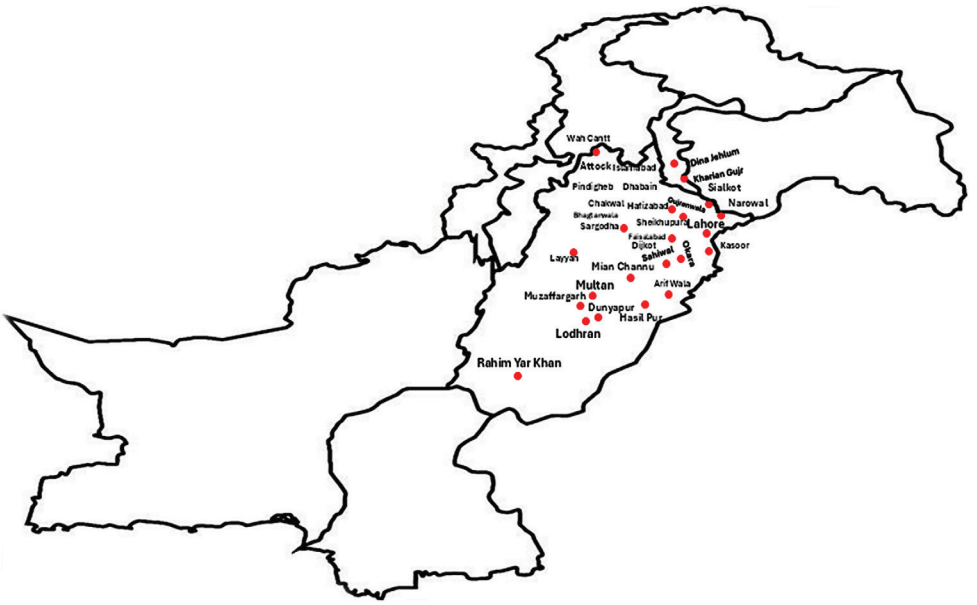
Table 2: Details of Areas Visited

Location Name	Latitude	Longitude	Location Name	Latitude	Longitude
Arif Wala	30.3002	73.0669	Layyah	30.9646	70.939
Attock	33.768	72.3602	Lodhran	29.54	71.6324
Bhagtanwala	32.4	72.65	Mandi Bahauddin	32.5834	73.4844
Chakwal	32.9331	72.8586	Mian Channu	30.4467	72.3573
Dhabain	33.1667	73.1667	Multan	30.1575	71.5249
Dijkot	31.2167	73.0167	Muzaffargarh	30.0703	71.1937

Location Name	Latitude	Longitude	Location Name	Latitude	Longitude
Dina Jehlum	33.0167	73.6	Narowal	32.1	74.8833
Dunyapur	29.8	71.7333	Okara	30.809	73.4458
Faisalabad	31.4504	73.135	Pindigheb	33.2333	72.2667
Gujranwala	32.1877	74.1945	Rahim Yar Khan	28.4202	70.2952
Hafizabad	32.0709	73.688	Sahiwal	30.67	73.1
Hasil Pur	29.7124	72.5551	Sargodha	32.0836	72.6711
Islamabad	33.6844	73.0479	Shahkot	31.5696	73.4784
Jaranwala	31.3333	73.4333	Sheikhupura	31.7131	73.9783
Kasoor	31.115	74.4467	Sialkot	32.4927	74.5319
Kharian Gujr	32.8117	73.8655	Wah Cantt	33.7496	72.4166
Lahore	31.5204	74.3587			

Source: Authors' compilation.

Figure 3: Study Areas



Source: Authors' compilations.

4. FINDINGS

The findings based on the data collected from the 99 biofloc setups established in the key areas of Punjab are presented here.

Demographic Insights

58% of biofloc setup owners are new to this farming technology or have less than five years of experience in biofloc farming. According to this pattern, biofloc farming is still a relatively new technology in Pakistan, but it is quickly becoming popular among aquaculturists, probably due to its ability to increase sustainability and fish production. Formal training based on biofloc fish farming is one of the major obstacles in setting up this technology in Pakistan. The current study identified that 60.2% of farmers lack formal training, and they rely on unofficial networks for information sharing or self-learning techniques. Meanwhile, the rest of the 39.8% are aware of this through attending seminars or local workshops. The lack of experience, nevertheless, might also draw attention to possible difficulties with technical know-how and proficiency, which are essential for biofloc farming to be effective.

Tilapia and pangasius were most popular among farmers related to Biofloc culture due to their market value and adaptability to environmental factors. More than 90% of farmers preferred pangasius and tilapia for their setups. The low percentages of other species (3.1%) and ornamental fish (5.1%) suggest that farming practices are not very diverse. However, many farmers may not be able to achieve diversification at this time due to the need for greater investment, sophisticated expertise, and access to particular markets. Lack of awareness about fish species being cultured in biofloc setups globally may be the reason for relying on pangasius and tilapia.

The data on setup tanks shows that biofloc farming is primarily a small-to-medium-scale activity. Most farmers (76%) operate with 1-10 tanks, suggesting a cautious investment approach, likely influenced by financial constraints or uncertainty about the system's profitability. The relatively low proportion of farmers with larger setups (24% for 10-20 tanks or more) reflects the need for scalability solutions and financial support for those looking to expand. Encouragingly, 42.1% of farmers are considering additional setups, indicating optimism about biofloc farming's potential.

Figure 4: A Biofloc Setup

Most farmers harvest their crops once (55.1%) or twice (41.8%) per year, which could be tied to the lifecycle of the fish species or their production strategies. Frequent harvests, such as more than twice per year (3.1%), are rare and likely associated with intensive farming practices. Similarly, most farmers harvest fish in the medium-size range of 7-12 inches (71.6%), aligning with market preferences for medium-sized fish. Larger sizes, while fetching higher prices, require longer growing periods and higher costs, which might deter farmers from pursuing such a strategy.

The data on plans reveals a balanced outlook. While 42.1% of farmers are optimistic and plan to install more biofloc setups, 57.9% are not considering expansion. This reluctance could stem from challenges such as high initial costs, technical barriers, or limited market access. Among those intending to expand, tilapia (38.9%) and pangasius (31.6%) remain the preferred species, reinforcing their dominance. Interestingly, 20.0% of farmers aim to diversify with other catfish species, signalling an interest in exploring alternatives.

Preferences for new culture systems show an even split between indoor (36.8%) and outdoor (36.8%) setups, with a significant minority (26.3%) opting for none. This reflects a diversity of strategies based on individual circumstances, such as available resources, costs, or environmental factors. Similarly, the water supply is predominantly managed through motor pumps (57.9%), with 42.1% using canal water, reflecting both mechanised and traditional methods.

Feeding strategies predominantly focus on moderate levels, with 43.2% applying 2% body weight and 35.8% using 1%. These patterns likely aim to balance growth rates with feed costs, as feed represents a significant

operational expense. A smaller proportion (21.1%) opts for higher feeding rates (3%), likely aiming for faster growth or larger harvest sizes. In terms of feed brands, Hi-Tech is slightly more popular (58.9%) than Supreme (41.1%), suggesting farmer preferences based on availability, cost, or performance.

Harvesting methods show a preference for nets (61.1%), which are cost-effective and easier to manage. Water drainage (38.9%) is less common and might be used in specific setups where nets are less practical or when a complete system overhaul is planned post-harvest.

Table 3: Demographic Data Related to Biofloc

Farming experience	
less than 1 year	29 (29.3%)
less than 5 years	28 (28.3%)
less than 10 years	25 (25.3%)
less than 20 years	17 (17.2%)
Farmed fishes	
Pangasius	45 (45.5%)
Tilapia	46 (46.5%)
Ornamental fish	5 (5.1%)
Other	3 (3.0%)
Setup Tanks	
1-5 tanks	43 (43.0%)
5-10 tanks	33 (33.0%)
10-20 tanks	14 (14.0%)
more than 20	10 (10.0%)
Formal Training	
Yes	39 (39.8%)
No	59 (60.2%)
Crops per year	
1 time	54 (55.1%)
2 time	41 (41.8%)
more than 2	3 (3.1%)
More Biofloc Setup Installation	
Yes	40 (42.1%)
No	55 (57.9%)
Fishes Intended to be Cultured in a New Setup	
Pangasius	30 (31.6%)
Tilapia	37 (38.9%)

Fishes Intended to be Cultured in a New Setup	
Other Catfish	19 (20.0%)
None	9 (9.5%)
Preferred Culture System for a New Setup	
Indoor	35 (36.8%)
Outdoor	35 (36.8%)
None	25 (26.3%)
Water Supply	
Motor Pumps	55 (57.9%)
Canal Water	40 (42.1%)
Average size of fish at harvest	
5-8 inch	16 (16.8%)
7-10 inch	36 (37.9%)
9-12 inch	32 (33.7%)
More than 12	11 (11.6%)
Harvesting Method	
Nets	58 (61.1%)
Water drainage	37 (38.9%)
Commonly Used Feed	
Hi-tech	56 (58.9%)
Supreme	39 (41.1%)
Feed Application	
1% body weight	34 (35.8%)
2% body weight	41 (43.2%)
3% body weight	20 (21.1%)

Source: Authors' calculations.

Thematic Analysis

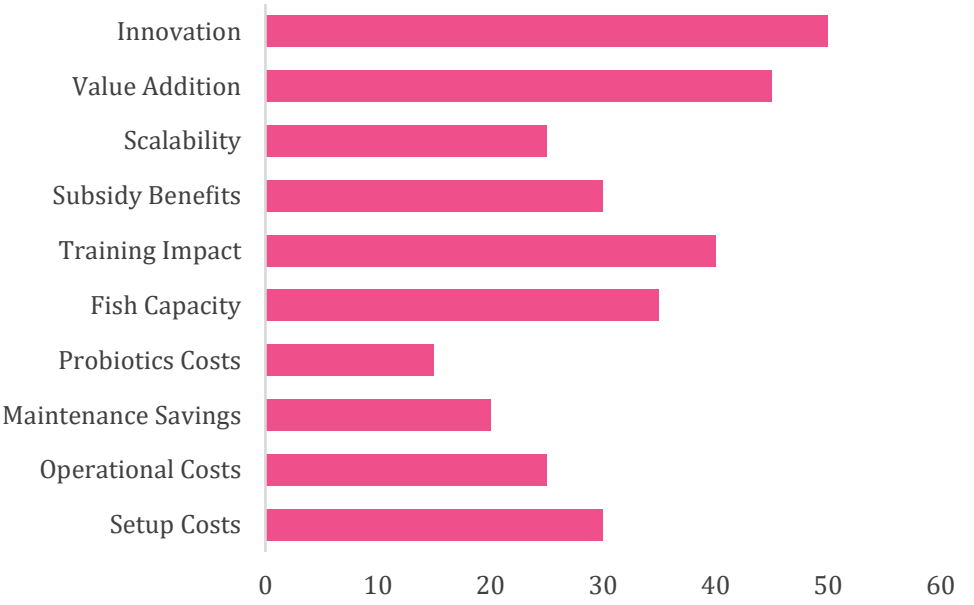
Economic Viability: Themes and Factors

Cost Factors

Setup costs for biofloc and traditional aquaculture vary significantly by setup size and capacity. Higher tank capacities, aeration, and an electrification biofloc system increase fixed costs but reduce operational costs per unit of yield. Running costs are primarily driven by feed, water, and energy expenses. Maintenance costs are minimal in biofloc systems compared to traditional systems. Probiotics and additives are a recurring expense unique to biofloc.

Initial costs for monitoring equipment are similar across systems. Equipment depreciation in the biofloc system impacts long-term profitability. Policies like subsidies can offset initial costs.

Figure 5: Economic Viability: Key Factors and Their Impact



Source: Authors' calculations.

Productivity and Revenue

Fish production capacity correlates directly to tank size and operational efficiency, with larger, well-managed tanks supporting higher outputs. The quality of seed stock significantly influences both survival rates and overall yield, making it a critical factor in aquaculture success. Biofloc systems have higher yields per cubic metre compared to traditional systems. However, the profitability of fish farming is based on market prices, which fluctuate depending on fish quality and species. Continuous monitoring of water quality parameters plays an important role in enhancing productivity and profitability. Use of an automated feeder reduces feed waste and optimises feeding efficiency. High feed conversion ratios directly lead to high profitability. Formal farmer training can help them achieve high revenues by applying learned management techniques. Value-added products, in addition to this, can also increase revenue.

Impact of Formal Training

Formal training plays an important role in increasing the understanding of farmers towards farm monitoring and maintenance of water quality, management of fish disease & mortality, feed optimisation, sustainable use of resources and adoption of innovative practices. Hands-on training not only improves their personal skills but also their knowledge about the precise use of probiotics and additives, and increases the operational efficiency of farms. Formal training provides a big platform for farmers from diverse areas to share their practical knowledge, expertise, market trends and new technologies. In conclusion, long-term success in aquaculture is strongly supported by continuous learning and monitoring, both of which are essential to well-structured training programmes.

Table 4: Impact Weights for Economic Viability

Factor	Impact Weight
Setup costs	30
Operational costs	25
Maintenance savings	20
Probiotics costs	15
Fish capacity	35
Training impact	40
Subsidy benefits	30
Scalability	25
Value addition	45
Innovation	50

Source: Authors' calculations.

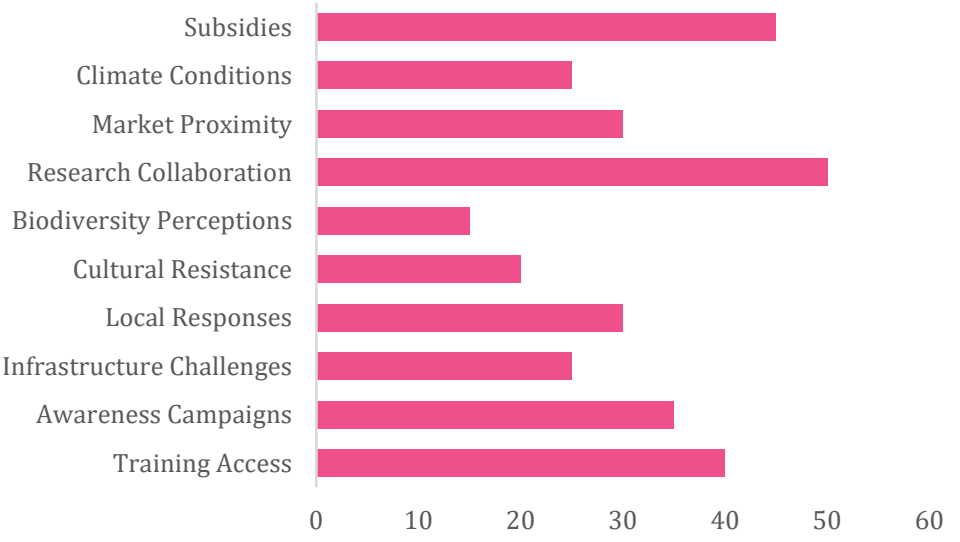
Factors Influencing Adoption: Themes and Factors

Knowledge and Awareness

A lack of formal training appears as a major obstacle to adopting biofloc technology, especially among those farmers who belong to rural areas. Farmers struggle to acquire technical knowledge of daily farm management (feed, water quality) due to a lack of formal training, poor internet access and limited digital skills. Insufficient knowledge about government subsidies lowers investment in biofloc systems.

In rural locations, community networks and change-averse culture have a greater impact on the adoption of biofloc technology. Misconceptions communicated through peers regarding the complexity of Biofloc hinder its adoption. Success on the neighbouring farms can be used for demonstration to highlight the effectiveness of biofloc.

Figure 6: Factors Influencing Adoption: Key Challenges and Enablers



Source: Authors' calculations.

Infrastructure and Regional Challenges

High electricity bills are another major challenge for aquaculture operations in rural areas, where power supply is often not reliable. Unstable electric power supply in rural settings can slow down the efficiency of the aeration system, which is vital for the success of biofloc farming. In addition to energy concerns, farmers in remote areas frequently face difficulties in tank construction due to limited access to raw materials and skilled people. The availability of high-quality seed stock is also inconsistent across regions, even though they do not know where they can purchase good-quality seed. Furthermore, the lack of water in arid areas negatively impacts the sustainability of biofloc systems, while biodiversity considerations, shaped by geographic and ecological contexts, should be addressed to ensure environmental compatibility. Infrastructure deficiencies, especially those related to tank monitoring and control, further limit operational efficiency.

Proximity to markets contributes significantly to profitability, as transportation costs and post-harvest losses can erode potential gains. Regional disparities in government support also affect the rate of biofloc adoption.

Research Collaboration

Partnerships with universities drive innovation in aquaculture practices, while joint ventures with NGOs can support rural farmers to adopt these innovations. Overall, collaborative platforms improve knowledge-sharing among farmers. Collaborative research improves disease management practices, develops cost-effective probiotics and promotes water quality management techniques. Research on local fish species suitability enhances the adoption of technology. Further long-term sustainability studies on the use of biofloc will help in policy decisions.

Table 5: Impact Weights for Factors Influencing Adoption

Factor	Impact Weight
Training Access	40
Awareness Campaigns	35
Infrastructure Challenges	25
Local Responses	30
Cultural Resistance	20
Biodiversity Perceptions	15
Research Collaboration	50
Market Proximity	30
Climate Conditions	25
Subsidies	45

Source: Authors' calculations.

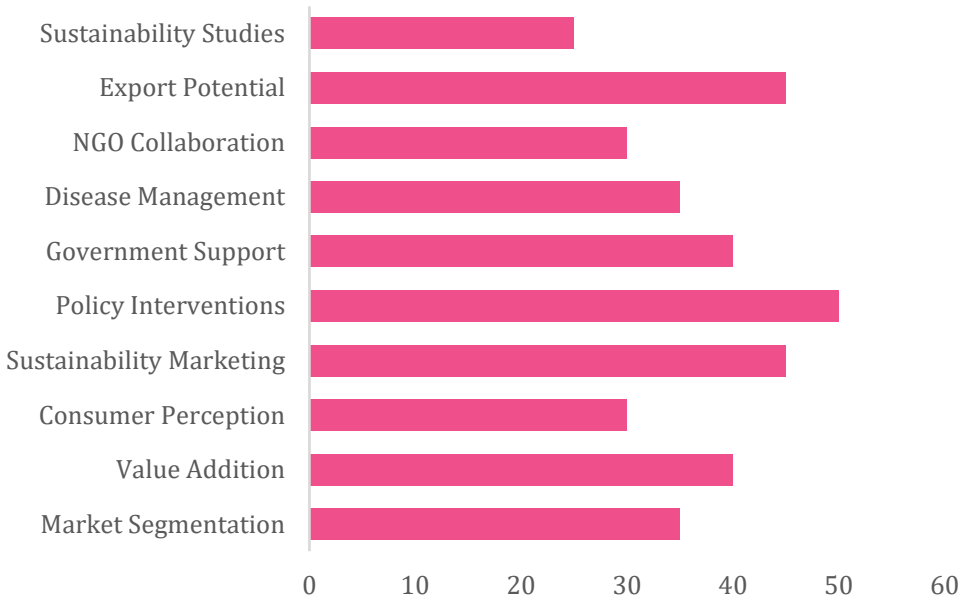
Strategic Recommendations: Themes and Factors

Market and Consumer Insights

Market segmentation for biofloc products increases profitability by targeting specific consumer groups. Value addition (e.g., processed fish) further improves market appeal. Marketing campaigns emphasise biofloc's environmental benefits that develop positive Consumer perceptions of sustainable practices, while awareness campaigns are required to deter the negative perception of consumers about the system and its efficiency.

Partnerships with retail chains boost biofloc products' visibility. Certification programmes for Biofloc farms play a vital role in increasing consumers' trust, while quality assurance practices enhance consumer confidence. These measures not only support domestic market expansion but also unlock export opportunities. Furthermore, the integration of e-commerce platforms has broadened market access, enabling small- and medium-scale producers to directly reach consumers and niche markets.

Figure 7: Strategic Recommendations: Key Areas for Growth



Source: Authors' calculations.

Policy and Sustainability

Subsidies on electricity and tax exemptions for sustainable practices by the government can encourage the biofloc adoption rate. Long-term governmental policies can promote investments in biofloc farming. Sustainability programmes can enhance resource utilisation, while disease management strategies can improve system efficiency.

Research on feed efficiency can enhance the system's profitability, while policies promoting renewable energy reduce operational costs. Government training programmes teach farmers technical skills, increasing adoption rates.

Collaboration with NGOs supports underprivileged farmers. Regional sustainability studies provide data to improve policies and resource distribution, ensuring solutions match local needs.

Table 6: Impact Weights for Strategic Recommendations

Factor	Impact Weight
Market Segmentation	35
Value Addition	40
Consumer Perception	30
Sustainability Marketing	45
Policy Interventions	50
Government Support	40
Disease Management	35
NGO Collaboration	30
Export Potential	45
Sustainability Studies	25

Source: Authors' calculations.

Factors Influencing Biofloc Adoption Success: Thematic Analysis

High-Importance Factors: Key Findings

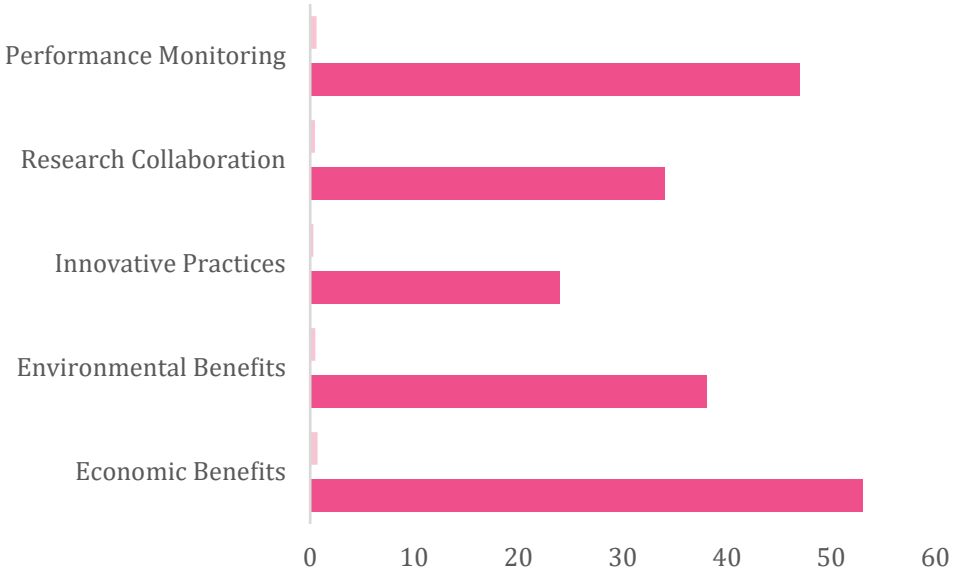
1. Economic benefits (e.g., reduced feed costs, increased profitability)
2. Innovative practices (e.g., photoperiod manipulation, automated feeding systems)
3. Environmental benefits (e.g., reduced water usage, improved water quality)
4. Performance monitoring (e.g., fish growth, water quality)
5. Research collaboration (e.g., partnerships with universities or experts)

Table 7: High Importance Factors

Factor	Frequency	Percentage
Economic Benefits	53	71.6%
Environmental Benefits	38	51.4%
Innovative Practices	24	32.4%
Research Collaboration	34	45.9%
Performance Monitoring	47	63.5%

Source: Authors' calculations.

Figure 8: High-Importance Factors Influencing Biofloc Success



Source: Authors' calculations.

Moderate Importance Factors: Key Findings

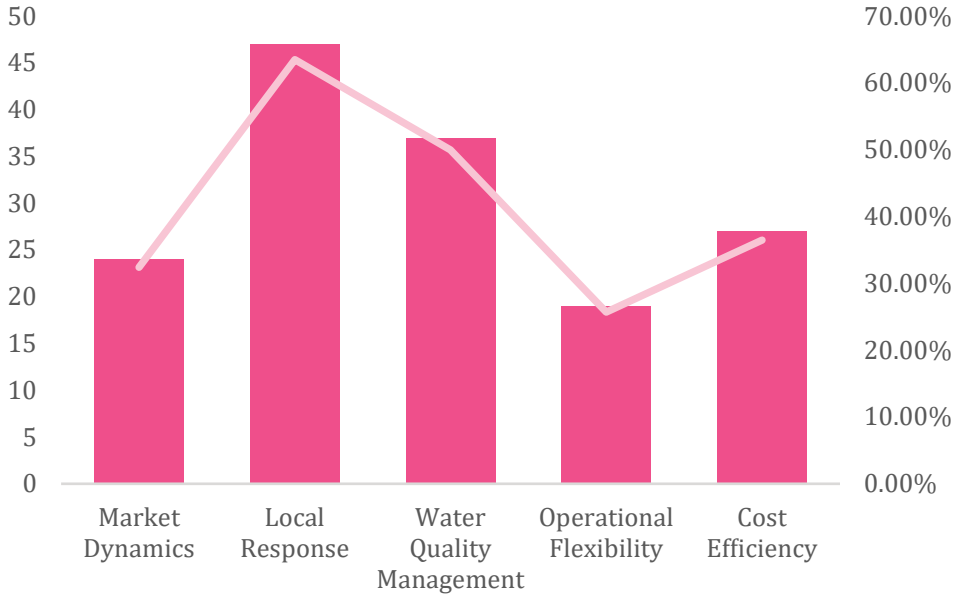
1. Operational flexibility (e.g., ease of adoption processes)
2. Market dynamics (e.g., value addition, collaborations)
3. Water quality management (e.g., satisfied users reporting stability)
4. Local response (e.g., positive feedback, local acceptance)
5. Cost efficiency (e.g., decreasing operational costs)

Table 8: Moderate-Importance Factors

Factor	Frequency	Percentage
Market Dynamics	24	32.4%
Local Response	47	63.5%
Water Quality Management	37	50.0%
Operational Flexibility	19	25.7%
Cost Efficiency	27	36.5%

Source: Authors' calculations.

Figure 9: Moderate-Importance Factors Influencing Biofloc Success



Source: Authors' calculations.

Low-Importance or Emerging Factors: Key Findings

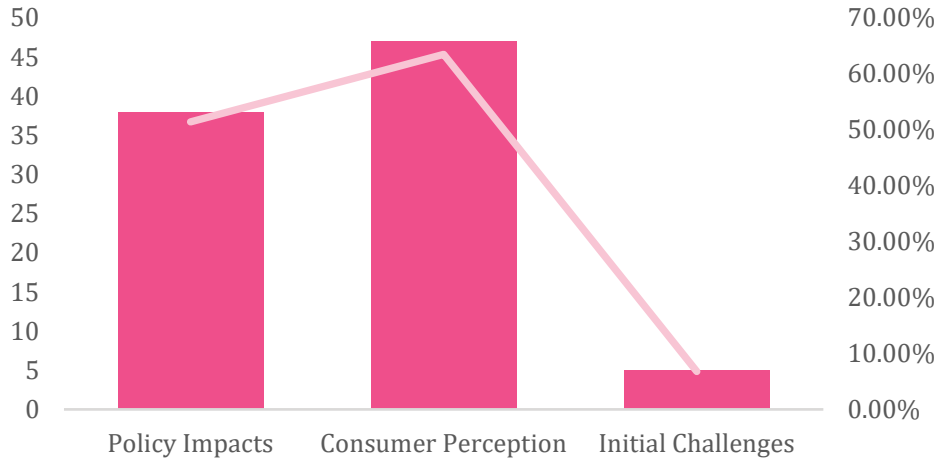
1. Policy impacts (e.g., electricity costs, tax issues)
2. Consumer perception (e.g., varying attitudes toward biofloc products)
3. Initial challenges (e.g., technical hurdles, cost of setup)

Table 9: Low-Importance or Emerging Factors

Factor	Frequency	Percentage
Policy Impacts	38	51.4%
Consumer Perception	47	63.5%
Initial Challenges	5	6.8%

Source: Authors' calculations.

Figure 10: Low-Importance Factors Influencing Biofloc Success



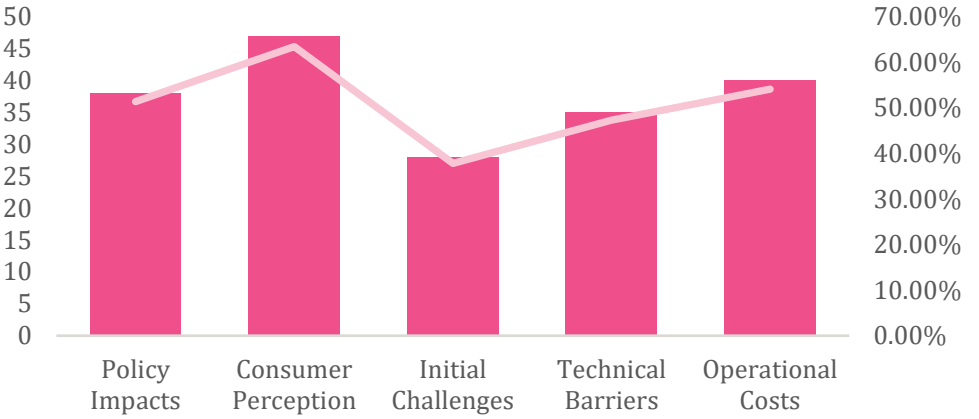
Source: Authors' calculations.

Challenges Influencing Biofloc Adoption: Thematic Analysis

High-Importance Challenges: Key Findings

1. Policy impacts: Issues like electricity costs and taxation were frequently mentioned.
2. Consumer perception: Mixed or negative consumer attitudes present a significant hurdle.
3. Initial challenges: Start-up complexities such as training gaps and high costs.
4. Technical barriers: Problems with technical adoption and operational inefficiencies.
5. Operational costs: Rising costs in setup and maintenance impact adoption rates.

Figure 11: High-Importance Challenges Influencing Biofloc Adoption



Source: Authors' calculations.

Table 10: High-Importance Challenges

Factor	Frequency	Percentage
Policy Impacts	38	51.4%
Consumer Perception	47	63.5%
Initial Challenges	28	37.8%
Technical Barriers	35	47.3%
Operational Costs	40	54.1%

Source: Authors' calculations.

Moderate Importance Challenges: Key Findings

1. Local resistance: Biofloc Farmers faced hesitation/opposition from local communities. This reluctance slowed adoption in certain areas.

2. Infrastructure gaps: The limited availability of infrastructure, such as aerators, probiotics, and IoTs to support adoption, is an important obstacle.

3. Lack of formal training: Lack of training for biofloc farmers and stakeholders.

4. Lack of awareness of regulatory policies: lack of awareness about tax benefits, licensing, and food safety regulations, hindered investment in Biofloc systems.

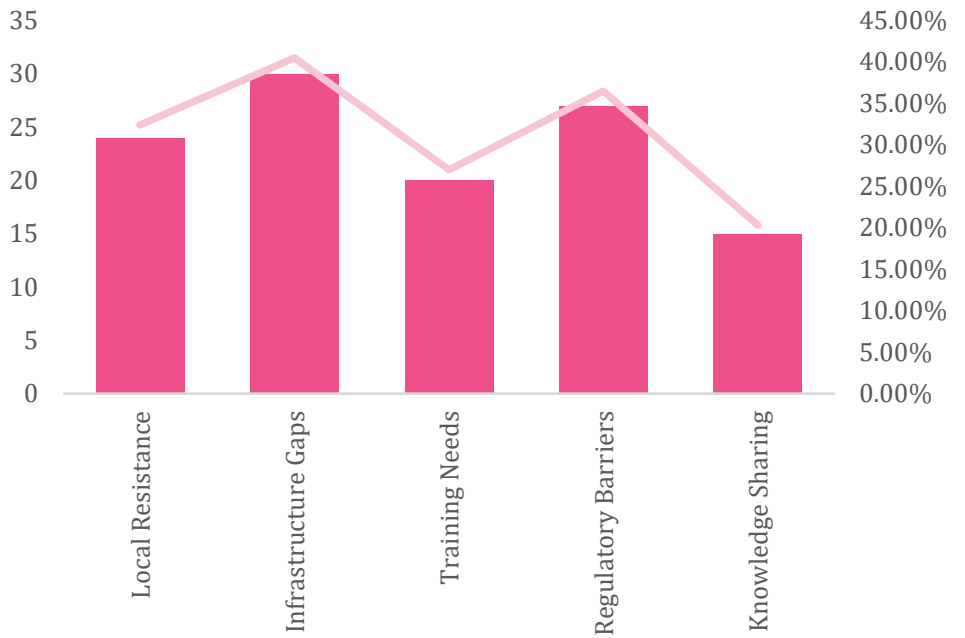
5. Exchange of information among biofloc setup holders: Limited dissemination of best practices.

Table 11: Moderate Importance Challenges

Factor	Frequency	Percentage
Local Resistance	24	32.4%
Infrastructure Gaps	30	40.5%
Training Needs	20	27.0%
Regulatory Barriers	27	36.5%
Knowledge Sharing	15	20.3%

Source: Authors' calculations.

Figure 12: Moderate Importance Challenges Influencing Biofloc Adoption



Source: Authors' calculations.

Low-Importance or Emerging Challenges: Key Findings

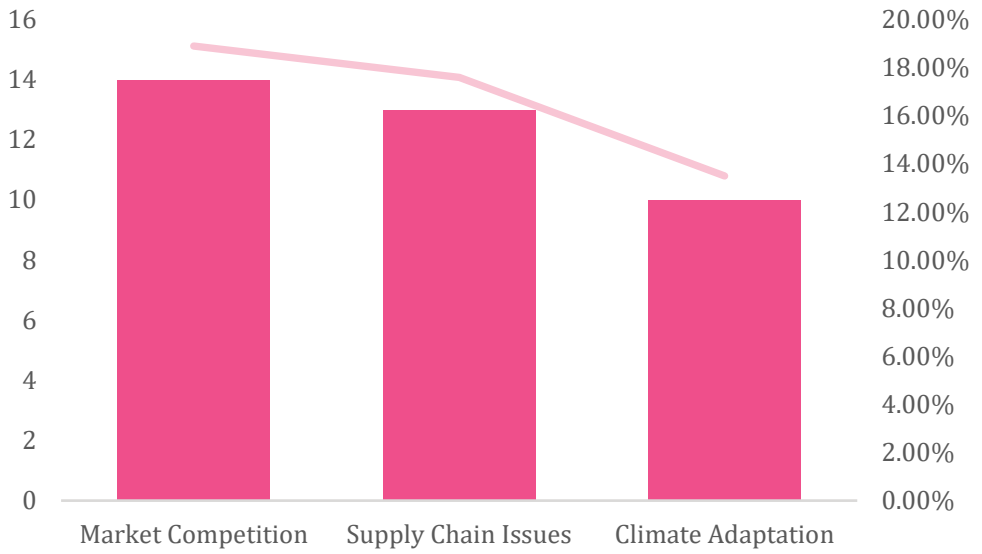
1. Market competition for alternatives to biofloc: Pressure from competitors adopting alternative technologies.
2. Supply chain issues: Difficulty in accessing reliable inputs.
3. Climatic issues: Local and regional climatic changes affect the biofloc's efficiency

Table 12: Low-Importance or Emerging Challenges

Factor	Frequency	Percentage
Market Competition	14	18.9%
Supply Chain Issues	13	17.6%
Climate Adaptation	10	13.5%

Source: Authors' calculations.

Figure 13: Low-Importance Challenges Influencing Biofloc Adoption



Source: Authors' calculations.

Economic Analysis of Traditional Pond System (1 Acre) and Biofloc Tank System (4 Tanks/Acre)

There are notable distinctions in infrastructure and working needs between BFT and traditional aquaculture when comparing fixed and operating costs (Table 13). Although BFT has higher initial fixed costs (PKR 1,750,000) as compared to traditional aquaculture setups (PKR 12,000,000). It also requires specialised equipment such as aerators (PKR 100,000) and PVC pipe fittings (PKR 80,000) for efficient oxygen and water management, but per-crop running costs of BFT (PKR 60,000) are significantly lower compared to those of traditional aquaculture, which uses probiotics and efficient feed conversion ratios. Traditional aquaculture's running costs are significantly higher (PKR 175,000) because of larger water and feed requirements. BFT offers long-term

benefits despite a higher initial setup investment, including lower running costs, reduced use of land, feed, and labour, and better control over water quality parameters, making it a more efficient and sustainable substitute to Traditional Aquaculture.

Table 13: Fixed Capital Costs

Sr. No.	Component	Traditional Aquaculture (PKR)	Biofloc Technology (PKR) 4 tanks/acre
1.	Set up of tanks/ponds	250,000	520,000/acre
2.	Shed material	No Need	40,000
3.	Water supply (borewell)	250,000	100,000
4.	PVC pipe fittings	0	80,000
5.	Nets and accessories	50,000	10,000
6.	Blower, air stones, aeration equipment	No Need	100,000
7.	Electrification	5,000,000	200,000
8.	Power generator	No Need	100,000
9.	Monitoring equipment (weighing scale, pH meter, DO meter)	500,000	500,000
10.	Miscellaneous expenses	100,000	100,000
Total fixed cost		1,200,000	1,750,000
Input cost for one crop (running cost)			
Seed cost, feed cost, probiotics, test kits, etc.		175,000	66,000
Total cost		1,375,000	1,816,000

Source: Bismillah Biofloc, Afnan Farms, Saeed Farms, and Chattha Farms

Comparative analysis of operational costs for BFT and traditional aquaculture reveals notable differences in operating expenses, providing insight into the latter's effectiveness and cost-effectiveness. One key distinction is the cost of feed, with traditional aquaculture requiring much greater expenditures (between PKR 40,000 and PKR 80,000 for each crop) (Table 14). Low effectiveness in feed conversion ratios is one of the marked differences that make the traditional aquaculture inferior to BFT. As a result of its optimised nutrient usage and decreased waste, BFT, on the other hand, can maintain feed costs at an exceptionally low level, at only PKR 14,000 to PKR 17,000 per crop. However, compared to traditional aquaculture (PKR 10,000), biofloc systems have higher seed prices (PKR 30,000). The use of better seed stock or greater amounts required to reach the required stocking densities in biofloc systems is the reason behind this. Despite this discrepancy, the advantages of better

fish health and increased survival rates frequently outweigh the extra cost of seeds. With yearly costs of only PKR 12,000, much less than the PKR 55,000 needed for traditional aquaculture, water costs further highlight the effectiveness of BFT. This sharp contrast results from the smaller water quantities used in biofloc systems, where microbiological activities guarantee a constantly stable water quality. Furthermore, traditional aquaculture has ongoing expenses for carbon sources and probiotics.

Another area of differentiation is maintenance costs. Because of its creative design and low infrastructure wear, BFT completely eliminates the maintenance costs associated with traditional aquaculture, which require an additional PKR 25,000 for every crop. Due to the labour-intensive nature of pond care, traditional aquaculture charges PKR 20,000 per acre, while biofloc systems, which rely on automated processes and simplified operations, only cost PKR 5,000 per acre. The cost of the monitoring equipment is the sole operational expense equivalent, staying at PKR 25,000 for both systems. In contrast to BFT, which requires PKR 66,000, traditional aquaculture's entire operating costs, when added up, exceed PKR 175,000 for each crop.

Table 14: Running Cost

Sr. No.	Particulars	Traditional Aquaculture (PKR)	Biofloc Technology (PKR)
1	Feed costs	40,000-80,000	14,000-17,000
2	Seed (PKR10)	10,000	30,000
3	Water cost	55,000/year	10,000/year
4	Probiotics and carbon sources	-	2,500/crop
5	Maintenance costs	25,000	2,000
6	Labor costs	20,000/acre	5,000/acre
7	Monitoring equipment usage	25,000	25,000
Total running costs		175,000	66,000

Source: Authors' calculations.

Both noteworthy and indicative of their divergent operating efficiencies are the differences in fish productivity and revenue creation between BFT and traditional aquaculture. In traditional aquaculture, there are only two to five fish per cubic meter, or roughly 1,000 fish overall, which is a rather low stocking density. The poor yield of 0.5 kilograms per cubic meter, which is the result of this limited capacity, leads to a yearly production of 1,000 kilograms of fish. On the other hand, BFT uses its sophisticated system design to support 3,000 fish at a significantly greater stocking density of 25–40 fish per cubic meter (Table 15).

Due to their improved quality and increased market demand, fish raised in these systems fetch a premium price of PKR 400–700 per kilogram, further favouring BFT in the market dynamics. On the other hand, fish from traditional aquaculture sell for between PKR 300 and 550 per kilogram, which suggests a quality discrepancy that reduces potential earnings.

Gross revenue is drastically different as a result of this disparity in pricing and production. The gross earnings from traditional aquaculture range from PKR 300,000 to PKR 550,000 per year. Comparatively speaking, BFT generates a substantially larger gross revenue range of PKR 1,200,000–2,100,000, demonstrating its capacity to optimise profits through better product quality and effective resource usage. Feed costs serve as another example of how the two systems differ in terms of economic efficiency. Due to less effective feed conversion ratios, traditional aquaculture incurs feed expenditures of about PKR 80,000 per year. However, BFT significantly lowers these costs to just PKR 17,000. This decrease guarantees that biofloc systems are significantly more economical when paired with increased yields. Traditional Aquaculture's net revenue is limited to PKR 220,000–470,000 annually, whereas Biofloc Technology delivers a remarkable net revenue range of PKR 1,183,000–2,083,000. This substantial financial advantage underscores the value of BFT as a transformative approach to aquaculture.

Table 15: Yield of Fish

Sr. No.	Parameter	Traditional Aquaculture (PKR)	Biofloc Technology (PKR)
1.	Stocking density (fish/m^3)/number of fish	2-5/m3/1,000 fishes	25-40 /m3/3,000
2.	Yield per m^3 (kg)	0.5 kg/m3/1 ton	20kg/m3
3.	Annual yield (kg)	1,000 kg	3,000kg
4.	Sale price per kg (PKR)	300-550/kg	400-700/kg
5.	Gross revenue (PKR)	300,000-550,000	1,200,000-2,100,000
6.	Feed cost (PKR)	80,000	17,000
7.	Net revenue (PKR)	220,000-470,000	1,183,000-2,083,000

Source: Authors' calculations.

The economic feasibility analysis reveals that BFT is significantly more profitable and sustainable than traditional aquaculture after two production cycles. Although BFT requires a higher initial capital investment of PKR 1,750,000 compared to traditional aquaculture's PKR 1,200,000, it benefits from much lower running costs of PKR 66,000 per crop compared to PKR 175,000 for traditional aquaculture. As a result, the total cost for biofloc (PKR 1,816,000) remains manageable, especially when contrasted with its higher gross income of PKR 1,200,000–2,100,000 per crop, far exceeding traditional aquaculture's gross income of PKR 300,000–550,000 per crop. At the end of one crop, after deducting the recurring costs for the second crop, biofloc generates a gross income of PKR 1,134,000–2,034,000 compared to traditional aquaculture's PKR 125,000–375,000. By the end of two crops, biofloc accumulates a gross income of PKR 2,334,000–4,134,000, compared to traditional aquaculture's PKR 425,000–925,000. Its operational efficiency ensures a recurring cost of only PKR 66,000 per crop, compared to PKR 175,000 for traditional aquaculture. Ultimately, after two crops, traditional aquaculture gets a net profit of approximately PKR 250000-750000 while BFT achieves a net profit of PKR 2,268,000–4,068,000, highlighting its superior economic feasibility and profitability (Table 16).

Table 16: Economic Feasibility

	Components	Traditional Pond	Biofloc
1	Capital cost	1,200,000	1,750,000
2	Running cost	175,000	66,000
3	Total cost	1,375,000	1,816,000
4	Gross income per crop	300,000-550,000	1,200,000-2,100,000
5	Gross income at the end of one crop, after deducting the recurring cost for the 2nd crop	125,000-375,000	1,134,000-2,034,000
6	Gross income from the 2nd crop	300,000-550,000	1200000-2100000
7	Gross income at the end of the 2nd crop	425,000-925,000	2,334,000-4,134,000
8	Recurring cost for the next crop	175,000	66,000
9	Net profit at the end of the 2nd crop	250,000-750,000	2,268,000-4,068,000

Source: Authors' calculations.

Initial Cost of Biofloc and Pond Aquaculture System

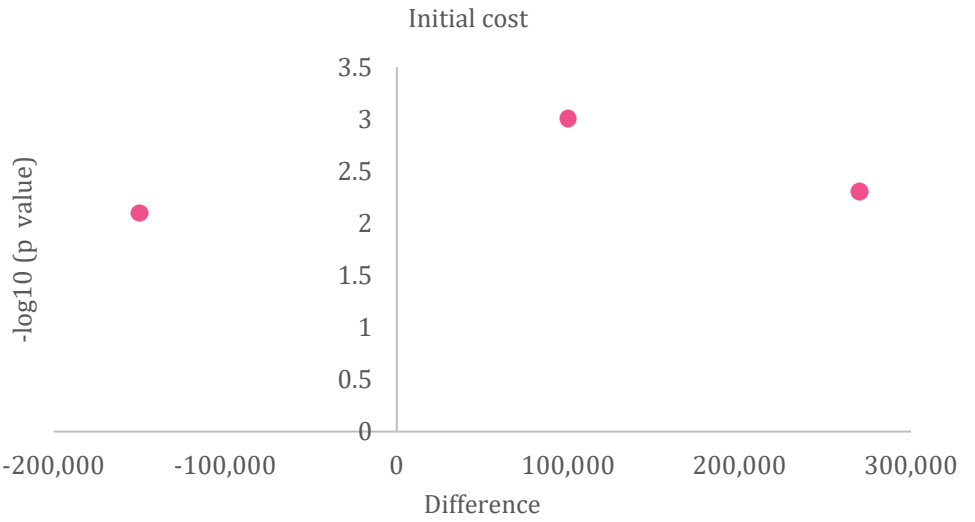
The paired t-test analysis compared the costs of biofloc and traditional pond aquaculture systems in Pakistani Rupees, highlighting significant differences across various cost components. For the initial cost (Table 17 and Figure 15), constructing a tank for the biofloc system averages PKR 520,000, which is substantially higher than the PKR 250,000 required for a pond in the traditional system, with a significant difference of PKR 270,000. This indicates that traditional systems are more cost-efficient in terms of infrastructure setup. However, the water supply system for traditional ponds costs PKR 250,000, significantly exceeding the PKR 100,000 required for the biofloc system, resulting in a notable saving of PKR 150,000 in favour of biofloc. Similarly, water aeration equipment, unique to the biofloc system, requires an investment of PKR 100,000, whereas traditional systems incur no such expense. This additional cost for biofloc, though significant, highlights its need for advanced water management.

Table 17: Comparison of the Initial Cost for Biofloc and Traditional Pond Aquaculture Systems

Factors	p-value	Mean of Biofloc System	Mean of the Tradition-al Pond System	Difference	SE of difference	t ratio	df
Tank (80,000 litre size) pond (1 acre) construction	0.005	520,000	250,000	270,000	1,977.14450	136.567	28.000
Water supply	0.008	100,000	250,000	-150,000	3.17490	-47245.559	28.000
Water aeration equipment	0.001	100,000	0.000	100,000	1,046.79626	95.652	28.000

Source: Authors' calculations.

Figure 14: Volcano Graph Showing the Initial Cost Analysis for the Biofloc and Traditional Pond Aquaculture



Source: Authors' calculations.

Operational Cost of Biofloc and Pond Aquaculture System

Operational cost results are given in Table 18 and Figure 16. Results show a different trend. Feed costs in biofloc systems average PKR 17,000, significantly lower than the PKR 80,000 required in traditional systems, showing savings of PKR 63,000 and reflecting better feed efficiency in biofloc. Both systems have identical costs for monitoring equipment usage at PKR 25,000, showing no difference in this aspect. However, water costs are markedly lower in biofloc systems at PKR 10,000 compared to PKR 55,000 for traditional systems, saving PKR 40,000. Probiotics and additives, unique to biofloc systems, cost PKR 2,500, which is an additional expense not incurred on traditional systems but necessary for maintaining water quality in biofloc setups. Finally, labour costs in traditional systems are significantly higher at PKR 20,000 compared to PKR 5,000 in biofloc systems, offering a saving of PKR 15,000.

Overall, the analysis shows that while biofloc systems demand higher initial investments, particularly for water filtration and tank construction, they significantly reduce operational costs, including feed, labour, and maintenance. Traditional systems are less expensive to establish but incur higher ongoing expenses, making biofloc systems potentially more economical in the long term despite the additional initial costs. The results

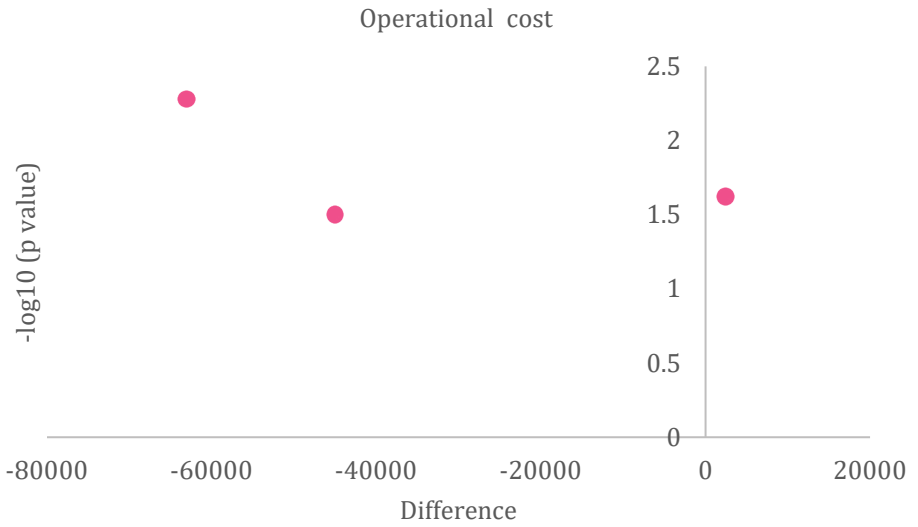
underline the trade-offs between these systems, with biofloc offering advanced technology and efficiency at a premium, whereas traditional systems provide a simpler, more cost-effective entry point with higher recurring costs.

Table 18: Comparison of the Operational Cost for Biofloc and Traditional Pond Aquaculture Systems

Factors	p-value	Mean of Biofloc System	Mean of the Traditional Pond System	Difference	SE of difference	t ratio	df
Feed cost	0.005212	17,000	80,000	-63000	60.14439	-1,048.991	28.000
Solar system installation		25,000	25,000	0.000	0.000		
Water cost	0.031279	10,000	55,000	-45000	20.91	-2,150.839	28.000
Probiotics and additives	0.023704	2,500	0.000	2500	4.24	588.63	28.000
Labour		5,000	20,000	-15000	4.98	-3,012.121	28

Source: Authors' calculations.

Figure 15: Volcano Graph Showing the Operational Cost Analysis for the Biofloc and Traditional Pond Aquaculture



Source: Authors' calculations.

Emergy Synthesis

The emergy synthesis of a system includes determining the research boundaries, organisation of input and output data, determining the emergy baseline, calculating the emergy flow and the emergy indicators. Sustainable ecological performance of any system can be measured through emergy indicators (ELR, EYR, SI).

Table 19: Comparative Emergy Analysis for Traditional Aquaculture and Biofloc System

System	Fixed Costs (PKR)	Running Costs (PKR)	Total Cost (PKR)	Fish Yield (kg)	Emergy Input (seJ)	Emergy Output (seJ)	EYR	ELR (Assumed)	SI
Traditional Aquaculture	1,200,000	175,000	1,375,000	1,000	6.875E+12	3,500,000,000	0.000509091	2.5	0.000203636
Biofloc Technology	1,750,000	66,000	1,816,000	3,000	9.08E+12	10,500,000,000	0.001156388	1.5	0.000770925

Source: Authors' calculations.

Efficiency, sustainability, and environmental impact all differ significantly between Biofloc Technology and Traditional Aquaculture, according to the emergy study. Traditional aquaculture yields 1,000 kilograms of fish a year, with fixed expenses of PKR 1,200,000 and operating costs of PKR 175,000. This results in an environmental loading ratio (ELR) of 2.5, a Sustainability Index (SI) of 0.000204, and an emergy yield ratio (EYR) of 0.000509. On the other hand, Biofloc Technology achieves a significantly larger production of 3,000 kilograms per year with running expenses of only PKR 66,000, although having higher fixed costs of PKR 1,750,000. With a more favourable EYR of 0.001156, an ELR of 1.5, and a SI of 0.000771, this system stands out for its increased sustainability, less dependency on non-renewable resources, and increased efficiency.

5. CONCLUSION

A ground-breaking answer to the problems facing conventional aquaculture is BFT. It is a revolutionary method for sustainable food production because of its capacity to increase output, preserve land and water resources, and produce significant financial rewards. According to this study, biofloc systems have a number of benefits over traditional techniques, such as up to three times greater production and a 60% lower operating cost. Additionally, biofloc's advantages for the environment—such as lower effluent discharge and effective resource use—make it a major force behind sustainable aquaculture.

Numerous obstacles hinder the widespread use of BFT, despite its potential. Significant obstacles include high upfront investment costs, a lack of technical know-how, constrictive legislative frameworks, and inadequate training availability. These difficulties show that in order to promote and expand the usage of biofloc systems, targeted measures are required. By resolving these problems, aquaculture businesses will be able to make full use of this cutting-edge technology, promoting both economic expansion and sustainable development. This study emphasises how crucial it is for researchers, industry stakeholders, and legislators to work together to remove current obstacles. Collaboration and biofloc system investments can help the aquaculture industry shift to more profitable, efficient, and sustainable methods.

6. POLICY RECOMMENDATIONS

1. Financial Support:

- Subsidies and grants should be introduced for biofloc farmers, particularly for small-scale farmers, to reduce the financial burden of capital costs at the beginning of a biofloc setup.
- Offer financing alternatives or low-interest loans specifically designed for small and medium-sized farms.
- To promote sustainable practices, provide tax incentives to farmers and businesses who implement biofloc systems.

2. Capacity Building:

- Hands-on training related to technical aspects of biofloc setup, including feed optimisation, disease management and water quality management, should be introduced at the district level, particularly in rural settings.
- Create certification programmes to verify farmers' proficiency in biofloc operations and boost consumer confidence.
- Establish demonstration farms to promote broader use and highlight the useful advantages of biofloc systems.

3. Infrastructure Development:

- Transport facilities and fish markets linked roads in rural areas should be constructed to enhance the market access of biofloc-raised products.
- Availability of disease-free, good-quality fish seed, fish feed, and probiotics must be ensured near biofloc setups.

4. Regulatory Reforms:

- Develop region-specific guidelines to address local challenges, such as water availability and climate conditions.
- Simplify regulatory procedures to make it easier for farmers to comply with environmental and operational requirements.
- Renewable energy technologies should be promoted through supportive policies and incentives.

5. Market Development:

- Awareness about the ecological and health benefits of biofloc raised fish among fish consumers through social media, news channels, and local seminars can be launched.
- Eco-labelling and certification programmes should be launched to improve marketability and consumer trust in biofloc products.

6. Research and Collaboration:

- Collaboration between academia, industry and government needs to be strengthened in order to address technical issues in biofloc systems.
- Longitudinal studies are required on the scalability and sustainability of biofloc setups under varying environmental and geographical conditions.

7. Public-Private Partnerships:

- Collaborate with non-governmental organisations to provide technical support and resources for disadvantaged farmers.
- Foster joint ventures between government bodies and private organisations to fund and promote biofloc acceptance.

These recommendations aim to discuss the economic, technical, and controlling barriers hindering the adoption of biofloc know-how.

REFERENCES

Aguilera-Rivera, D., Escalante-Herrera, K., Gaxiola, G., Prieto-Davó, A., Rodríguez-Fuentes, G., Guerra-Castro, E., ... & Rodríguez-Canul, R. (2019). Immune response of the Pacific white shrimp, Litopenaeus vannamei, previously reared in biofloc and after an infection assay with Vibrio harveyi. *Journal of the World Aquaculture Society, 50*(1), 119-136.

Ahmad, M. & Farooq, U., 2010. The state of food security in Pakistan: Future challenges and coping strategies. *The Pakistan Development Review, 49*(4), 903-923..

Anand, P. S., Kohli, M. P. S., Kumar, S., Sundaray, J. K., Roy, S. D., Venkateshwarlu, G., ... & Pailan, G. H. (2014). Effect of dietary supplementation of biofloc on growth performance and digestive enzyme activities in Penaeus monodon. *Aquaculture, 418,* 108-115.

Arifin, H. (2024). Application of biofloc technology as an environmentally friendly solution to increase the productivity of freshwater fish cultivation. *International Journal of Social and Human, 1*(2), 88–96.

Avnimelech, Y., 1999. Carbon/nitrogen ratio as a control element in aquaculture systems. *Aquaculture, 176*(3-4), pp.227-235.

Avnimelech, Y., 2009. Biofloc technology: A practical guide book. World Aquaculture Society.

Browdy, C. L., Bratvold, D., Stokes, A. D., & McIntosh, R. P. (2001). Perspectives on the application of closed shrimp culture systems. In *The New Wave, Proceedings of the Special Session on Sustainable Shrimp Culture, Aquaculture 2001* (pp. 20-34). The World Aquaculture Society, Baton Rouge, USA.

Cardona, E., Saulnier, D., Lorgeoux, B., Chim, L., & Gueguen, Y. (2015). Rearing effect of biofloc on antioxidant and antimicrobial transcriptional response in Litopenaeus stylirostris shrimp facing an experimental sub-lethal hydrogen peroxide stress. *Fish & Shellfish Immunology, 45*(2), 933-939.

Crab, R., Defoirdt, T., Bossier, P., & Verstraete, W. (2012). Biofloc technology in aquaculture: Beneficial effects and future challenges. *Aquaculture, 356,* 351-356.

da Silva, K. R., Wasielesky Jr, W., & Abreu, P. C. (2013). Nitrogen and phosphorus dynamics in the biofloc production of the Pacific white shrimp, Litopenaeus vannamei. *Journal of the World Aquaculture Society, 44*(1), 30-41.

Das, B. K., Meena, D. K., Das, A., & Sahoo, A. K. (2022). Prospects of smart aquaculture in the Indian Scenario: A new horizon in the management of aquaculture production potential. In *Smart and Sustainable Food Technologies* (pp. 59-85). Singapore: Springer Nature Singapore.

de Schryver, P., & Verstraete, W. (2009). Nitrogen removal from aquaculture pond water by heterotrophic nitrogen assimilation in lab-scale sequencing batch reactors. *Bioresource Technology, 100*(3), 1162-1167.

De Schryver, P., Crab, R., Defoirdt, T., Boon, N., & Verstraete, W. (2008). The basics of bio-flocs technology: the added value for aquaculture. *Aquaculture, 277*(3-4), 125-137.

Deswati, D., Yani, E., Safni, S., Norita Tetra, O., & Pardi, H. (2022). Development methods in aquaponics systems using biofloc to improve water quality (ammonia, nitrite, nitrate) and growth of tilapia and samhong mustard. *International Journal of Environmental Analytical Chemistry, 102*(19), 7824-7834.

Duan, Y., Zhang, Y., Dong, H., Wang, Y., & Zhang, J. (2017). Effect of the dietary probiotic Clostridium butyricum on growth, intestine antioxidant capacity and resistance to high temperature stress in kuruma shrimp Marsupenaeus japonicus. *Journal of Thermal Biology, 66,* 93-100.

Emerenciano, M., Cuzon, G., Goguenheim, J., Gaxiola, G., & Aquacop. (2012). Floc contribution on spawning performance of blue shrimp Litopenaeus stylirostris. *Aquaculture Research, 44*(1), 75-85.

Emerenciano, M., Gaxiola, G., & Cuzon, G. (2013). Biofloc technology (BFT): A review for aquaculture application and animal food industry. *Biomass Now-cultivation and Utilization, 12,* 301-328.

FAO (Food and Agriculture Organization of the United Nations). 2016. *The state of world fisheries and aquaculture 2016: Contributing to food security and nutrition for all.* Rome.

FAO (Food and Agriculture Organization of the United Nations). 2020. The state of world fisheries and aquaculture 2020: Sustainability in action. Rome.

FAO (Food and Agriculture Organization of the United Nations). 2022. *Blue transformation - Roadmap 2022–2030: A vision for FAO's work on aquatic food systems.* Rome.

FAO (Food and Agriculture Organization of the United Nations). 2024. FishStat: Global aquaculture production 1950-2022. www.fao.org/fishery/en/statistics/software/fishstat

Fasolin, L. H., Pereira, R. N., Pinheiro, A. C., Martins, J. T., Andrade, C. C. P., Ramos, O. L., & Vicente, A. A. (2019). Emergent food proteins–Towards sustainability, health and innovation. *Food Research International, 125,* 108586.

GOI (Government of India). 2023. *Handbook on fisheries statistics 2023.* Department of Fisheries, Government of India, New Delhi.

GOP (Government of Pakistan). 2024. Agriculture Statistics. Pakistan Bureau of Statistics. https://www.pbs.gov.pk/agriculture-statistics/

Habib, S. S., Batool, A. I., Rehman, M. F. U., & Naz, S. (2022). Comparative analysis of the haemato-biochemical parameters and growth characteristics of Oreochromis niloticus (Nile tilapia) cultured under different feed and habitats (biofloc technology and earthen pond system). *Aquaculture Research, 53*(17), 6184-6192.

Habib, S. S., Batool, A. I., Rehman, M. F. U., & Naz, S. (2023). Assessment and bioaccumulation of heavy metals in fish feeds, water, and some tissues of Cyprinus carpio cultured in different environments (Biofloc Technology and Earthen Pond System). *Biological Trace Element Research, 201*(7), 3474-3486.

Hossam, R., Heakl, A., & Gomaa, W. (2024). Precision aquaculture: An integrated computer vision and IoT approach for optimized tilapia feeding. *arXiv preprint arXiv:2409.08695.*

Jarwar, A. A. (2008). A status overview of fisheries and aquaculture development in Pakistan with context to other Asian countries. *Aquaculture Asia, 13*(2), 13-18.

Jatobá, A., & Lehmann, M. (2021). Blackout in the biofloc caused fish mortality by ammonia. *Revista de Agroecologia no Semiárido, 5*(4), 09-13.

Javed, M., & Abbas, K. (2018). Inland fisheries and aquaculture in Pakistan. In I. A. Khan & M. S. Khan (Eds.), *Developing sustainable agriculture in Pakistan* (pp. 543-559). CRC Press.

Kausar, R. (2017). Best management practices in aquaculture in Pakistan. *Best Management Practices in Aquaculture, 69.*

Khanjani, M. H., & Sharifinia, M. (2020). Biofloc technology as a promising tool to improve aquaculture production. *Reviews in Aquaculture, 12*(3), 1836-1850.

Khanjani, M. H., Alizadeh, M., & Sharifinia, M. (2020). Rearing of the Pacific white shrimp, Litopenaeus vannamei in a biofloc system: The effects of different food sources and salinity levels. *Aquaculture Nutrition, 26*(2), 328-337.

Khanjani, M. H., Mozanzadeh, M. T., Sharifinia, M., & Emerenciano, M. G. C. (2024). Broodstock and seed production in biofloc technology (BFT): An updated review focused on fish and penaeid shrimp. *Aquaculture, 579,* 740278.

Khanjani, M. H., Sharifinia, M., & Emerenciano, M. G. C. (2023). A detailed look at the impacts of biofloc on immunological and hematological parameters and improving resistance to diseases. *Fish & Shellfish Immunology, 137,* 108796.

Laghari, M. Y. (2018). Aquaculture in Pakistan: Challenges and opportunities. *International Journal of Fisheries and Aquatic Studies, 6*(2), 56-59.

Little, D. C., Newton, R. W., & Beveridge, M. C. M. (2016). Aquaculture: a rapidly growing and significant source of sustainable food? Status, transitions and potential. *Proceedings of the Nutrition Society, 75*(3), 274-286.

Little, D., Barman, B. K., Belton, B., Beveridge, M., Bush, S. J., Dabaddle, L., ... & Sukadi, F. (2012). *Alleviating poverty through aquaculture: progress, opportunities and improvements* [Paper presentation]. Proceedings of the Global Conference on Aquaculture 2010. Phuket, Thailand. 22-25 September 2010. FAO, Rome and NACA, Bangkok

Liu, H., Li, H., Wei, H., Zhu, X., Han, D., Jin, J., ... & Xie, S. (2019). Biofloc formation improves water quality and fish yield in a freshwater pond aquaculture system. *Aquaculture, 506*, 256-269.

Meeran, N. M. (2000). Influence of socio-personal, socio-economic and socio-psychological characteristics on the adoption behaviour of shrimp farmers. *J. Ext. Edu, 11*(2), 2742-46.

Megahed, M. E. (2010). The effect of microbial biofloc on water quality, survival and growth of the green tiger shrimp (Penaeus semisulcatus) fed with different crude protein levels. *Journal of the Arabian Aquaculture Society, 5*(2), 119-142.

Minabi, K., Sourinejad, I., Alizadeh, M., Ghatrami, E. R., & Khanjani, M. H. (2020). Effects of different carbon to nitrogen ratios in the biofloc system on water quality, growth, and body composition of common carp (Cyprinus carpio L.) fingerlings. *Aquaculture International, 28,* 1883-1898.

Mordenti, O., Casalini, A., Mandelli, M., & Di Biase, A. (2014). A closed recirculating aquaculture system for artificial seed production of the European eel (Anguilla anguilla): Technology development for spontaneous spawning and egg incubation. *Aquacultural Engineering, 58,* 88-94.

PakFishOnline. (n.d.). https://pakfishonline.com/

Panigrahi, A., Otta, S. K., Kumaraguru Vasagam, K. P., Shyne Anand, P. S., Biju, I. F., & Aravind, R. (2019). Training manual on Biofloc technology for nursery and grow out aquaculture. *CIBA TM series, 15,* 172.

Rani, P., Thakur, J., & Upadhyay, A. (2017). Partial replacement of protein using microfloc meal for the diet of mrigal, Cirrhinus mrigal fingerlings. *International Journal of Current Microbiology and Applied Sciences, 6*(10), 1524-1529.

Ray, A.J., Seaborn, G., Leffler, J.W., Wilde, S.B., Lawson, A. & Browdy, C.L. (2010) Characterization of microbial communities in minimal-exchange, intensive aquaculture systems and the effects of suspended solids management. *Aquaculture, 310*(1–2), 130–138. https://doi.org/10.1016/j.aquaculture.2010.10.019

Rind, K. H., Habib, S. S., Ujan, J. A., Fazio, F., Naz, S., Batool, A. I., ... & Khan, K. (2023). The effects of different carbon sources on water quality, growth performance, hematology, immune, and antioxidant status in cultured Nile Tilapia with biofloc technology. *Fishes, 8*(10), 512.

Stockhausen, L., Vilvert, M. P., Silva, M., Dartora, A., Lehmann, N. B., & Jatobá, A. (2023). Feed cost reduction with total replacement of fish meal by soybean meal for Nile tilapia reared in biofloc system. *Arquivo Brasileiro de Medicina Veterinaria e Zootecnia, 75*(2), 360-364.

Subasinghe, R., 2017. *World aquaculture 2015: A brief overview.* FAO Fisheries and Aquaculture Circular No. 1140. Rome.

Wasim, M. W. K., & Abbas, G. (2024). Review of fisheries resources and the effect of marine pollution in the coastal waters of Pakistan. *Journal of Zoology and Systematics, 2*(1), 23-43.

Wuyep, S. Z., & Rampedi, I. T. (2018). Urban fish farming in Jos, Nigeria: Contributions towards employment opportunities, income generation, and poverty alleviation for improved livelihoods. *Agriculture, 8*(7), 110.

Xu, W. J., & Pan, L. Q. (2013). Enhancement of immune response and antioxidant status of Litopenaeus vannamei juvenile in biofloc-based culture tanks manipulating the high C/N ratio of feed input. *Aquaculture, 412,* 117-124.

Zimmermann, S., Kiessling, A., & Zhang, J. (2023). The future of intensive tilapia production and the circular bioeconomy without effluents: biofloc technology, recirculation aquaculture systems, bio-RAS, partitioned aquaculture systems and integrated multitrophic aquaculture. *Reviews in Aquaculture, 15,* 22-31.

EVALUATING THE SOCIOECONOMIC IMPACT OF THE HYDERABAD-MIRPURKHAS DUAL CARRIAGEWAY ON REGIONAL DEVELOPMENT UNDER PPP INITIATIVES

Hira Hussain[1] and Ayaz Ali[2]

ABSTRACT

The Hyderabad-Mirpurkhas Dual Carriageway Project (HMDC) is a major infrastructure initiative to improve travel time reduction, fuel efficiency, and consumption, and foster regional economic development in Sindh, Pakistan. This report presents an in-depth analysis of the project's impact on various stakeholders, including travelers/commuters, transporters, including goods and public, small and medium enterprises (SMEs) and businesses, agricultural communities (i.e., landowners, farmers, and tenants), HMDC project employees and local communities. The study findings reveal that the dual carriageway has substantially improved travel efficiency, with respondents experiencing significant reductions in travel times and enhanced fuel efficiency. These improvements have led to notable reductions in transportation costs and increased operational efficiency for commuters. Economic activity has also seen a boost in the region, where a notable increase in new business establishments has been observed. Moreover, the study findings reveal that more than 200 employees were working in the current operation and maintenance phase, including a small number of females working as toll operators in the HMDC. However, despite these positive outcomes, several challenges persist. Respondents expressed concerns over high toll charges and insufficient gender inclusivity in the jobs created by the HMDC project and newly established businesses. It is noteworthy that the overlay of HMDC has been extended for 2-3 years after an inspection, as it was due after 10 years of construction, reflecting the high-quality build of the

[1] Independent Consultant, Hyderabad.

[2] Independent Consultant, Karachi.

HMDC. In addition, the revenue model of the HMDC has been marked successful in achieving the set revenue generation targets. Furthermore, the environmental impacts have been largely positive. However, issues such as traffic congestion during peak hours and an increase in the number of road accidents have been reported. The report recommends several measures to enhance the project's benefits and address the existing challenges. These include reevaluating toll policies to make the charges reasonable, improving road maintenance and safety measures, promoting greater gender inclusivity in business opportunities, and enhancing amenities along the route. Additionally, strengthening environmental measures and addressing traffic management issues are essential for sustaining the dual carriageway's positive impacts. These recommendations aim to ensure continued progress in transportation efficiency and economic development, ultimately contributing to the overall advancement of Sindh.

1. INTRODUCTION

The Hyderabad-Mirpurkhas Dual Carriageway (HMDC) Project is a significant infrastructure initiative aimed at addressing critical transportation challenges and stimulating regional development in Sindh, Pakistan. The project was executed under a Public-Private Partnership (PPP) model and focused on enhancing connectivity, reducing travel time, and creating employment opportunities. It serves as an important case study for evaluating the benefits and challenges of PPPs in large-scale infrastructure development.

This research was driven by the need to assess the socioeconomic impact of the HMDC project on local communities and the region. The study aims to provide a comprehensive understanding of the project's contribution to reducing travel time, improving fuel efficiency, and generating both direct and indirect employment opportunities. Additionally, the research examines the project's impact on land values, agricultural development, and regional economic growth. These insights are crucial for policymakers and decision-makers when considering future infrastructure initiatives.

The research employed a mixed-methods approach, incorporating quantitative surveys, qualitative key informant interviews (KIIs), and focus group discussions (FGDs), including the desk study to gather data from a wide range of stakeholders. These included commuters, transporters, small and medium enterprises (SMEs), local businesses, landowners, farmers, tenants, government officials, and community members. This robust methodology ensured a thorough analysis of the project's socioeconomic impacts and provided valuable insights into the effectiveness of the PPP model in promoting sustainable development outcomes.

The HMDC Project was launched to address the growing transportation needs of the region, with the primary objective of mitigating traffic congestion and providing efficient connectivity between Hyderabad and Mirpurkhas. The project involved the extensive upgrading of a 58.7-kilometre stretch of road in a two-lane highway, which was previously a single road. Through this transformation, the project sought to enhance travel efficiency, improve safety, and provide a better experience for travelers. The initiative was conceived in response to the increasing demand for improved regional infrastructure in Sindh, ultimately enhancing the economic and social well-being of the area.

The HMDC project began its journey in December 2008, adopting the design, build, finance, operate, maintain, and transfer (DBFOT) model within a PPP framework. A pivotal milestone was achieved in November 2009 when the Concession Agreement was executed, leading to the formation of a Special Purpose Vehicle (SPV) and the selection of Deokjae Connecting Roads (Private) Limited as the preferred bidder. The financial structure of the project was supported by a blend of equity, bank loans, and subordinated debt, with significant contributions from both the private partner and the Government of Sindh (GoS).

The HMDC project was expected to bring substantial social benefits, including reduced travel time, enhanced safety, and the creation of 5,000 direct and 22,000 indirect job opportunities. It was also anticipated to have a positive impact on land values, facilitate the development of Sindh's agricultural belt, and provide local communities with new business and employment opportunities. The improvements in regional connectivity were likely to contribute to overall economic growth and improved law and order in the area.

Despite its successes, the HMDC project faced challenges of optimizing outcomes and ensuring equitable benefits for all stakeholders. The study identified certain policy gaps that, if left unaddressed, can undermine the long-term value of infrastructure investments. These gaps and challenges are explored in detail in the study, along with evidence-based recommendations to address them and improve the effectiveness of future infrastructure projects.

This research aims to provide valuable insights into the socioeconomic impacts of the HMDC project, as well as offer lessons for future infrastructure planning and policy formulation in Pakistan. The findings not only highlight the project's successes but also provide recommendations for improving the PPP model and ensuring that large-scale infrastructure projects achieve their full potential in terms of socioeconomic benefits.

2. LITERATURE REVIEW

This section reviews the literature to provide a critical analysis of the existing studies on infrastructure development, particularly focusing on the PPPs. The review explores methodologies, findings, and gaps in research, presenting both positive and negative outcomes to situate this study within the broader academic discourse.

Public-Private Partnerships in Infrastructure Development

The PPPs have emerged as a pivotal mechanism for infrastructure development, offering a collaborative approach between the public and private sectors to enhance the economic value of infrastructure outputs. This model has been extensively applied across various sectors, including transportation, to improve the efficiency and sustainability of infrastructure delivery (Cui et al., 2018). The adoption of the PPPs is driven by the need to leverage the private sector's expertise and resources, thereby facilitating the development of large-scale infrastructure projects that might otherwise be constrained by public sector limitations.

The spatial spillover effects of PPP infrastructure projects are crucial in understanding their comprehensive socioeconomic impact. Several studies have demonstrated that the PPPs in transportation can lead to significant regional economic integration, with positive externalities extending beyond the immediate area of the project (Chen, 2021). This is particularly relevant for projects like the HMDC, which can enhance connectivity and economic interactions across regions, thereby supporting broader regional development goals.

Global Perspectives

PPPs have emerged as an important model for financing and managing large-scale infrastructure projects worldwide. The World Bank's PPP in Infrastructure Resource Center offers extensive resources on best practices, challenges, and success factors associated with PPPs. According to the World Bank, successful PPPs centre on clear contractual frameworks, risk-sharing mechanisms, and a stable regulatory environment (PPRC, World Bank, n.d.).

The economic benefits of PPPs in transportation infrastructure are well-documented. In China, transportation PPP investments have been shown to significantly promote low-carbon economic development, enhancing both

benefits and efficiency (Guo et al., 2022). This is achieved through the spatial spillover effects of PPP projects, which contribute to the economic development of the neighbouring regions. The involvement of state-owned enterprises and large-scale projects further amplifies these positive impacts (Guo et al., 2022). Similarly, the economic growth effects of PPPs have been verified through empirical studies, highlighting their role in promoting regional economic integration and sustainable development (Chen, 2021).

Globally, PPP projects indicate significant improvements in infrastructure quality and efficiency. A study by Grimsey & Lewis (2004) highlighted that PPPs often lead to enhanced project delivery due to the private sector's expertise and innovation. They noted that PPPs can result in better-maintained infrastructure and improved service delivery. Additionally, PPPs have been shown to reduce life-cycle costs as private partners have a vested interest in the project's sustainability.

Industrial Heterogeneity and Economic Benefits

The economic impact of PPP projects varies across different sectors, with transportation infrastructure often yielding the most substantial benefits. Research indicates that transportation PPPs can bring greater economic benefits compared to other sectors, such as energy and water, due to their critical role in facilitating movement and trade (Chen, 2021). This industrial heterogeneity underscores the importance of strategic investment in transportation infrastructure to maximise economic returns and support sustainable regional development.

Challenges and Future Directions in PPP Research

However, challenges persist. Research by Hodge & Greve (2007) discusses complexities in negotiation and the risk of financial difficulties in PPP projects. They found that while PPPs can bring about efficiency gains, they also pose risks related to cost overruns, delays, and contractual disputes. Moreover, public opposition can arise due to the perception of the privatization of public assets, which necessitates transparent and inclusive planning processes (Hodge & Greve, 2007).

Despite the proven benefits of PPPs, there are still challenges and gaps in research that need to be addressed. Current studies highlight the need for more comprehensive evaluations of PPP projects to better understand their long-term socioeconomic impacts and to refine the models for future projects

(Cui et al., 2018). Future research should focus on exploring new methodologies and frameworks to assess the effectiveness of PPPs in different contexts, including the socioeconomic impacts of specific projects like the HMDC dual carriageway.

Pakistan Context

In Pakistan, PPPs have been increasingly adopted as a strategy for infrastructure development, particularly in the transportation sector. Studies have shown that PPPs in Pakistan have the potential to significantly enhance economic growth and regional development. The involvement of private sector expertise and capital in infrastructure projects has led to improved project efficiency and sustainability. However, challenges such as regulatory hurdles and the need for capacity building in public institutions remain (Cui et al., 2018).

PPPs have been pivotal in addressing infrastructure deficits. The Institute of Policy Reforms (IPR) provides insights into local PPP projects, outlining successes and areas needing improvement (IPR). Specific to road infrastructure, the Lahore-Sheikhupura-Faisalabad Dual Carriageway serves as a critical case study. The project has significantly improved regional connectivity and economic growth by reducing travel time and facilitating smoother logistics. It has also spurred industrial growth along its corridor, creating jobs and boosting local economies (NHA, n.d.).

Similarly, the M-2 Motorway project between Lahore and Islamabad underscores the transformative potential of PPPs in enhancing connectivity and economic activities. This project has reduced travel time, improved safety, and contributed to regional economic development by facilitating the movement of goods and people (InfraPPP, 2014; Haider, n.d.).

However, negative findings highlight challenges such as financial mismanagement and project delays. A study on the Karachi-Hyderabad Motorway (M9) revealed issues with toll management and maintenance, leading to public dissatisfaction. This underscores the importance of effective governance and accountability mechanisms in PPP projects.

Socioeconomic Impacts of Infrastructure Projects

Job Creation and Economic Opportunities

Infrastructure projects, particularly road construction, are known catalysts for local economic development. The HMDC project is projected to create thousands of direct and indirect jobs, contributing to regional employment. This aligns with findings from global studies, such as the European Investment Bank (EIB) study, which highlights that improved road networks can lead to significant economic development, reduced travel time, and increased accessibility to markets and services (EIB, 2023).

Another study on the socioeconomic impacts of the M5 Motorway in Hungary found that the project created thousands of jobs and stimulated local economies by improving access to markets and reducing transportation costs (EIB, 2023).

Conversely, negative impacts have been reported in some cases. Road projects can lead to environmental degradation, displacement of communities, and increased pollution. A study by the International Institute for Environment and Development (IIED) emphasizes the need for comprehensive environmental impact assessments to mitigate these negative effects (IIED, n.d.).

Infrastructure projects, particularly those involving road construction, have been shown to significantly impact local economies through job creation and enhanced economic opportunities. Research indicates that such projects can lead to both direct and indirect employment. Similarly, the HMDC Project was expected to create 5,000 direct and 22,000 indirect job opportunities (Government of Sindh, n.d.). This aligns with findings from studies on the socioeconomic impacts of similar projects, such as the Karakorum Highway, which underscores the broader economic benefits of improved transportation infrastructure (TRIS, n.d.).

Land Values and Agricultural Development

The impact of infrastructure projects on land values and agricultural practices is another critical area of study. The literature review indicated that improved road connectivity could lead to increased land values and stimulate agricultural development by facilitating better market access for farmers. Improved road connectivity often leads to increased land values and stimulates agricultural productivity by facilitating better market access for

farmers. Studies have shown that infrastructure projects can uplift land values and support agricultural activities. For instance, research on the impact of road infrastructure on agricultural productivity indicates that improved transportation networks can enhance market access, reduce input costs, and increase agricultural incomes (Llanto, 2012).

However, challenges in managing land acquisitions and mitigating negative agricultural impacts require careful planning and community consultation. Studies have highlighted the need for inclusive and participatory approaches in infrastructure development to ensure that the benefits are equitably distributed and adverse impacts are minimized.

Technological Innovations in Infrastructure

The integration of advanced technologies such as Electronic Toll and Traffic Management Systems (ETTMS) in projects like the HMDC enhances operational efficiency and user experience. Research from IEEE Xplore emphasized the role of intelligent transportation systems (ITS) in optimizing traffic flow, reducing operational costs, and improving safety (An et al., 2011).

Studies on technological innovations in infrastructure projects highlight the benefits of integrating advanced systems for toll collection, traffic monitoring, and maintenance management. For instance, a study published in the IEEE Xplore Digital Library discusses the advantages of using intelligent transportation systems (ITS) in road projects, including enhanced traffic management, reduced congestion, and improved safety (Riaz et al., 2021). However, the adoption of these technologies requires substantial investment and a skilled workforce, posing implementation challenges.

The evaluation of the Lahore-Sheikhupura-Faisalabad Dual Carriageway BOT project underscores the importance of innovative funding models, like BOT, for large-scale infrastructure projects, demonstrating their viability in addressing funding constraints and accelerating project completion. Key lessons include the need for comprehensive evaluation frameworks to accurately measure benefits and costs, the critical role of safety and maintenance in sustaining long-term benefits, and the value of continuous investment in road infrastructure for economic growth. These findings suggest that adopting similar approaches in Sindh Province can enhance infrastructure development, improve project outcomes, and ultimately contribute to regional economic advancement (Ahmed et al., 2029).

However, challenges such as land acquisition disputes and initial operational issues have been reported, highlighting the complexities involved in executing

PPP projects effectively. Addressing these challenges requires robust legal frameworks, effective stakeholder engagement, and transparent decision-making processes (NHA, n.d.).

Gaps in Current Knowledge

While the existing literature provides valuable insights into the socioeconomic impacts and operational dynamics of PPP projects, several knowledge gaps remain. Specifically, there is a need for more detailed studies on the long-term sustainability of PPP projects in developing countries, including the socioeconomic outcomes post-implementation, comprehensive assessments of environmental impacts, and strategies for mitigating social disruptions. Addressing these gaps is crucial for enhancing the effectiveness and inclusivity of future infrastructure developments (PPRC, World Bank, n.d.). This research aims to address these gaps by providing a comprehensive analysis of the HMDC Project, focusing on its long-term impacts on travel efficiency, economic development, and regional transformation.

Furthermore, detailed case studies on the long-term sustainability of PPP projects in developing countries, including the socioeconomic outcomes post-implementation, are needed. Additionally, research on the effectiveness of various risk management strategies and stakeholder engagement approaches can inform better practices and policies (Grimsey & Lewis, 2004).

In conclusion, the literature review underscores the dual nature of PPP projects in infrastructure development, emphasizing both their potential benefits and inherent challenges. This research contributes to a better understanding of PPP dynamics by critically analyzing existing studies and integrating findings from diverse contexts like the HMDC and Lahore-Sheikhupura-Faisalabad Motorway. Successful PPP projects require clear contractual frameworks, effective risk management, stakeholder engagement, and the integration of advanced technologies. The HMDC Project, like many others, demonstrates the potential benefits of PPPs in reducing travel time, generating employment, and fostering economic development. However, it also underscores the need to address environmental concerns and community impacts (PPRC, World Bank, n.d.).

Policymakers and stakeholders must leverage these insights to foster sustainable, inclusive, and technologically advanced infrastructure solutions. Future PPP initiatives can be better designed to maximize socioeconomic benefits and minimize adverse impacts by addressing the identified gaps in knowledge and incorporating lessons learned from previous projects.

3. RESEARCH METHODOLOGY

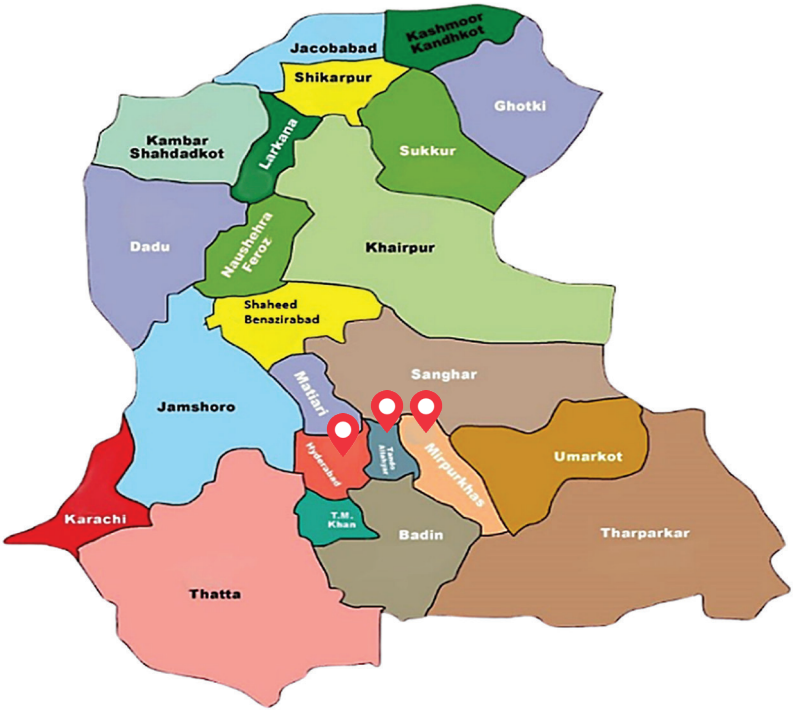
Research Design

This research study adopted a mixed-methods research design to triangulate findings and provide a comprehensive understanding of the socioeconomic impacts of the HMDC project. The combination of qualitative and quantitative methods enhanced the robustness of the research, allowing for a multifaceted exploration of the project's impact. Diverse stakeholders were engaged through surveys, focus group discussions (FGDs), and key informant interviews (KIIs).

The study was conducted in the following targeted areas:

- District Hyderabad
- District Tando Allahyar
- District Mirpurkhas

Figure 1: Targeted Districts in Sindh



Source: Authors' computations.

Sampling Strategy

The study used a combination of sampling techniques, including random, stratified random, and convenience sampling, to ensure representation from various stakeholder groups. The participants included transporters, commuters/travelers, local businesses/SMEs, landowners/farmers/tenants, Deokjae project employees and officials, relevant government officials, and community members.

Sampling Methodology

To calculate the sample size with an error margin of 5% and a confidence level of 90%, the following formula was used:

$$n = \frac{NxZ^2.p.(1-p)}{(N-1).E^2 + Z^2.p.(1-p)}$$

where:

- n = desired sample size
- N = total population size
- Z = Z-score (corresponding to the desired confidence level, typically 1.645 for a 90% confidence level)
- p = estimated proportion of the population that possesses the attribute being measured (specified as 50%, so p = 0.5)
- E = margin of error (5%, so E = 0.05)

Sample Size and Participant Distribution

Given the demographics, particularly the female population (47-48%) in the targeted districts according to the 2023 Census, a minimum of 30% female participants were included in the study, though efforts were made to include as many female participants as possible. The sampling distribution is given below.

Quantitative Data Participants

Private Transport Owners/Operators: Surveys were conducted with 40 transport owners, including 20 public transport owners and 20 goods transport owners. Convenience sampling was used to select participants. Since the total target was 40, 20 transporters from each category were surveyed. This included 42% of transporters from Hyderabad, 32% from Mirpurkhas, and 28% from Tando Allahyar. The sample size was allocated to each district based on the overall number of transporters.

Travelers/Commuters: A random sampling technique was employed to select 90 commuters, with a minimum of 30% being females, ensuring gender diversity. Only those who had been travelling on this route before and after the construction of the HMDC were included to collect relevant data on travel time reduction. The sample size included 41% of respondents from Hyderabad, 38% from Mirpurkhas, and 21% from Tando Allahyar.

Landowners/Farmers/Tenants: Stratified random sampling was used to select 90 participants from the agricultural community, ensuring representation of landowners, tenants, and farmers. Only those who had land alongside the HMDC before its construction were included for a comparative analysis. The sample size was distributed among the districts as follows: 30% from Hyderabad, 30% from Mirpurkhas, and 40% from Tando Allahyar.

Shopkeepers/SMEs Businesses: Convenience sampling was used to select 60 shopkeepers and SME owners, representing a variety of businesses situated along the HMDC route. The sample included businesses that existed before the construction to measure the socioeconomic impact. The total target was 60 businesses. Out of the 60 businesses, 37% of respondents belonged to Hyderabad, 40% were from Mirpurkhas, and 23% were from Tando Allahyar.

Employees Onboard Jobs Created During Construction: Convenience sampling identified 20 individuals who worked during the construction phase and post-construction of the HMDC. This group provided insights into job creation targets and the socioeconomic benefits of the project.

Qualitative Data Participants

Key Informant Interviews (KIIs)

Deokjae Project Officials, Finance Department, Works & Services, PPP Unit: 05

A convenience sampling was used to select five officials for KIIs to get their views and perspectives about the project investment and returns, along with its socioeconomic impact on the region. The officials included one from the provincial finance department concerned with this project, one from the Works & Services Department of Sindh, two officials from Deokjae, and one official from the PPP unit. Separate KII guides were prepared according to stakeholder requirements to ensure the collection of relevant and context-specific information.

Focus Group Discussions

Community members (FGDs): 03

Three FGDs were conducted with community members in all three target districts. In total, 60 people, including 45% female and 55% male, consisting of farmers, tenants, land owners, social workers, private employees, students, university faculty, religious leaders, government employees, businessmen, officials of local government, i.e. councilors, etc., participated in the FGDs. The participants were selected through convenience sampling. The FGDs helped get the community's perceptions and opinions about the socioeconomic impacts of the project in the region. FGDs protocols or guides were developed to capture relevant insights, views, perspectives and opinions from the targeted communities.

Data Collection Methods

1. **Surveys:** Structured surveys were administered to public transport owners/operators, goods transport owners/operators, travelers/commuters, landowners/farmers/tenants, shopkeepers/ SME businesses, and Project employees along the HMDC route. Questions were focused on travel experiences, perceived socioeconomic changes, sustainability and overall regional development and growth.

2. **Key Informant Interviews (KIIs):** KIIs were conducted with key stakeholders, including Deokjae project officials, the Works & Services Department of Sindh, the finance department representatives, and the PPP unit. These interviews provided insights into the socioeconomic impact and the effectiveness of the PPP model.

3. **Focus Group Discussions (FGDs):** FGDs were conducted with community members and local government representatives, ensuring diverse representation and providing a platform for in-depth discussions.

Table 1: Sample Size Distribution

Data Type	Target Audience/ Respondents	Data Collection Tools/Instruments/ Guides	Sample/ Target
Quantitative data – surveys	Target respondents	Structured survey tools	300
Total Survey Respondents		**300**	
Qualitative data - concerned stakeholders	**Stakeholders**	**Data Collection Instruments/ Tools/Guides**	**Target**
Community Level-FGDs	Community members (*male and female mix FGDs); participants including* general community, key influential personalities, social activists, local government officials, etc.*)*	FGD tools/guides	3
District Hyderabad		1	
District Mirpurkhas		1	
District Tando Allahyar		1	
Total FGDs		**3**	
District Level-KIIs	**Key stakeholders**	**KII tools/guides**	**5**
Deokjae Officials (District and HO Karachi)		2	
Works & Services Department		1	
PPP Unit Department		1	
Finance Department		1	
Total KIIs		**5**	

Sample Summary:
Total Survey: 300 (Individual respondents)
Total FGDs: 3 (60 participants)
Total KIIs: 5 (5 participants)
Overall coverage: 365 respondents and participants

Source: Authors' computations.

Data Safety and Ethical Considerations

Strict measures were taken to ensure the confidentiality and anonymity of participants. Informed consent was obtained from all interviewees, and data were securely stored and accessible only to the research team. Implemented strict data security measures, including encryption and access controls, to protect sensitive information. Strict compliance with ethical standards and confidentiality agreements was ensured. Detailed records of the data management processes, including data collection instruments and data analysis files, have been maintained.

Data Analysis

Quantitative Data Analysis: Quantitative data from surveys was analyzed using advanced statistical tools/software (including SPSS and MS Excel) to derive patterns. Data was entered into a statistical software program (e.g., SPSS, MS Excel) for analysis, including descriptive statistics and trend analysis.

Qualitative Data Analysis: Qualitative data from interviews KIIs, FGDs and document analysis underwent thematic coding to extract key themes and insights. Data were analyzed using advanced statistical tools/software, Atlas.ti and MS Excel.

Triangulation of Data:

- Integration of findings: Qualitative and quantitative data were triangulated to validate and complement each other, providing a holistic understanding of project impact and effectiveness.
- Convergence of evidence: Converging themes and patterns across different data sources were identified to strengthen the reliability and credibility of evaluation findings.
- Integration of data: Findings from quantitative surveys, qualitative interviews, focus groups, and document reviews were triangulated to validate conclusions and enhance the reliability and credibility of the findings.
- Cross-validation: Information obtained through different methodologies is compared and cross-validated to identify converging or diverging perspectives on project impact and effectiveness.

4. FINDINGS AND DISCUSSIONS

Survey Respondents' Demographic Profile

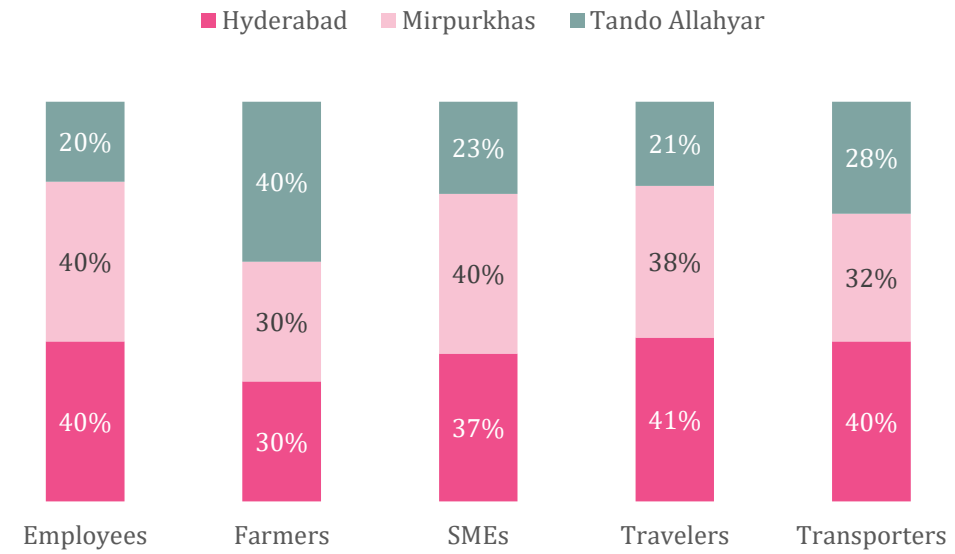
District of Respondents

The distribution of respondents from each category (employees, farmers, SMEs, travelers, and transporters) in each district is shown in Figure 2. Overall, 38% respondents were from Hyderabad, 36% from Mirpurkhas, and 26% from Tando Allahyar.

Among the employees, 40% each were from Hyderabad and Mirpurkhas, while 20% were from Tando Allahyar. Hyderabad and Mirpurkhas had a higher representation of employees because these are key hubs of employees working at toll gates. Fewer employees were surveyed in Tando Allahyar because of the absence of toll gates.

In the farmers/landowners/tenants category, Tando Allahyar contributed the largest share, accounting for 40% of respondents. Mirpurkhas and Hyderabad each contributed 30%, indicating that Tando Allahyar plays a more prominent role in agricultural activities compared to the other two districts.

Figure 2: Breakdown of Respondents from Each District



Source: Authors' calculations based on the study's primary survey data.

The SMEs category showed a more balanced distribution. Respondents from Mirpurkhas formed the largest group at 40%, followed closely by Hyderabad with 37%, and Tando Allahyar, which accounted for 23%. This highlights Mirpurkhas as a leading district for SME activities, with Hyderabad also showing significant representation.

For travelers, Hyderabad dominated, contributing 41% of the respondents, followed by Mirpurkhas at 38%. Tando Allahyar had the smallest share, making up only 21% of respondents. These figures indicate that Hyderabad serves as a key origin point for travelers, with Mirpurkhas also contributing a significant share.

Transporters from Hyderabad made up the largest proportion at 40%, followed by Mirpurkhas at 32%, and Tando Allahyar at 28%. While Hyderabad led in this category, the contributions from Mirpurkhas and Tando Allahyar were relatively close, showing a more even distribution compared to other categories.

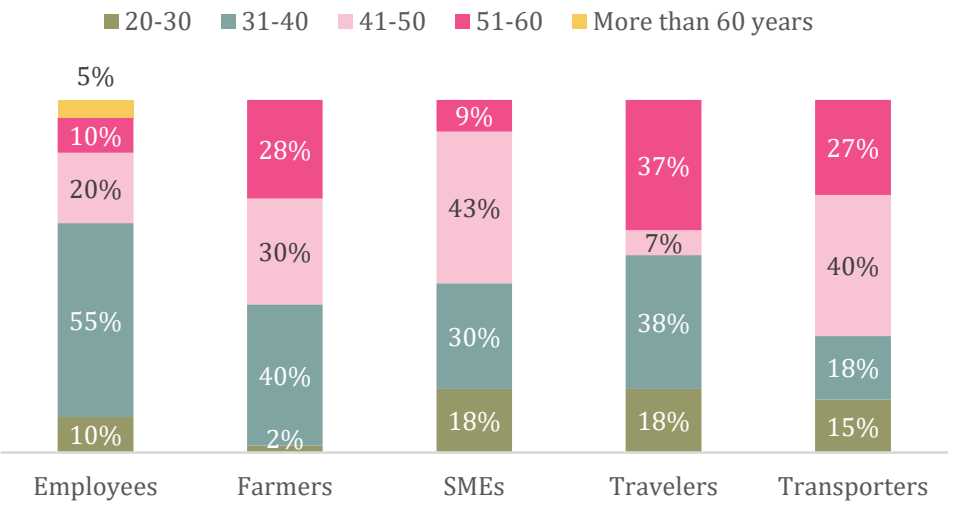
The survey results revealed distinct patterns across the categories. Hyderabad consistently emerged as a dominant district, particularly among employees, travelers, and transporters. Tando Allahyar stood out in the farmers' category, reflecting its significant agricultural base. In contrast, Mirpurkhas plays a leading role in SMEs, showcasing its strength in business activities. This distribution highlights the economic and demographic dynamics of these districts: Hyderabad exhibits a more diverse economic base, Mirpurkhas specializes in business, and Tando Allahyar leans heavily towards agriculture.

Age Groups of the Survey Respondents

Figure 3 shows the age distribution of respondents according to their age groups.

Among the employee category, the largest proportion of respondents, i.e., 55%, belonged to the 31-40-year age group. This was followed by 20% in the 20-30-year group, indicating a significant representation of younger professionals. The 41-50-year and more than 60-year age groups each comprised 10% of the respondents, while the 51-60-year group constituted only 5% of the respondents. This indicated that the employee category was primarily dominated by individuals in their early to mid-career stages.

Figure 3: Age Groups of Respondents



Source: Authors' calculations based on the study's primary survey data.

Landowners/farmers/tenants displayed a slightly different composition, with 40% of the respondents falling into the 31-40-year age group, 41-50-year age group had 30% of the respondents, while 28% were in the youngest category, i.e., 20-30 years. There were very few respondents in the 51-60-year age group at 2% and there were no respondents aged more than 60 years.

Respondents in the SMEs category were predominantly aged 41-50 years, accounting for 43% of the group. Those in the 31-40-year group made up 30% of the respondents, while 18% were aged 51-60 years. The youngest age group, i.e., 20-30 years, represented only 9% of the respondents in the SME category.

Travelers were mainly distributed between the 41-50- and 31-40-year age groups, comprising 38% and 37% of respondents, respectively. The age group 51-60 years included 18%, while only 7% were in the 20-30 years group.

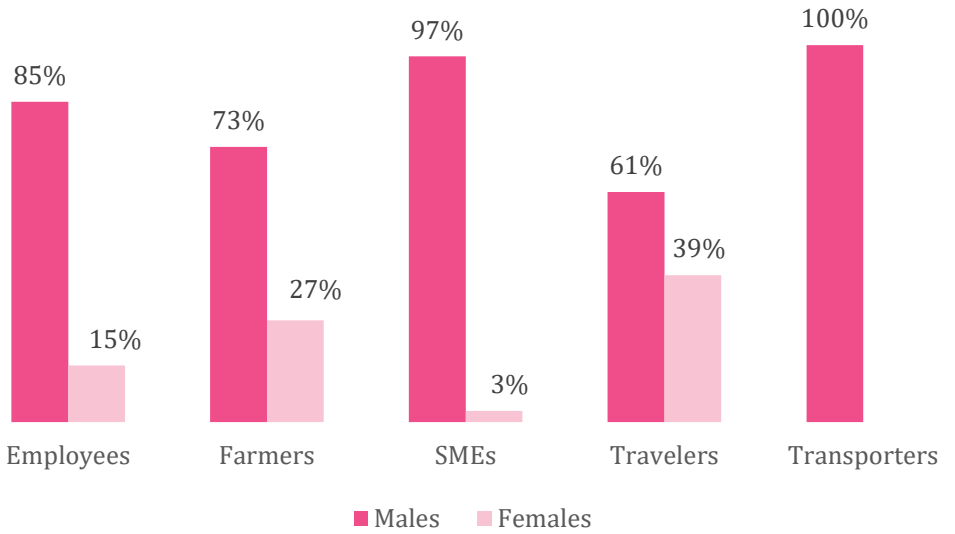
The transporter category showed a somewhat similar pattern, with 40% of respondents aged 41-50 years, followed by 27% in the 31-40-year group. The age group 51-60 years accounted for 18%, while the 20-30-year age group contributed 15% of the respondents. As in other categories, no respondents were aged more than 60 years.

The results show that the 31-40-year age group formed the majority, 36%, of the respondents in most categories, particularly in the employee, SME, travelers, and transporter categories. Older individuals, aged more than 60 years, were largely absent from all the categories, highlighting a limited presence of senior citizens in these economic activities. This reflects an active working population concentrated in the younger to middle-aged brackets, emphasizing the importance of supporting these age groups in economic engagement and development.

Gender of Respondents

Overall, 83% male respondents constituted the sample. The category-wise gender distribution of survey respondents across five categories is shown in Figure 4. In the employee category, 85% were male, while 15% were female, indicating a significant male majority in this category. Farmers also exhibited a male majority, with 73% male and 27% female respondents. The SMEs category had the highest male dominance, with 97% males, showcasing a stark gender disparity. Travelers were relatively more balanced compared to other groups, with 61% male and 39% female respondents. Transporters, however, were exclusively male, with 100% of the respondents being male.

Figure 4: Gender Distribution of Respondents



Source: Authors' calculations based on the study's primary survey data.

Educational Background of Respondents

The majority of the respondents 28% were illiterate, while only 19% had a primary education. Among the employee category, 5% were illiterate, 20% had completed primary education, and 5% had attained a middle school education. Respondents with matriculation made up 10%, those with intermediate education constituted 5%, and the majority, i.e., 50%, had a bachelor's degree. Additionally, 5% held a master's degree.

Landowners/tenants/farmers predominantly were in the illiterate category, comprising 55% of respondents, followed by 13% who had primary education and 5% with middle school education. Matriculation and intermediate qualifications were held by 8% and 7%, respectively. Only 7% of farmers had a bachelor's degree, 2% had a master's degree, and 3% had an MS/PhD.

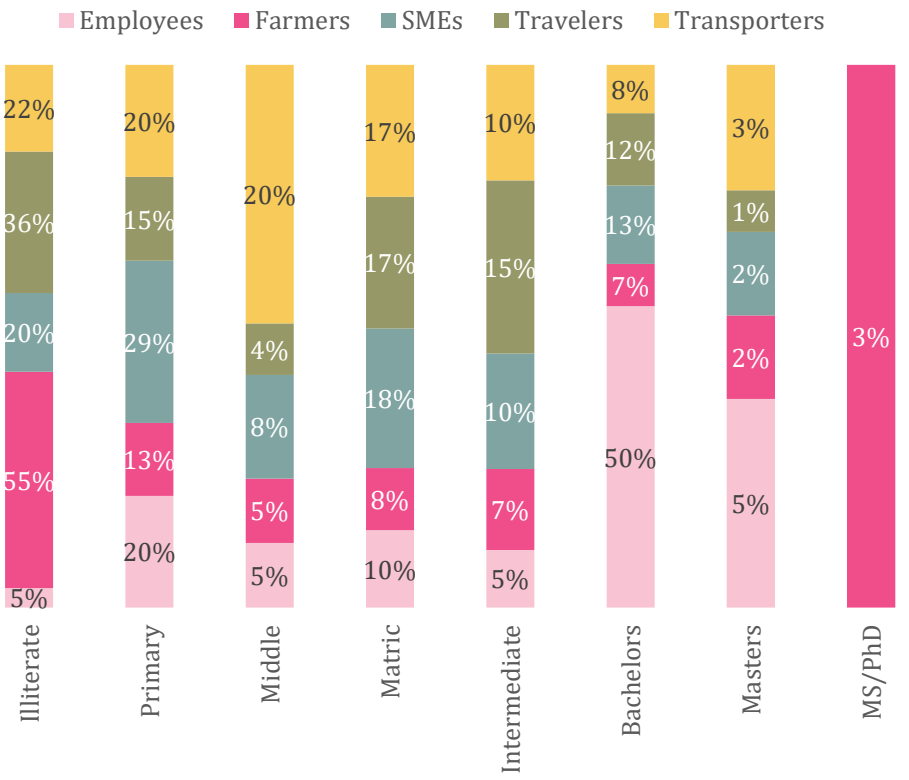
In the SME category, 20% of respondents were illiterate, while 29% had completed primary education, making it the largest group. Middle school education accounted for 8%, and matriculation was achieved by 18%. Intermediate and bachelor's qualifications were held by 10% and 13%, respectively, whereas only 2% had a master's degree.

Travelers were distributed more evenly across educational levels. Illiteracy was reported by 36% of respondents, while 15% had primary education and 4% had middle-level education. Matriculation was achieved by 17% of respondents, and 15% held intermediate qualifications. Those with bachelor's degrees made up 12%, while only 1% had a master's degree.

Transporters had 22% illiterate respondents, 20% with primary education, and 20% with middle school education. Matriculation and intermediate qualifications accounted for 17% and 10%, respectively, while only 8% had bachelor's degrees. A small proportion, 3%, had master's degrees.

The findings revealed a wide variation in education levels across all respondents, with employees being the most educated group, as 50% held a bachelor's degree, while farmers had the highest percentage of illiteracy (55%). Advanced degrees (master's and MS/PhD) were rare across all groups.

Figure 5: Educational Background of Respondents



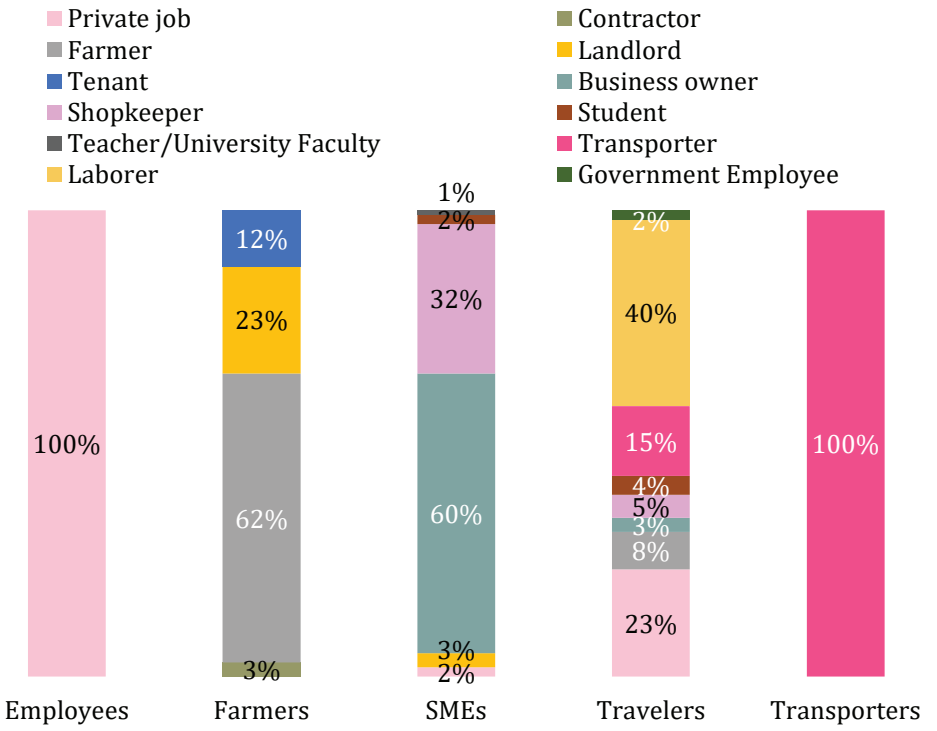
Source: Authors' calculations based on the study's primary survey data.

Occupation of Respondents

The majority of the respondents 25% were engaged in private jobs. All employees 100% were engaged in private jobs. Among farmers, 62% were engaged in farming, while 23% were landlords, and 12% were tenants. A small proportion (3%) identified as contractors.

In the SME category, 60% were business owners, 32% were shopkeepers, and 2% were students. Additionally, 1% were teachers or university faculty, and 3% identified as landlords.

Figure 6: Occupation of Respondents



Source: Authors' calculations based on the study's primary survey data

In the travelers category, 40% were laborers, making up the largest group, while 23% were engaged in private jobs. Other occupations included transporters (15%), farmers (8%), shopkeepers (5%), and students (4%). A small proportion (2%) were government employees, and 3% were business owners. Transporters were a homogeneous group, with all respondents (100%) identifying as transporters.

Roles and Responsibilities Participants

A clear and structured division of roles and responsibilities of the stakeholders interviewed and directly involved in the HMDC project was pivotal to the project's seamless execution. Senior officials from the HMDC operating private partner (Deokjae), Works & Services Department, the PPP Unit, and the Finance Department, the Government of Sindh, provided strategic oversight, ensuring that the project aligned with the broader goals of sustainable regional development and global practices of infrastructure development projects.

> *"Aligning day-to-day activities with the project's larger developmental vision, ensuring decisions were forward-looking and sustainable."* - A key informant

According to an official, the role of the PPP Unit begins at the project conception stage. He said that they work closely with other concerned departments to ensure alignment from the planning to the execution stages. This strategic vision avoided reactive decision-making and, instead, fostered proactive planning.

Operational duties, on the other hand, were effectively delegated to the Works & Services Department, ensuring efficient day-to-day implementation. Adding another layer of accountability, independent engineers monitored compliance and performance benchmarks. Independent oversight ensured we maintained quality and upheld the terms of the concession agreement, stated an official, highlighting the transparency fostered by this multi-tiered governance model.

In addition to the KIIs, 60 participants from diverse backgrounds participated in the FGDs conducted in the targeted research study districts. These were mixed FGDs, with female participation at 50 percent in Mirpurkhas and 25 percent in each Hyderabad and Tando Allahyar.

Impact of the HMDC Project on Travel Time Reduction and Fuel Efficiency

The Frequency of the Commute on the Hyderabad-Mirpurkhas route

The HMDC employees consistently commuted on the route daily, with 100% of respondents in this category reporting daily travel. This indicated that their work required them to use the route every day. Landowners/tenants/farmers showed a more diverse pattern, as 33% of the respondents travelled daily, likely to access markets or tend to agricultural activities, while weekly travel was reported by 28%, potentially reflecting periodic tasks such as selling produce or gathering supplies. Another 24% of farmers commuted monthly, indicating less frequent but purposeful use of the route, while 15% traveled occasionally, perhaps for specific events or infrequent needs.

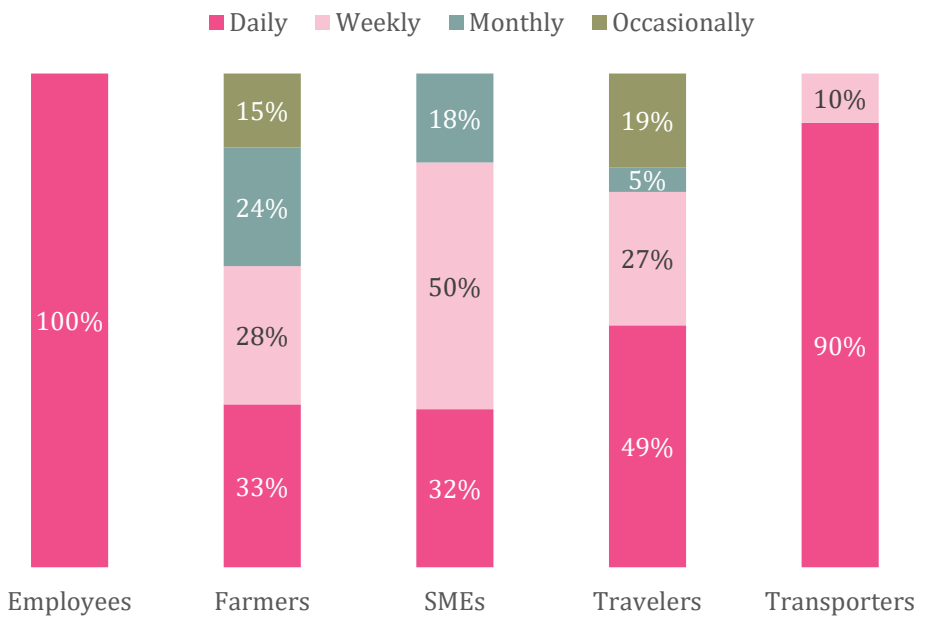
SME representatives exhibited varied travel frequencies. A total of 32% traveled daily, likely for business operations or customer interactions, while 50% commuted weekly, suggesting strategic trips for business-related activities. 18% of the respondents traveled monthly, representing infrequent

but planned engagements. There were no SME respondents who commuted occasionally, indicating a more regular travel pattern within this group.

Travelers had a broad range of commuting patterns. 49% of the respondents in this category traveled daily, possibly for work or personal errands. Weekly commuters made up 27% of the respondents, while only 5% traveled monthly, reflecting rare but consistent needs. Lastly, 19% commuted occasionally, showing sporadic and less predictable use of the route.

Transporters showed a heavy reliance on the route, with 90% traveling daily. This reflects their critical role in transporting goods and passengers, which demands consistent movement. Only 10% of transporters commuted weekly. The HMDC employees and transporters had the highest reliance on the route, with most of them traveling daily. Landowners/tenants/farmers and SMEs exhibited more flexible patterns, with significant weekly and monthly commuting, while travelers had a relatively balanced spread across daily, weekly, and occasional travel. These insights highlight the importance of the Hyderabad-Mirpurkhas route for various professional, economic, and personal purposes.

Figure 7: Commuting Frequency on the HMDC Route



Source: Authors' calculations based on the study's primary survey data

Average Travel Time from Hyderabad to Mirpurkhas Before the Construction of the Dual Carriageway

The data highlights the varying commute times experienced by employees, farmers, SMEs, travelers, and transporters on the Hyderabad-Mirpurkhas route before the construction of the dual carriageway. Employees primarily faced moderate delays, with 45% reporting a commute time of 90 minutes and 38% completing their journey in 60 minutes. A smaller group, 10%, managed the trip in 45 minutes, while only 7% reported needing 120 minutes to travel the route.

Farmers reported a wider range of commute times. A significant 38% needed 90 minutes to complete the journey, while 32% required 120 minutes, indicating notable delays for a large portion of this group. Additionally, 23% reported spending 60 minutes on the route, whereas only 5% completed their commute in 45 minutes. A small fraction, 2%, faced travel times exceeding 120 minutes, reflecting severe challenges for some farmers.

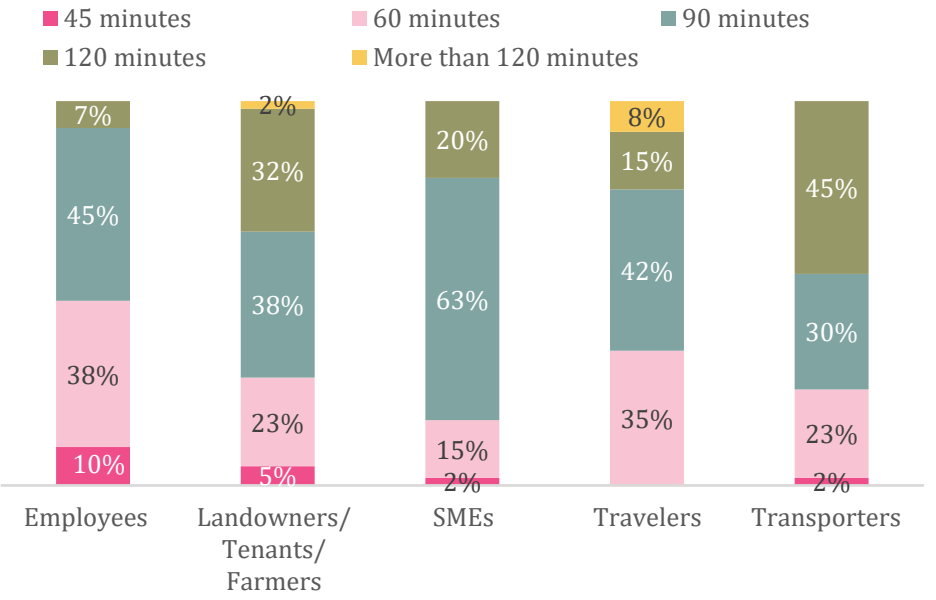
Respondents from SMEs faced longer commutes, with 63% reporting travel times of 90 minutes. Another 20% needed 120 minutes, showing considerable inefficiencies in their travel. A smaller share of the respondents in this category, 15%, completed the journey in 60 minutes, and just 2% reported a commute time of 45 minutes, indicating that shorter travel times were rare for this group.

Travelers showed a relatively balanced distribution of travel times. Among them, 42% reported spending 90 minutes on their journey, while 35% needed 60 minutes. Another 15% required 120 minutes to complete their travel, and 8% experienced travel times exceeding 120 minutes. None of the travelers reported a commute time as short as 45 minutes, highlighting the consistent inefficiency of the route for this group.

Transporters experienced the most severe delays, with 45% requiring 120 minutes to travel the route. Another 30% reported a 90-minute commute, while 23% managed to complete their journey in 60 minutes. Only 2% of transporters experienced a commute time of 45 minutes, underscoring the rarity of shorter trips in this category.

The findings reveal that the majority of respondents 44% faced long and inefficient commute times of 90 minutes on the Hyderabad-Mirpurkhas route before the dual carriageway's construction. Employees and travelers were more likely to experience moderate delays, while farmers, SMEs, and transporters faced more severe challenges, with many requiring 90 to 120 minutes or more to complete their journeys.

Figure 8: Average Travel Time Before the HMDC



Source: Authors' calculations based on the study's primary survey data

Condition of the Hyderabad-Mirpurkhas Route Before the Construction of the Dual Carriageway

A majority of all the respondents described the condition as suboptimal, with only a small fraction rating it as good and none considering it very good.

Among employees, 55% rated the route as poor, indicating significant dissatisfaction, while 33% viewed it as fair. A smaller proportion of respondents, 8%, considered the route good, and only 4% rated it as very poor, reflecting relatively less severe criticism compared to some other groups.

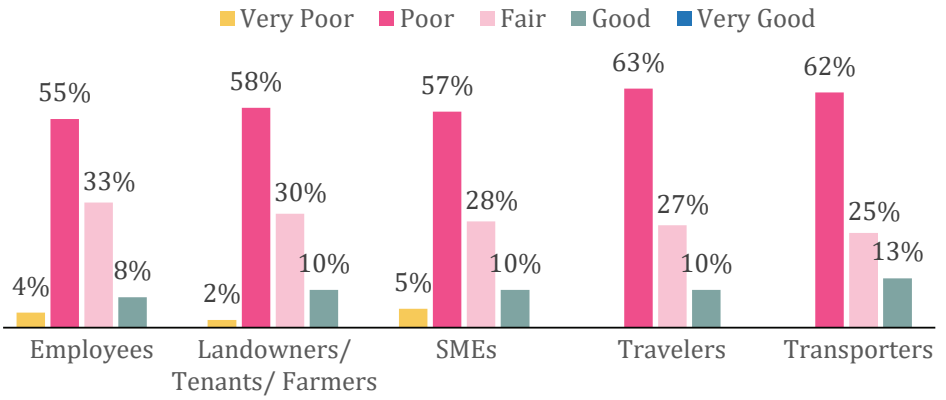
Similarly, farmers also expressed dissatisfaction, with 58% rating the condition as poor and 30% as fair, indicating that the route posed challenges for their commuting needs. Only 10% rated it as good, and only 2% considered it very poor, suggesting that while most found it inadequate, very few found it entirely unusable.

SME respondents shared similar sentiments, with 57% describing the route as poor, 28% as fair, and 10% as good. Interestingly, 5% of SMEs rated the route as very poor, indicating some extreme dissatisfaction within this group. Travelers largely agreed with the negative assessment, with 63% rating the route as poor, and 27% as Fair, highlighting that the route was inconvenient for most. A slightly higher proportion, 10%, rated it as good, but no traveller rated it as very poor.

Transporters, who heavily relied on the route for their activities, expressed a similar distribution of opinions. A significant majority, 62%, rated the condition as poor, while 25% considered it fair. A relatively higher percentage, 13%, described the route as good, likely reflecting that some transporters found it adequate for their needs. None rated it as very poor.

The survey results revealed that the majority of respondents, i.e., 59% across all groups, rated the condition of the Hyderabad-Mirpurkhas route before the dual carriageway's construction as poor, highlighting widespread dissatisfaction. A smaller proportion viewed it as fair, and only a few respondents rated it as good. The absence of a very good rating underscored the pressing need for the improvements brought by the dual carriageway project.

Figure 9: Condition of the Road Before the HMDC



Source: Authors' calculations based on the study's primary survey data

Average Time Saved in Travelling from Hyderabad to Mirpurkhas After the Construction of the HMDC

The time savings varied across all respondent groups, reflecting the diverse impacts of the infrastructure improvement on different types of users. Among employees, the majority, 45%, reported saving 25-30 minutes, on average, due to the project, indicating substantial improvement in travel efficiency for daily commuters. Additionally, 35% of employees saved more than 30 minutes, highlighting a significant benefit for a sizeable portion of this group. A smaller percentage, 20%, experienced a time saving of 15-20 minutes, while no employees reported saving less than 15 minutes.

Landowners, tenants, and farmers exhibited a more even distribution of time savings. 35% reported saving 25-30 minutes, reflecting the positive impact of the project on their commutes. Another 28% saved 15-20 minutes, while 20% experienced a time saving of more than 30 minutes. A smaller portion, 17%, reported saving only 5-10 minutes, indicating minimal but still noticeable improvements for some.

SMEs demonstrated a somewhat varied experience, with the majority, 50%, reporting a time saving of 15-20 minutes. This suggests that their business operations benefited from moderate improvements in travel time. Another 27% saved more than 30 minutes, while 18% reported a saving of 25-30 minutes. Only 5% of SMEs saved 5-10 minutes, showing that shorter time savings were less common for this group.

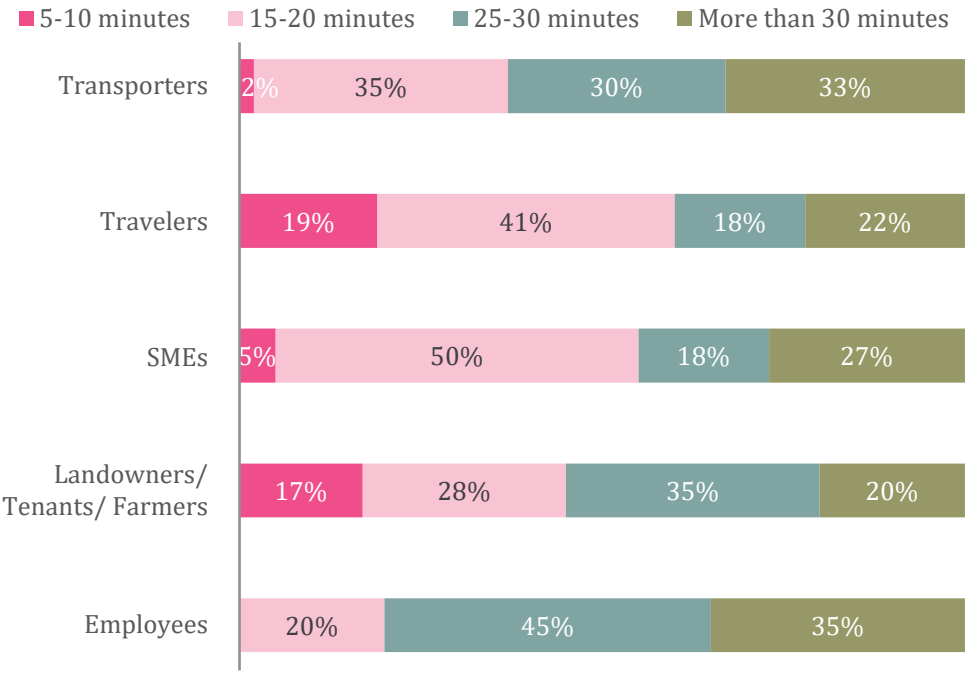
Travelers experienced more balanced time savings. 41% reported saving 15-20 minutes, reflecting moderate efficiency gains. Another 22% saved more than 30 minutes, and 18% saved 25-30 minutes. A notable 19% reported saving only 5-10 minutes.

Transporters, who heavily rely on the route for logistics and passenger transport, also experienced substantial time savings. A significant 35% reported saving 15-20 minutes, and 30% saved 25-30 minutes. Additionally, 33% of transporters saved more than 30 minutes, highlighting major benefits for their operations. Only 2% of transporters reported saving 5-10 minutes, indicating that most experienced notable improvements.

The HMDC project has brought substantial time savings for all types of users, with employees and transporters benefiting the most from longer time reductions of 25-30 minutes or more. Farmers and SMEs also experienced moderate to significant time savings, reflecting improved efficiency for their

agricultural and business needs. Travelers showed a balanced distribution, with most saving 15-20 minutes. The project enhanced travel efficiency and reduced commute times for users of the Hyderabad-Mirpurkhas route, as the majority, i.e., 35%, of the respondents from all sectors reported saving 15-20 minutes.

Figure 10: Saved Travel Time After HMDC's construction



Source: Authors' calculations based on the study's primary survey data

Insights from FGDs

The majority of participants shared that the construction of the HMDC has markedly improved travel efficiency, reducing travel times between key cities and rural areas. Respondents overwhelmingly appreciated the enhanced accessibility, particularly to urban markets and other essential destinations. One participant shared, "Previously, it took 2 hours to reach Hyderabad; now it takes 1.5 hours." Another respondent echoed the same sentiment: "We can now access Hyderabad, Mirpurkhas, and Khuwaja markets easily." This improvement has been particularly beneficial for commuters, traders, and businesses, reducing transportation costs and increasing regional connectivity.

"Before this road was constructed, it took us more than an hour to travel between cities. Now, it takes just 30 to 40 minutes. The time saved has had a big impact on business and commuting." - An FGD participant.

Monetary Impact of Time-saving

The data show that significant time savings were achieved by all respondents per trip after the construction of the HMDC. To show the impact of a reduction in travel time on productivity, the time saving was calculated assuming a minimum wage of PKR 35,000 per month, 22 working days in a month, and 8 working hours in a day. A reduction in the travel time of the travelers impacts their productivity. Travelers who saved 15-20 minutes on average earned an additional PKR 1,274 per month, which translates to PKR 15,293 per annum. Those who saved 25-30 minutes earned an additional PKR 2,002 or 24,031/- PKR annually. The highest savings were for those who saved more than 30 minutes, amounting to PKR 2,548 (PKR 30,584 per year). Moreover, those who saved an average of 5-10 minutes benefited to the tune of PKR 546 monthly or PKR 6,553 yearly. These savings reflect the dual impact of reduced travel time and increased economic efficiency for commuters. The HMDC has not only streamlined daily commutes but also contributed to improving financial well-being and productivity, showcasing the infrastructure's significant value to its users.

Table 2: Monetary Impact of Time-saving

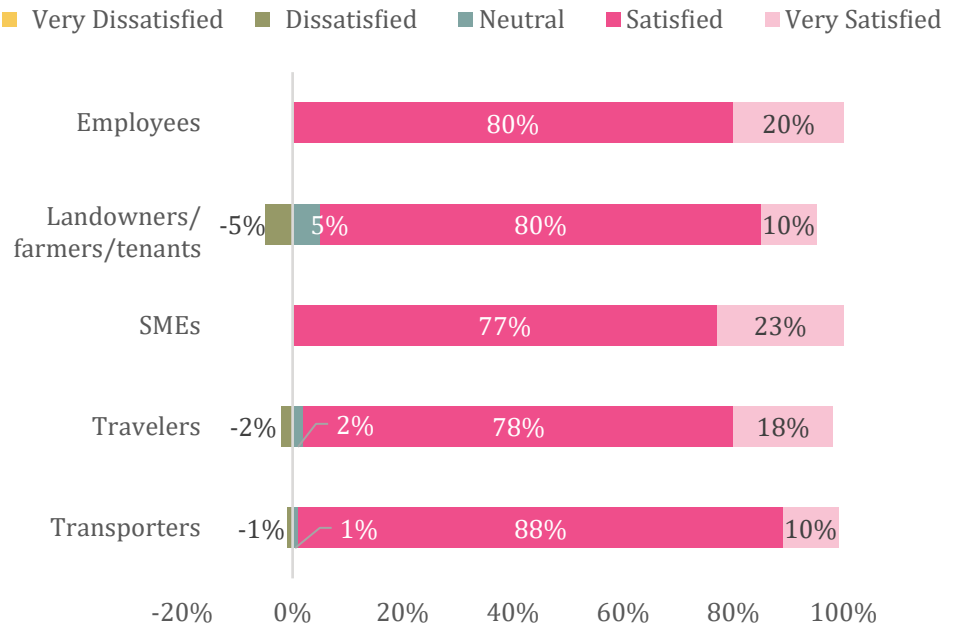
Time Saved (Minutes)	Time Saved (Minutes)	Daily Savings (PKR)	Monthly Savings (PKR)	Yearly Savings (PKR)
5-10	(5+10)/2 = 7.5	7.5×3.31=24.82	24.82 x 22=546.15	546.15 x 12=6,553.08
15-20	(15+20)/2 = 17.5	17.5 × 3.31=57.93	57.93 × 22=1,274.46	1,274.46 x 12=15,293.52
25-30	(25+30)/2 = 27.5	27.5 × 3.31=91.03	91.03 × 22=2,002.66	2,002.66 x 12=24,031.92
30+	35 (assumed average)	35 × 3.31=115.85	115.85 × 22=2,548.70	2,548.70 x 12=30,584.04

Source: Authors' calculations based on the study's primary survey data.

Satisfaction with the Current Condition of the HMDC

According to the analysis, the overall perception of the HMDC is largely positive, with notable variations among survey respondents. Transporters reported the highest satisfaction levels, with 88% satisfied and 10% were very satisfied, reflecting their reliance on the road for consistent operations. Travelers and SME owners exhibited similar trends, with 78% and 77% satisfied, respectively, and relatively higher proportions of very satisfied individuals (18% for travelers and 23% for SMEs), suggesting the road's significance in facilitating mobility and business activities. Landowners, farmers, and tenants, along with employees, shared identical satisfaction rates of 80%, though employees had a slightly higher proportion of very satisfied respondents at 20%, compared to 10% for the former group. Neutral responses were very few across all categories, indicating strong opinions about the road's condition. The absence of dissatisfaction across all groups highlighted the road's positive impact on connectivity and transportation needs in the region.

Figure 11: Satisfaction with the Current Condition of the HMDC



Source: Authors' calculations based on the study's primary survey data.

Impact of Improved Travel Time on Daily Routine or Schedule

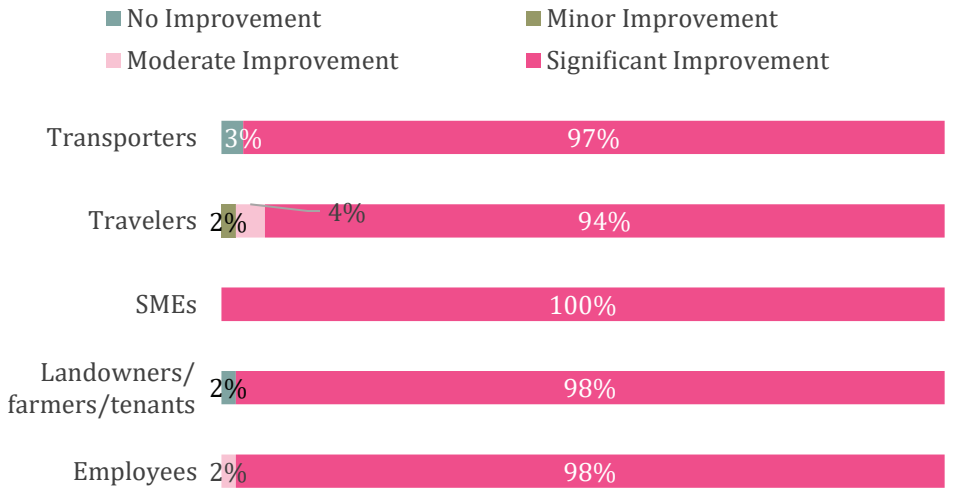
The survey results indicated that the improvement in travel time due to the HMDC project has a significant positive impact on the daily routines and schedules of various groups. Among employees, 98% reported a significant improvement in their daily routine, indicating that the reduced travel time provided considerable benefits, likely enhancing their overall work-life balance and productivity. Only 2% of employees noted a moderate improvement, indicating that nearly all employees experienced a positive change.

For landowners, tenants, and farmers, the impact was similarly strong, with 98% reporting significant improvement in their daily schedules. This shows that the improved travel time has benefited their agricultural activities by making commutes more efficient and saving valuable time, allowing for better management of their work. A small proportion, 2%, felt that there was no improvement, but this is an exception to the otherwise positive view.

100% of the SME respondents reported significant improvements, highlighting the importance of efficient travel for their daily operations. The reduction in travel time likely helped improve business efficiency, allowing SMEs to manage customer visits, deliveries, and other business-related activities more effectively. 94% of the travelers noted a significant improvement in their daily routine, with 4% indicating a moderate improvement. This suggests that while the majority of travelers benefited greatly from the improved infrastructure, a small portion experienced a more limited positive impact.

Transporters also experienced a substantial positive change, with 97% reporting a significant improvement in their daily routines. The time saved on the road likely enhanced their operational efficiency, leading to quicker deliveries and better time management.

Figure 12: Impact of Reduced Travel Time on Daily Life



Source: Authors' calculations based on the study's primary survey data.

Insights from KIIs and FGDs

The majority of participants reported significant improvements in their daily routines and schedules due to the reduced travel time from the HMDC project.

A Significant Increase in Fuel Efficiency after the Construction of the HMDC

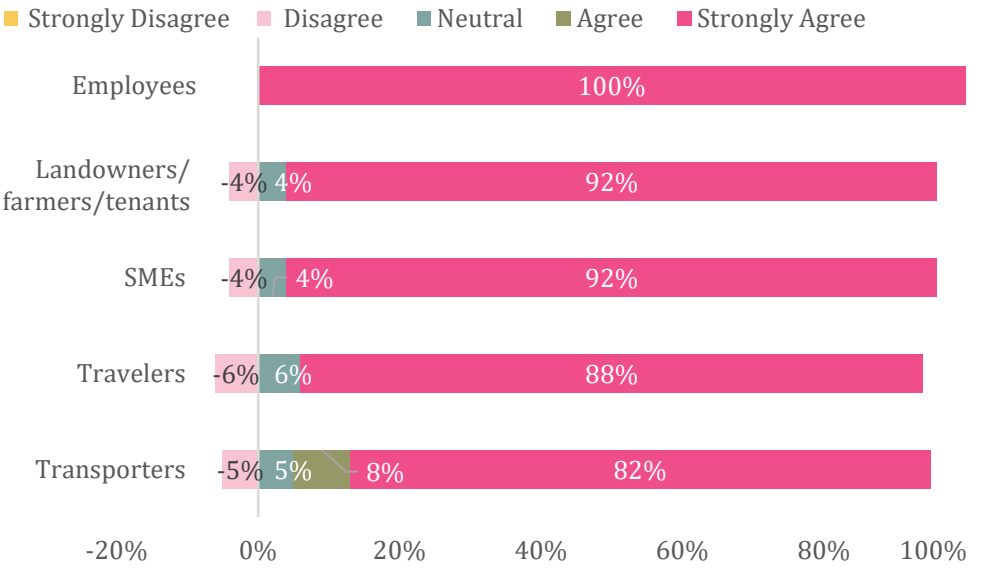
The data indicate a strong consensus among the respondents regarding the impact of HMDC on fuel efficiency. A significant majority of participants across all groups reported a positive change in fuel efficiency. Among employees, 100% of respondents strongly agreed that they had observed an increase in fuel consumption efficiency after the construction of the HMDC.

Similarly, 92% of landowners, tenants, and farmers also strongly agreed, reflecting a widespread perception of improved fuel efficiency. Only 8% of this group remained neutral, suggesting a small proportion did not perceive any significant change.

For SMEs, 92% of respondents strongly agreed with the statement, further reinforcing the general perception that the improved infrastructure had a positive impact on fuel efficiency. The remaining 8% of SMEs did not strongly agree but saw some level of improvement.

Among travelers, 88% strongly agreed, with 12% remaining neutral, indicating that while most travelers observed a significant improvement, a small portion did not experience a noticeable change in fuel consumption. Transporters also largely agreed, with 82% strongly acknowledging the improvement, 8% agreed, while 10% remained neutral.

Figure 13: Increase in Fuel Efficiency After HMDC



Source: Authors' calculations based on the study's primary survey data.

The majority of respondents strongly agreed that the HMDC project has led to a significant increase in fuel efficiency. This reflects the perception and strong endorsement that the improved infrastructure contributes positively to fuel consumption efficiency, making travel more economical for commuters.

Fuel Consumption in Liters for a Round Trip between Hyderabad and Mirpurkhas before and after the HMDC Project

A detailed comparison of fuel consumption before and after the construction of the HMDC reveals distinct changes in consumption patterns across different user groups.

Among employees, the share of those consuming less than 10 liters increased by 20 percentage points from 55% before the HMDC to 75% after. Conversely, the proportion consuming 10 to 15 liters decreased by 20 percentage points (from 45% to 25%), indicating a notable improvement in fuel efficiency.

Among landowners, tenants, and farmers, the proportion consuming less than 10 liters rose by 20 percentage points, from 17% before to 37% after the HMDC's construction. Those consuming 10 to 15 liters declined by 14 percentage points (from 56% to 42%). In contrast, the 16–25 liter group increased 2% slightly, from 11% to 13%, and the 26–35 liter group grew by 4% from 4% to 8%. The 36–60 liter group disappeared entirely, showing a 12% reduction. These shifts suggest improved efficiency in the lower consumption ranges, though some variation persisted in the mid-range categories.

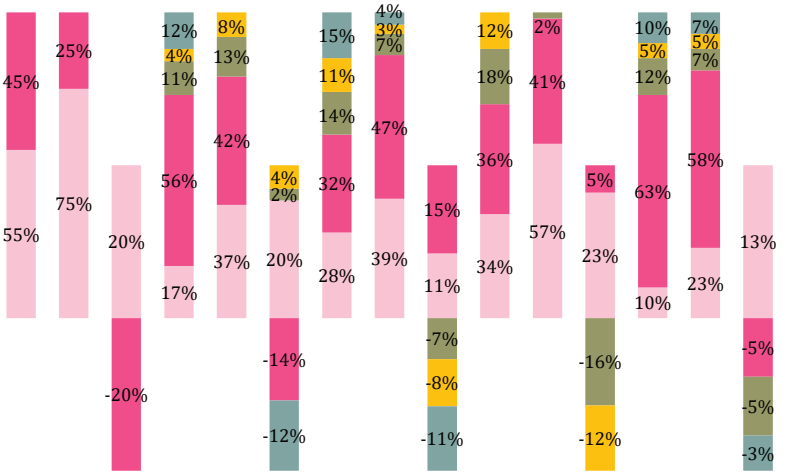
For SMEs, the proportion of respondents consuming less than 10 liters increased by 11 percentage points from 28% before HMDC to 39% after. The 10–15 liter category expanded by 15 percentage points (from 32% to 47%), while the 16–25 liter group fell by 7 points (from 14% to 7%). Similarly, the 26–35 liter range declined by 8%, from 11% to 3%, and the 36–60 liter group dropped sharply, 11% from 15% to 4%. These results point to a clear improvement in fuel efficiency among SMEs.

Travelers also reported substantial gains in fuel efficiency. The proportion consuming less than 10 liters rose by 23 percentage points from 34% before the HMDC to 57% after, while the 10–15 liter category increased slightly by 5% (from 36% to 41%). In contrast, the 16–25 liter group fell sharply with 16% from 18% to 2%, and the 26–35 liter category disappeared entirely, showing a 12-point decrease.

Transporters likewise experienced notable improvements. The share consuming less than 10 liters increased by 13 percentage points (from 10% to 23%), while the 10–15 liter group declined 5% slightly (from 63% to 58%). The 16–25 liter category dropped 5% from 12% to 7%, and the 36–60 liter group fell 3% from 10% to 7%. The 26–35 liter range remained constant at 5%. Although the improvements for transporters were less pronounced compared to other groups, they still reflected better fuel efficiency.

The HMDC project has resulted in a clear reduction in fuel consumption across most user groups, with the most significant improvements observed in the lower consumption categories. These findings reflect enhanced fuel efficiency and associated economic benefits, underscoring the project's positive impact on reducing operational costs and environmental pressures.

Figure 14: Fuel Consumption Difference: before and after the HMDC



	Emp. Before HMDC	Emp. After HMDC	Difference	LTF. Before HMDC	LTF. After HMDC	Difference	SMEs. Before HMDC	SMEs. After HMDC	Difference	Trv. Before HMDC	Trv. After HMDC	Difference	Trans. Before HMDC	Trans. After HMDC	Difference
36 to 60 liters				12%		-12%	15%	4%	-11%				10%	7%	-3%
26 to 35 liters				4%	8%	4%	11%	3%	-8%	12%		-12%	5%	5%	
16 to 25 liters				11%	13%	2%	14%	7%	-7%	18%	2%	-16%	12%	7%	-5%
10 to 15 liters	45%	25%	-20%	56%	42%	-14%	32%	47%	15%	36%	41%	5%	63%	58%	-5%
Less than 10 liters	55%	75%	20%	17%	37%	20%	28%	39%	11%	34%	57%	23%	10%	23%	13%

Source: Authors' calculations based on the study's primary survey data.

Socioeconomic Implications of the HMDC Project: Job Creation and Economic Opportunities

A Positive Impact of the HMDC Project on the Socioeconomic Condition of the Region

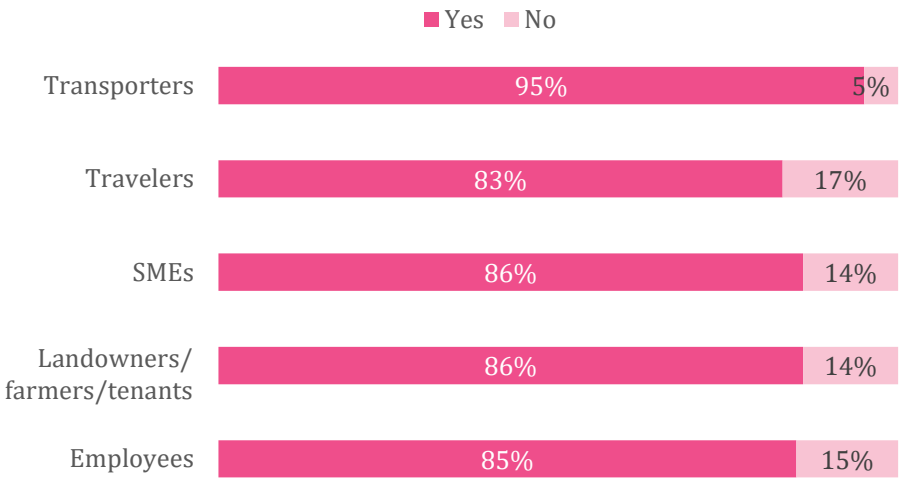
The survey data revealed a strong consensus among respondents regarding the positive socioeconomic impact of the Hyderabad-Mirpurkhas Dual Carriageway project on the area, with varying degrees of agreement across different user groups.

Among employees, 85% believed that the project had positively influenced the socioeconomic conditions of the area, while 15% disagreed. Similarly, 86% of landowners, tenants, and farmers felt that the project had a positive impact, leaving 14% who disagreed. This high level of agreement among these groups suggests that the HMDC has significantly contributed to improving the economic opportunities and quality of life in rural and agricultural settings.

SME owners mirrored these sentiments, with 86% acknowledging the project's positive socioeconomic effects and 14% expressing disagreement. Travelers also showed strong support, with 83% agreeing on the positive impact, although 17% felt otherwise. This response indicated that the HMDC enhanced access and mobility, benefiting both business and leisure activities for these groups.

Transporters had the highest level of agreement, with 95% affirming the positive socioeconomic impact of the project, and only 5% dissenting. This overwhelming response reflects the significant operational efficiencies and cost savings transporters experienced due to the improved road infrastructure.

Figure 15: Positive Socioeconomic Impacts of HMDC in the Region



Source: Authors' calculations based on the study's primary survey data.

Insights from KIIs and FGDs

The majority of the participants regarded the HMDC project as a catalyst for socioeconomic development across various groups, improving connectivity, reducing travel times, and enhancing economic activities in the region.

How the Project Has Positively Impacted the Socioeconomic Conditions of the Region?

The data highlighted several ways in which the HMDC has positively impacted the socioeconomic conditions of the area, with varying priorities and experiences across different groups. The majority of the respondents, i.e., 31%, shared that there was a boost in local businesses after HMDC.

For employees, the most significant impact was seen in the support for the establishment of new SMEs, as reported by 70% of respondents. Additionally, 30% of employees noted that the enhanced infrastructure brought by the project contributed to the socioeconomic improvements in the region.

The benefits were concentrated in two key areas among landowners, tenants, and farmers. 50% of the respondents reported that the HMDC boosted local businesses, and the same proportion (i.e., 50%) emphasized improved access to multiple markets. These findings suggest that agricultural and rural communities have benefited from better market integration and economic opportunities.

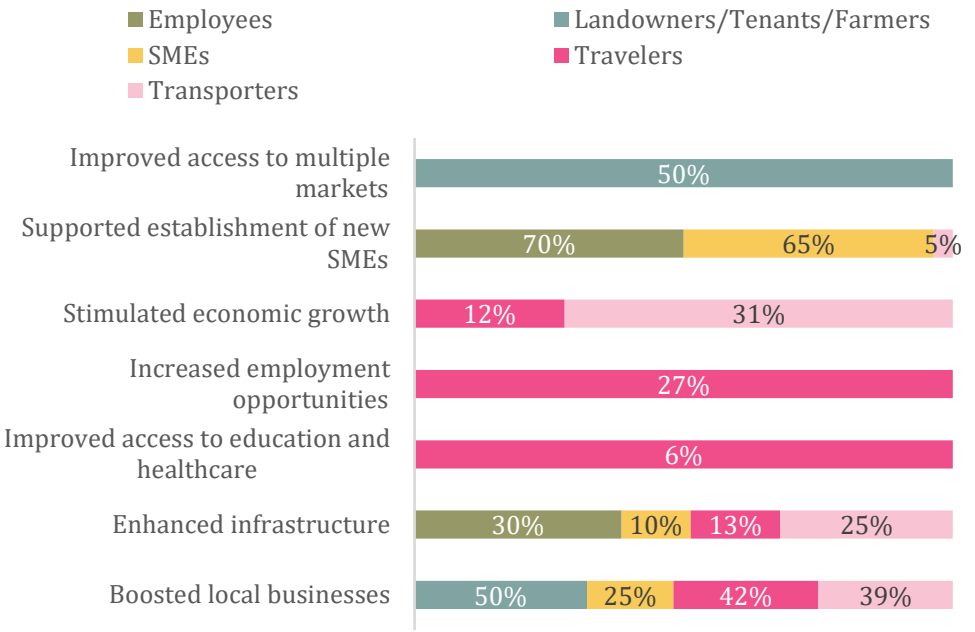
SMEs owners identified multiple benefits, with 65% indicating that the project supported the establishment of new businesses. Boosting local businesses was noted by 25% of SMEs, and enhanced infrastructure was reported by 10%. These responses illustrate how improved connectivity fosters entrepreneurial growth and facilitates market access for smaller enterprises.

Travelers pointed to several socioeconomic improvements, with 42% citing a boost in local businesses and 13% recognizing enhanced infrastructure. Additionally, 6% noted improved access to education and healthcare, while 27% acknowledged increased employment opportunities, reflecting the broad-ranging benefits that better transportation has provided to local communities.

Transporters experienced a notable impact on their economic activities. 39% of the respondents reported that local businesses had been boosted, while 31% mentioned that the project stimulated broader economic growth in the area. Enhanced infrastructure was highlighted by 25%, and 5% pointed to the establishment of new SMEs. These responses underscored the transport sector's vital role in facilitating regional economic development.

The HMDC project has positively influenced the socioeconomic landscape through enhanced infrastructure, better access to markets, increased employment opportunities, and the stimulation of local businesses. These developments have contributed to the economic vitality of the region, with specific benefits tailored to the needs and activities of different groups.

Figure 16: Positive Impact of the HMDC on Socioeconomic Conditions of the Region



Source: Authors' calculations based on the study's primary survey data.

Insights from KIIs and FGDs

The project spurred socioeconomic activity, as observed by all participants. For instance, farm-to-market access has improved, industries have been set up, and job opportunities have increased. Key informants highlighted its impact on travel time, fuel consumption, health, and education. According to the key informants, the road's construction has brought better access to healthcare and educational facilities, directly improving local lives, including reduced travel time and improved fuel consumption after the construction of the HMDC. These impacts underscore the project's pivotal role in uplifting the region's socioeconomic fabric.

"The improved road has made it so much easier and convenient for farmers and traders to transport goods. It's a huge relief for business operations, especially with perishable goods. Moreover, it has provided ease to travelers, transporters, and businesses." - FGD par-ticipants.

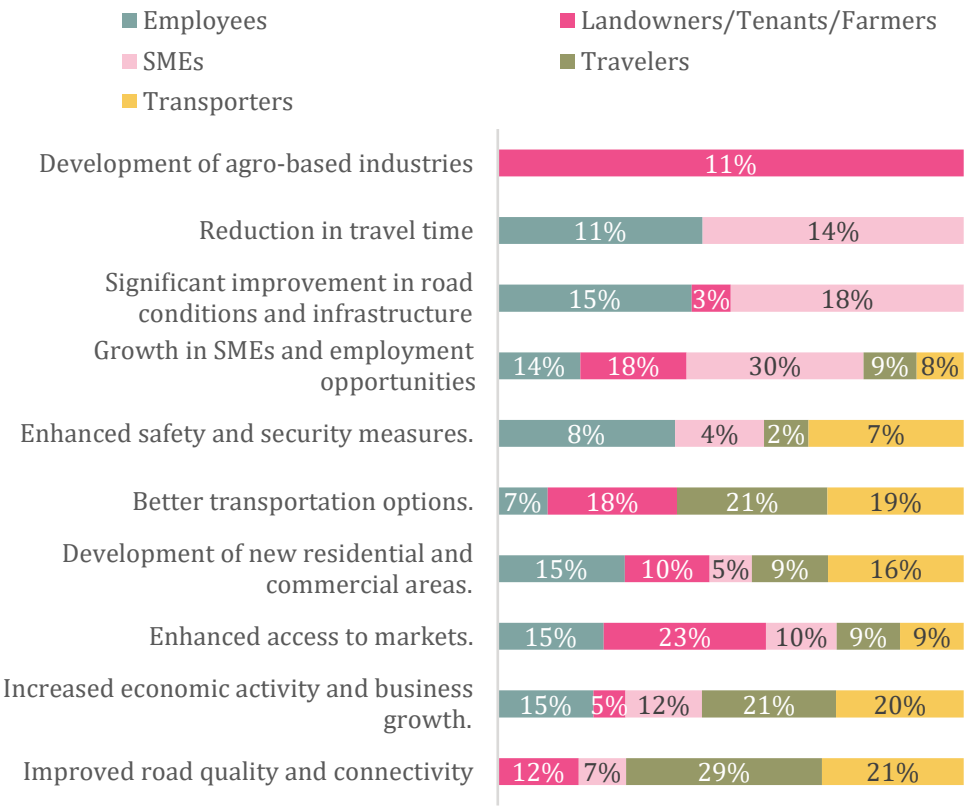
Changes Observed in the Overall Development and Infrastructure of the Region Since the Construction of the HMDC

The research study revealed that the majority of the respondents (16%) witnessed the growth of SMEs and employment opportunities in the region. A significant proportion of travelers (29%) observed improved road quality and connectivity, which was also noted by 21% of transporters, 12% of landowners/farmers, and 7% of SMEs. Enhanced access to markets was highlighted predominantly by landowners/farmers (23%), while 15% of employees and 10% of SMEs also shared this view.

Regarding economic activity and business growth, 15% of employees, 21% of travelers, 20% of transporters, and 12% of SMEs acknowledged this improvement. Better transportation options were noted by 21% of travelers, followed by 19% of transporters and 18% of landowners/farmers, but this change was less pronounced among employees and SMEs. The development of new residential and commercial areas was recognised by 15% of employees, 10% of landowners/farmers/tenants, and smaller proportions of travelers (9%) and transporters (16%).

Growth in SMEs and employment opportunities stood out most for SMEs (30%), with 18% of landowners, 14% of employees, 9% of travelers, and 8% of transporters also noting this change. Improvements in road conditions and infrastructure were particularly significant for SMEs (18%) and employees (15%), with 3% of landowners/farmers also acknowledging this change. Reduction in travel time was another improvement that resonated with 14% of SMEs, 11% of employees, and a smaller group of other respondents. The development of agro-based industries was uniquely reported by 11% of landowners/tenants and farmers. Lastly, enhanced safety and security measures were observed by 8% of employees, 7% of transporters, and 4% of SMEs, with minimal input from other groups.

Figure 17: Changes and Development after the HMDC



Source: Authors' calculations based on the study's primary survey data.

Insights from KIIs and FGDs

The perceptions of the changes varied across groups, with travelers and SMEs particularly emphasizing road quality, connectivity, and transportation improvements. At the same time, landowners/farmers prioritized enhanced access to markets and the development of agro-industries. Employees and transporters acknowledged a diverse range of benefits, highlighting the multifaceted impact of the HMDC project on regional development and infrastructure.

> *"This surge in land values has spurred new investments, especially in real estate and housing developments. New housing schemes and businesses are popping up along the road. The economic activity has increased, and many people have started new ventures."* – An FGD participant.

The majority of participants observed a noticeable increase in business activity along the dual carriageway, with new shops, factories, and markets emerging in the wake of the road's completion. One participant noted: *"Before HMDC, there were 4 shops; now there are 72 in Khuwaja Market."* Another participant commented on the direct impact on employment: *"So many people have acquired jobs and labour work after the construction of this road."* These changes indicate a thriving local economy, with new businesses providing job opportunities and contributing to economic growth in the region.

The Establishment of New SMEs/Businesses after the HMDC

The data revealed that different stakeholders had varying levels of awareness of establishing new SMEs and businesses following the construction of the HMDC.

Among employees, 65% reported the establishment of new businesses, while 5% disagreed, and 30% were unsure, indicating that while a majority acknowledged the creation of new SMEs, there was a significant portion of employees who were uncertain about such developments.

Landowners, tenants, and farmers displayed a higher level of awareness, with 85% confirming the emergence of new businesses, while only 10% stated otherwise. However, 5% of this group were unsure, indicating a minor degree of uncertainty in recognizing the impact of HMDC on business growth.

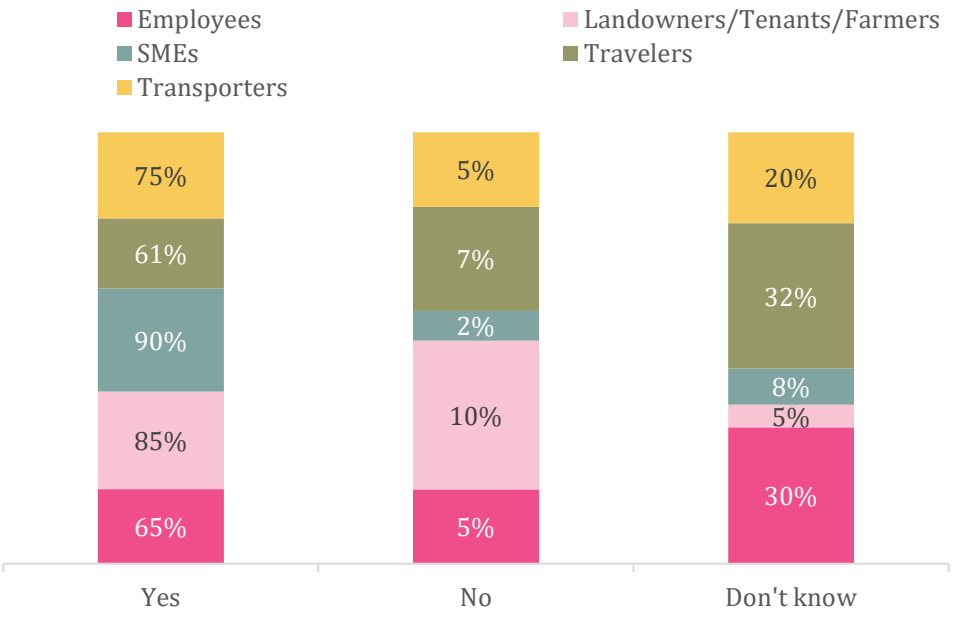
SMEs themselves were the most confident in the positive economic impact of the HMDC, with 90% affirming the establishment of new businesses. A small 2% disagreed, and 8% were uncertain, suggesting that the majority of SMEs felt the benefits of the road project in fostering business activity.

Travelers showed a lower level of acknowledgement compared to other groups, with 61% confirming the emergence of new businesses and 7% disagreeing. However, a notable 32% of travelers were uncertain about the creation of new businesses, highlighting that the road project's effect on local entrepreneurship might not have been as visible to this group.

Transporters reported a relatively high level of awareness, with 75% acknowledging the establishment of new businesses, while 5% disagreed. A smaller portion, 20%, was uncertain, suggesting that while most transporters recognized the development of new businesses, there was still some level of uncertainty.

The research results suggested that landowners, SMEs, and transporters were most aware of new business establishments due to the HMDC, while employees and travelers exhibited a higher level of uncertainty regarding this economic outcome.

Figure 18: New Businesses Established After the HMDC



Source: Authors' calculations based on the study's primary survey data.

Insights from KIIs and FGDs

The majority of respondents shared that alongside the road, new infrastructure has emerged, including petrol pumps, factories, and showrooms, signaling the growth of the local economy. The majority of the respondents mentioned that a cotton factory and motor showroom had been established after the HMDC. These developments reflect the positive effects of the road on regional infrastructure, which supports local businesses and employment opportunities.

There has been a noticeable increase in residential development along the road, with land being repurposed for housing schemes. The majority of the participants noted that land beside the road was being sold for PKR 1,500–2,000 per square foot for housing. This transformation is turning the

region into a semi-urban area, creating new opportunities for residents and businesses. However, the shift from agricultural to residential land raises questions about the long-term implications for local food production.

Creation of New Jobs for the Community as A Result of the HMDC Project

The perceptions of various stakeholders regarding the creation of new jobs in their communities as a result of the HMDC project were also recorded.

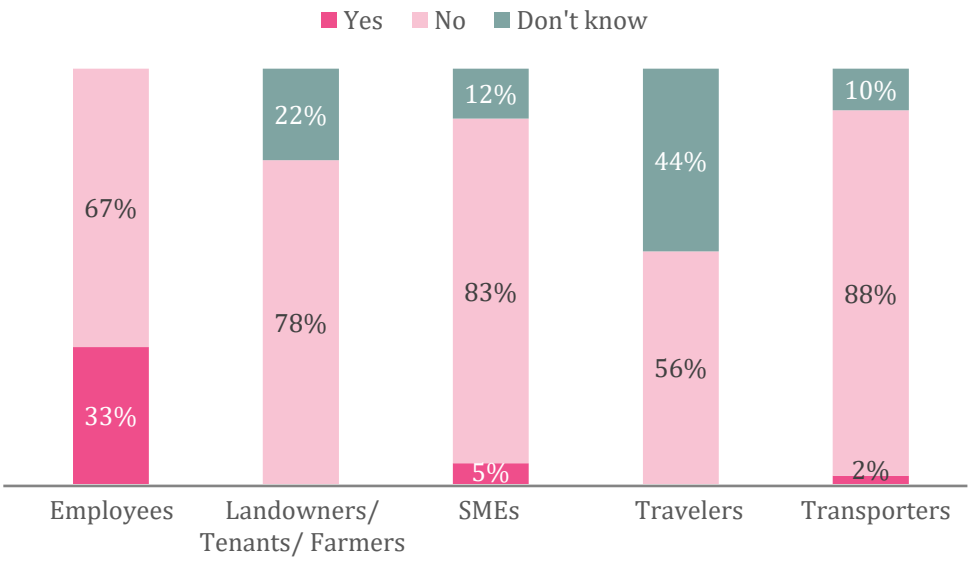
Among employees, 33% reported that new jobs had been created in their community, while 67% believed no new jobs were generated. This indicates limited job creation for this group despite the project. Landowners, tenants, and farmers had a largely negative view, with 78% stating that no jobs were created and only 22% expressing uncertainty. None explicitly reported job creation, reflecting minimal direct employment benefits for this group.

SMEs overwhelmingly indicated that no new jobs were established, with 83% responding negatively and 12% expressing uncertainty. Only 5% acknowledged job creation, suggesting a limited economic impact on employment within this sector. Travelers were divided, with 56% stating no new jobs were created, while 44% were unsure. No one confirmed new job creation, possibly due to indirect involvement with community-level employment opportunities.

Transporters were the most skeptical, with 88% reporting no job creation, 10% expressing uncertainty, and only 2% acknowledging new jobs. This underscores minimal perceived benefits in terms of employment for this stakeholder group.

The HMDC project appears to have had a negligible impact on job creation across all surveyed groups, with a majority either denying its effect or being uncertain. These findings suggest that while the project may have provided other economic or infrastructural benefits, its direct influence on employment opportunities is limited.

Figure 19: Creation of New Jobs



Source: Authors' calculations based on the study's primary survey data.

Insights from FGDs and KIIs

The majority of the participants strongly endorsed that employment generation was another standout achievement, with over 200 jobs created during the project's life cycle. Particular efforts were made to empower women. Integrating women into the workforce has been one of the most rewarding outcomes, shared by one of the officials during the interview, emphasizing the importance of inclusivity in economic growth.

> *"For many women, this project marked their first formal employment opportunity, fostering both economic independence and social equity."* – A key informant.

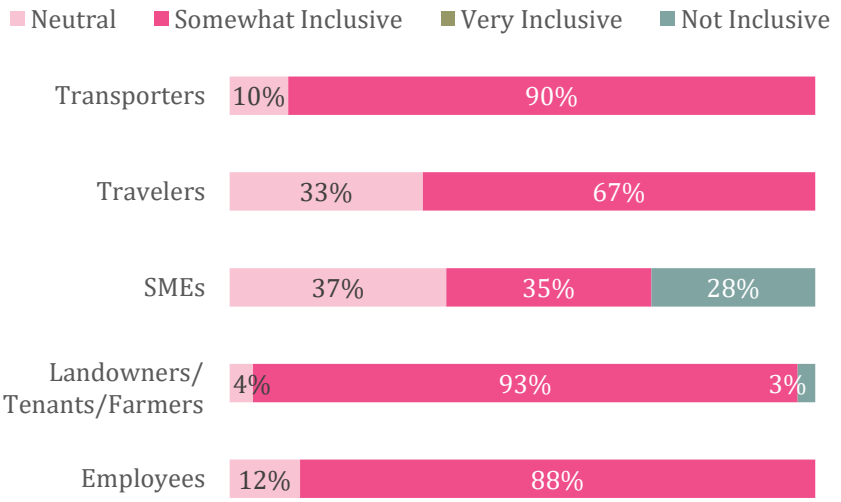
Inclusivity of Job Creation in Terms of Gender and Diversity

The survey also provided insights into perceptions of job creation inclusivity in terms of gender and diversity. Among employees, majority of the respondents i.e., 88% viewed job creation as somewhat inclusive, with the remaining 12% expressing a neutral stance. Similarly, the majority of landowners/tenants/farmers, at 93%, saw job creation as somewhat inclusive, with a minimal 4% remaining neutral and 3% perceiving it as not inclusive.

For SMEs, the perception was split, with 35% viewing job creation as somewhat inclusive, 37% as neutral, and a significant 28% considering it not inclusive. Among travelers, 67% found job creation somewhat inclusive, 33% neutral, and no respondents identified it as very inclusive or not inclusive. Transporters largely echoed a positive sentiment, with 90% considering job creation somewhat inclusive, 10% neutral, and none labeling it as very inclusive or not inclusive.

Perceptions across groups highlight a dominant view of job creation being somewhat inclusive, though notable percentages, particularly within SMEs and travelers, reflected a neutral or less favorable assessment of inclusivity.

Figure 20: Gender Inclusivity in New Jobs



Source: Authors' calculations based on the study's primary survey data.

Insights from FGDs and KIIs

However, there were concerns about the inclusivity of the economic benefits, particularly for gender and marginalized groups. A few respondents pointed out that women and other vulnerable communities have not had access to the new job opportunities created by the road. One respondent explained: *"Especially for females, there are very limited jobs or opportunities."* This highlights the need for more targeted initiatives to ensure that all community members, including women and marginalized groups, benefit equally from the economic changes brought about by the project.

> *"Including more women in the workforce is not just a social imperative but an economic opportunity."* – Community members in an FGD.

The Influence of the Project on Land Values, Agricultural Development, and Overall Regional Growth

Rating of the HMDC Project and Its Impact on Landowners/Tenants/ Farmers

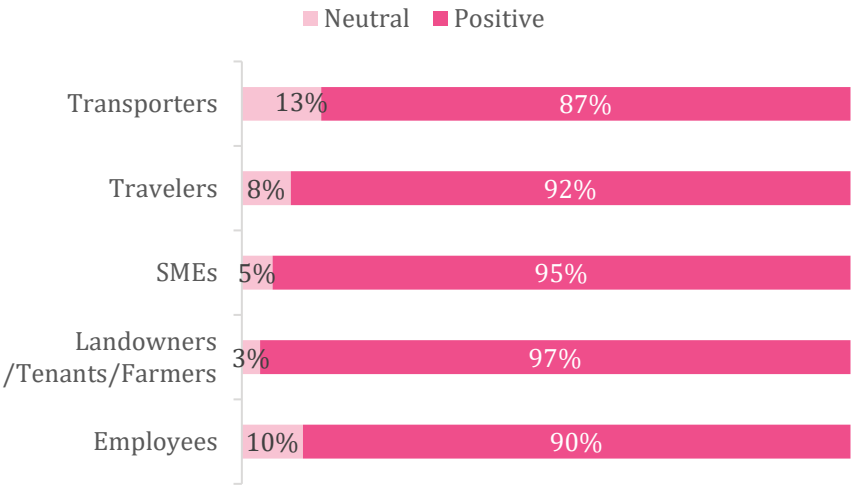
The HMDC project has been overwhelmingly rated positively by various stakeholders, reflecting its significant impact on the region's agricultural community. Among landowners, tenants, and farmers, an impressive 97% viewed the project as positive, indicating widespread recognition of its benefits in enhancing access to markets, improving transportation efficiency, and facilitating agricultural development.

Similarly, 95% of SMEs rated the project positively, acknowledging its role in boosting agricultural trade and logistics. Employees and travelers also shared this positive sentiment, with 90% and 92%, respectively, rating the project favorably. These groups likely appreciated the improved connectivity and accessibility the project has brought to the region.

Transporters, while still largely positive, reported the lowest percentage among the groups, with 87% rating the project positively. This could reflect challenges such as toll costs or specific issues related to transportation logistics.

The project's positive impact on the agricultural sector and the regional connectivity has been widely recognized, with minimal neutrality or dissatisfaction across stakeholder groups. This reflects the project's effectiveness in addressing key regional transportation and agricultural needs.

Figure 21: Impact of the HMDC on the Farming Community



Source: Authors' calculations based on the study's primary survey data.

Insights from KIIs and FGDs

For the majority of the participants, the road has had a positive impact on agriculture by improving the transportation of crops to urban markets, reducing spoilage, and enabling farmers to get better prices. As one farmer shared: "*Crop yield can now be transported to the market easily.*" This improvement has made agriculture more profitable, particularly for farmers who can now sell their products with fewer delays and better price negotiations. This is especially important for perishable goods, which previously faced significant challenges in reaching markets on time.

> *"With the new road, transporting our crops has become much easier. This has directly led to better sales and increased income. The quicker movement of goods has also reduced costs for farmers, particularly those dealing in perishable goods."* – FGD participants

Rating of the Contribution of the HMDC to the Promotion of Agricultural Activity in the Region

The HMDC was perceived as a key driver in promoting agricultural activity in the region, with varying levels of acknowledgment across different stakeholder groups. A significant majority, including 70% of employees, 62% of landowners and farmers, 75% of SMEs, and 80% of transporters, rated the project as having made a significant contribution to agricultural activity. This

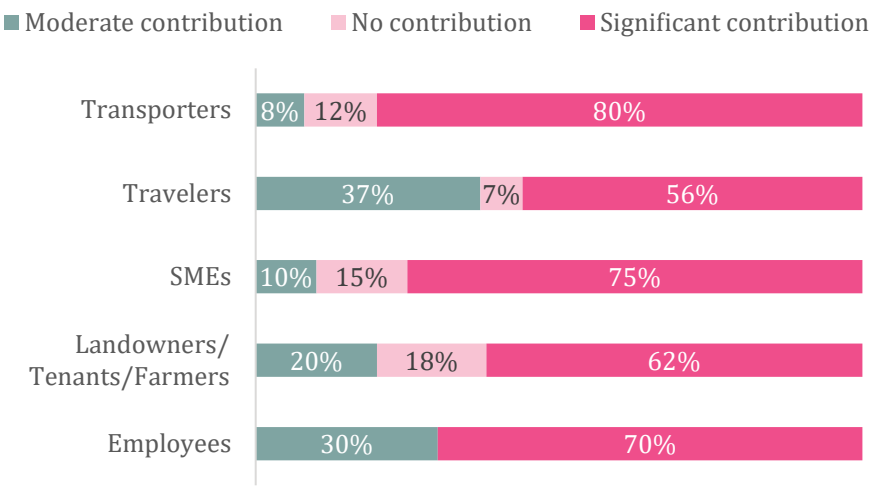
highlights the crucial role of the project in facilitating market access, reducing transportation costs, and improving logistics for agricultural products.

Travelers were slightly less enthusiastic, with 56% perceiving a significant contribution, while 37% rated the contribution as moderate. This mixed sentiment might reflect the indirect involvement of travelers in agricultural activities compared to other stakeholders.

On the other hand, 18% of landowners/farmers and 15% of SMEs believed the HMDC did not contribute to agricultural activity, possibly indicating localized challenges or unmet expectations in specific areas. Among travelers, 7% shared this sentiment, while 12% of transporters also felt the project had no noticeable impact.

The HMDC has been widely recognized for its positive impact on promoting agricultural activity, with the majority acknowledging its significant role, despite some differences in perception based on stakeholders' specific engagements with agriculture.

Figure 22: Contribution of HMDC in Agricultural Activity



Source: Authors' calculations based on the study's primary survey data.

Insights from KIIs and FGDs

The establishment of mango processing units stood out as an example of agro-industrial diversification, creating significant value addition. There is a shift from raw produce export to processing in the region, which has added jobs and revenue streams, noted a project official. Moreover, these industries have been established with the support of USAID and other development partners. This shows that the HMDC has attracted new investors and opened new avenues for economic growth in the region.

> *"The establishment of mango processing units demonstrated the project's ability to catalyze industrial diversification in the region."*
> – A key informant

Impact of the HMDC on Land Value in the Region

The survey data showed great awareness of the impact of the HMDC on land values across most stakeholder groups.

Among employees, 83% reported noticing an impact on land value, with only 11% stating no impact, and 6% being unsure. This indicates that a large majority of employees observed or recognized the positive effect of the HMDC on land values.

Landowners, tenants, and farmers recognized increases in land value, with 98% confirming an impact. Only 2% reported no noticeable effect, while none were uncertain. This suggests that the HMDC has had a highly visible and positive impact on land values in areas where landowners are present.

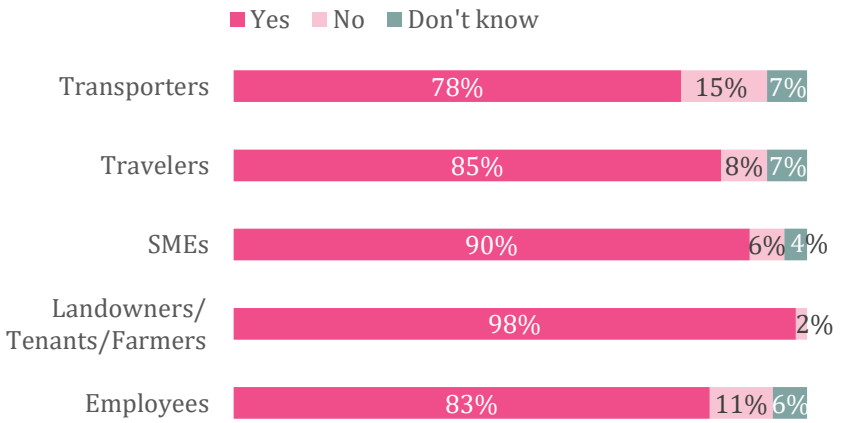
SMEs also acknowledged the impact, with 90% observing changes in land value. A smaller proportion, 6%, indicated no impact, while 4% were uncertain. This high recognition among SMEs suggests that the road project's influence on land value is noticeable to local businesses, likely due to increased accessibility and business activity in the area.

Travelers reported a similarly high recognition rate, with 85% noticing an impact on land value, while 8% saw no effect and 7% were unsure. This suggests that the improved infrastructure brought about by HMDC was visible enough to travelers, though some uncertainty remained for a small portion of respondents.

Transporters reported the lowest level of recognition, with 78% acknowledging an impact on land values. However, 15% of transporters felt there was no noticeable impact, and 7% were uncertain. This indicates that while most transporters recognized changes in land value, a significant proportion did not perceive any effects.

The findings from the KIIs, FGDs, and survey results revealed that the majority of the participants acknowledged the HMDC's positive influence, with a notable surge in land values.

Figure 23: Impact of HMDC on Land Value



Source: Authors' calculations based on the study's primary survey data.

The Extent of Increase in the Value of Land/Property after the HMDC Project

45% of employees reported an increase in land/property values between PKR 100,000 and PKR 500,000. Additionally, 25% reported the increase exceeding PKR 5 million, and 17% indicated gains of PKR 600,000 to PKR 1 million. Smaller percentages noted increases of PKR 1-2 million (5%) and PKR 3-4 million (8%), suggesting that while moderate increases were more common, a significant minority benefited from substantial gains.

Landowners, tenants, and farmers reported significant increases in land/property values, with 54% observing gains of PKR 3-4 million and 26% reporting increases of more than PKR 5 million. However, only 5% reported increases of PKR 100,000 – PKR 500,000 or PKR 600,000 to PKR 1 million, and 10% indicated increases of PKR 1-2 million. This highlights the considerable impact of the HMDC project on agricultural land values.

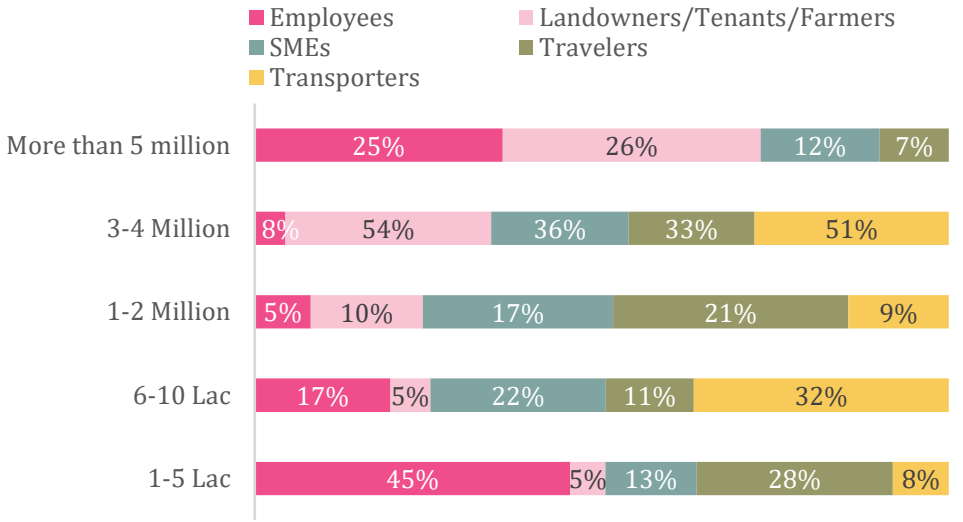
SMEs primarily reported increases of PKR 1-2 million (17%), followed by gains of PKR 600,000– 1 million (22%) and PKR 3-4 million (36%). A smaller proportion (13%) noted increases of PKR 100,000 – 500,000, while 12% experienced increases of more than PKR 5 million. These findings suggest that the project had a varied impact on commercial land/property values, with most gains falling within the mid-range.

Travelers observed a mixed impact on land/property values, with 21% reporting increases of PKR 1-2 million and 28% citing gains of PKR 100,000-500,000. Additionally, 33% noted increases of PKR 3-4 million, while smaller percentages reported gains of PKR 600,000-1 million (11%) or more than PKR 5 million (7%). These responses suggest a diverse impact on land/property values for individuals frequently using the HMDC.

Transporters predominantly reported increases in the land/property values of PKR 3-4 million (51%), with 32% indicating gains of PKR 600,000-1 million. Smaller proportions noted increases of PKR 1-2 million range (9%) and PKR 100,000-500,000 (8%). This suggests that transporters perceived relatively moderate but consistent increases in land/property values attributable to the HMDC.

The HMDC project appears to have significantly increased land and property values, with an increase of 3-4 million reported by 36% of all stakeholders, reflecting the varied use and ownership of land and property along the route

Figure 24: Increase in Land/Property Value After the HMDC



Source: Authors' calculations based on the study's primary survey data.

Insights from KIIs and FGDs

The HMDC road has led to a dramatic increase in land/property values, which has benefited landowners. The majority of the participants were of the view that, *"Before HMDC, an acre was worth PKR 4–7 million; now it has exceeded PKR 10 million."* This increase in land prices has brought significant economic opportunities to landowners who have sold or developed their land.

Noticeable Changes in the Overall Agriculture Sector of the Region Since the Construction of the HMDC

The construction of the HMDC has brought notable changes to the agricultural sector in the region, as reported by different stakeholder groups. Improved access to agricultural markets was identified as a significant benefit, with 30% of employees, 23% of landowners and farmers, and 33% of SMEs acknowledging this change. However, only 7% of travelers and 16% of transporters observed this improvement, reflecting variations in perception depending on their roles in the sector.

Increased transportation efficiency for farm products was another key improvement, highlighted by 14% of employees, 18% of landowners and farmers, 20% of SMEs, and 33% of transporters. This underscores the importance of the HMDC in reducing transit times and improving logistics for perishable and non-perishable agricultural goods.

12% of the landowners and farmers reported an improvement in the availability of agricultural inputs, such as seeds, fertilizers, and machinery, while 10% of SMEs reported the same. Additionally, an increase in the value of crop yield was noted by 11% of landowners, 16% of farmers, and 16% of SMEs, suggesting enhanced economic returns on agricultural activities.

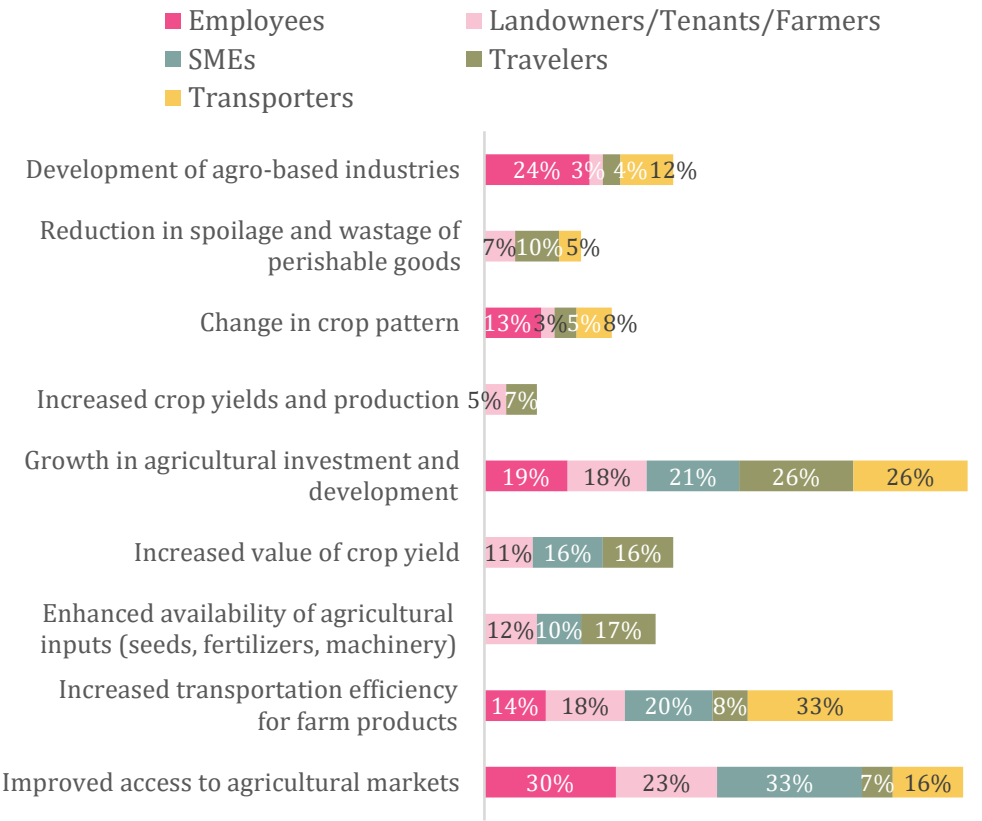
Growth in agricultural investment and development was recognized as a positive outcome by 19% of employees, 18% of landowners, and 21% of SMEs. Notably, 26% of travelers and transporters also perceived this as a significant change, indicating broader recognition of the HMDC's impact on regional development.

Some stakeholders mentioned changes in crop patterns, with 13% of employees and 3% of landowners and farmers noting this shift. Additionally, 7% of landowners and 5% of travelers observed a reduction in spoilage and wastage of perishable goods, likely due to improved transportation facilities.

Finally, the development of agro-based industries was identified as a positive change by 24% of employees, 3% of landowners, and 12% of transporters. However, this benefit was less commonly reported by SMEs (4%) and travelers (4%), possibly reflecting differences in their engagement with agricultural industrialization.

Overall, 22% of the respondents reported growth in agricultural investment and better access to agricultural markets in each category as a significant change in the agriculture sector since the construction of the HMDC. The HMDC has facilitated better market access, improved transportation, and fostered investment and development in agriculture, while also addressing challenges related to wastage and input availability. These changes have contributed to the growth and modernization of the agricultural sector in the region.

Figure 25: Changes in the Agricultural Sector after the HMDC



Source: Authors' calculations based on the study's primary survey data.

Insights from KIIs and FGDs

There has been a noticeable shift in agricultural practices due to better market access. Many landowners/farmers have transitioned from growing traditional crops to higher-value crops, which offer better returns. A majority of the participants explained that *"Wheat cultivation has reduced in many parts of the region, and people are now harvesting bananas."*

Additionally, most of the growers are now cultivating grass as they are earning more from cultivating grass due to extended and easy access to markets, i.e., Hyderabad, Mirpur Khas, Tando Allahyar, and Karachi. This change reflects the economic adaptability of farmers, who are taking advantage of the new infrastructure to cultivate crops that have higher market demand.

Several participants highlighted the evolving dynamics of land use in the region, emphasizing the trend of converting non-agricultural land into residential or commercial properties, driven by rising land values. As the majority of the participants pointed out, "People have started converting their non-agricultural lands into housing schemes." This transformation underscores the region's economic growth and the increasing demand for housing, infrastructure, and urban amenities. It signifies a shift towards diversification, creating opportunities for expanded economic activities, improved living conditions, and enhanced infrastructure development. It indicates a shift in priorities driven by urbanization and demographic changes, showcasing the region's adaptability to new economic and social realities.

There has been a noticeable increase in residential development along the road, due to which the land is being repurposed for housing schemes. The majority of the participants noted that land along the road, which was previously sold for PKR 500-700 per square foot, is now worth PKR 1,500–2,000 per square foot. This transformation is turning the region into a semi-urban area, creating new opportunities for residents and businesses.

Provision of Agricultural Land from the Community for HMDC Project Development

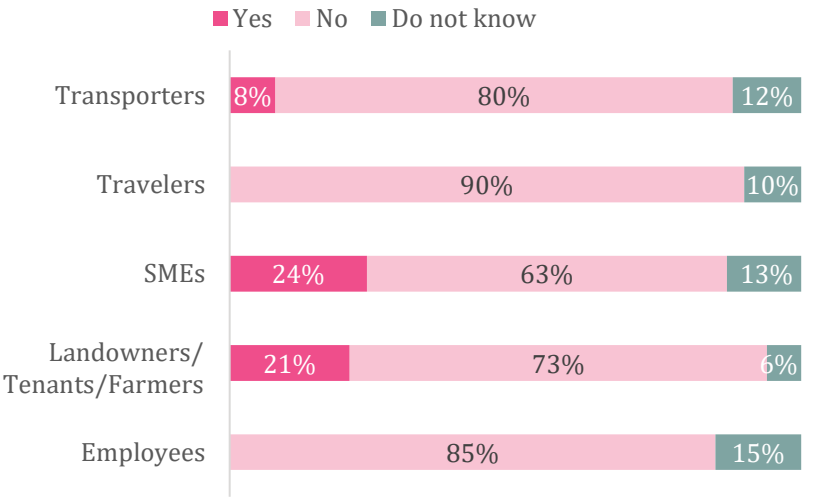
The survey responses indicated that a minority of individuals and communities provided agricultural land for the HMDC project. Among landowners, tenants, and farmers, 21% reported that they contributed their land for the project, while a slightly higher percentage (24%) of SMEs indicated the same. However, only 8% of transporters confirmed land provision, reflecting a relatively low level of direct involvement by this group.

The majority of respondents across all stakeholder categories stated that neither they nor their community members had provided land for the project. This response was most pronounced among employees (85%), travelers (90%), and transporters (80%), highlighting their limited connection to land ownership or usage in the context of the HMDC development.

A small percentage in each group did not know whether anyone in their community had provided land. This was evident among 15% of employees, 6% of landowners and farmers, 13% of SMEs, 10% of travelers, and 12% of transporters. This may reflect a lack of awareness or indirect involvement in the land acquisition process.

Some individuals and communities contributed agricultural land for the project. Most did not, and a smaller group was unsure whether their community had provided land.

Figure 26: Provision of Land for the Construction of the HMDC



Source: Authors' calculations based on the study's primary survey data.

Insights from KIIs and FGDs

There were also concerns regarding the fairness of the land acquisition process. Several participants mentioned that some landowners did not receive adequate compensation or were not informed about how their land was used. A few respondents stated that, *"Some people received incentives*

through referrals, but many did not know how much land was utilized or received nothing." These insights highlight the need for more transparent and equitable land acquisition practices, as well as clearer communication about the compensation process.

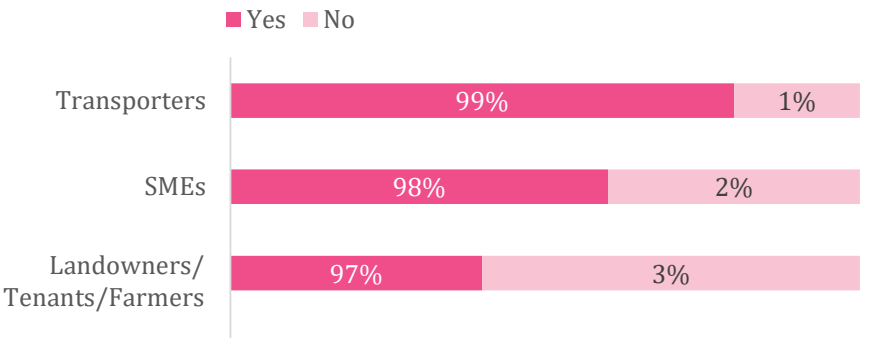
Satisfaction with the Process and Policies of the PPP and the Government of Sindh for Property Compensation and Resettlement

Those who provided agricultural land for the HMDC project expressed great satisfaction with the process and policies of the PPP initiative of the Government of Sindh regarding property compensation or resettlement. An impressive 97% of landowners and tenants expressed satisfaction, closely followed by 98% of SMEs, and 99% of transporters. This indicates that the majority of stakeholders found the compensation or resettlement measures to be fair and effectively implemented.

Only a small minority reported dissatisfaction, with 3% of landowners and tenants, 2% of SMEs, and just 1% of transporters indicating that the policies or processes did not meet their expectations. These responses suggest that while the overall perception of the PPP framework was highly positive, there may be isolated cases where improvements could have been made to address specific grievances or concerns.

This high level of satisfaction reflects well on the efforts of the Government of Sindh to ensure equitable compensation and resettlement policies during the HMDC development.

Figure 27: Satisfaction with Land Compensation Policy



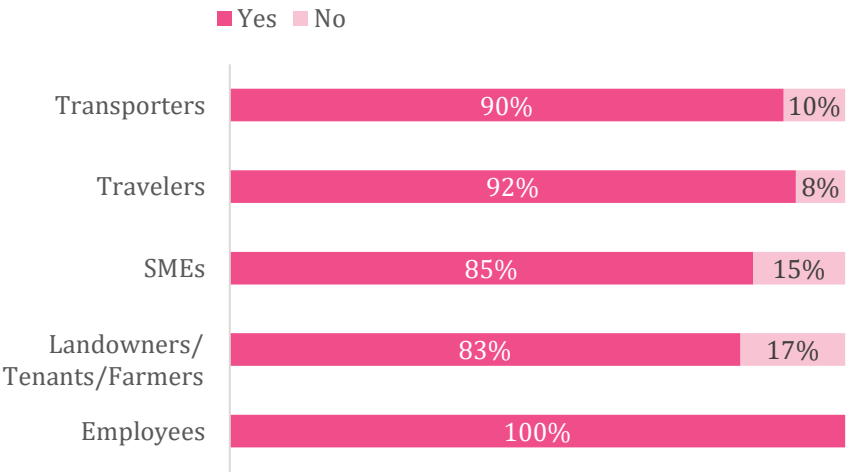
Source: Authors' calculations based on the study's primary survey data.

Environment and People Friendliness of the HMDC Project

The HMDC is largely viewed as being both people- and environment-friendly by most stakeholders. Respondents from the employees category were unanimous about the project's people- and environment-friendliness. Similarly, the majority of travelers (92%), transporters (90%), SMEs (85%), and landowners/tenants/farmers (83%) also shared this positive sentiment.

However, a minority of stakeholders expressed concerns, with 17% of landowners/tenants/farmers and 15% of SMEs indicating that the HMDC might not be as people- or environment-friendly as it is perceived to be. Travelers (8%) and transporters (10%) also voiced similar reservations, albeit in smaller proportions. These concerns may stem from localized environmental impacts or specific community issues that remain unaddressed. The responses highlight a broadly favorable perception of the HMDC in terms of its contribution to community welfare and environmental sustainability, though some room for improvement remains in addressing the concerns of specific groups.

Figure 28: Environment- and People-Friendliness



Source: Authors' calculations based on the study's primary survey data.

Insights from KIIs and FGDs

A majority of the participants recognized the efforts made to address environmental concerns, particularly through tree-planting initiatives along the road. Participants observed that, *"Tree plantation has increased after the construction of the HMDC."* However, some participants expressed concern that native species were being replaced with Conocarpus in huge quantities, which is not a native species to the area. While the road project has caused some environmental degradation, these efforts indicate a commitment to balancing development with environmental sustainability.

Despite the infrastructure improvements, concerns were raised about road safety, particularly with the rise in traffic volume. Some participants reported that the increase in vehicles has led to more accidents. A majority of the participants expressed that, *"Several people have lost their lives and livestock, and suffered from severe injuries due to accidents on the new road."*

This highlights the urgent need for safety measures, such as pedestrian bridges, traffic control devices, and awareness campaigns, to prevent further accidents and fatalities.

The Effectiveness of the PPP Model in the Successful Implementation and Sustainability of the HMDC Project

Public-Private Partnership Governance

The PPP framework as the governance model was singled out as a key driver of the project's success. This model ensured shared risks and benefits by fostering collaboration between public and private entities. Clear revenue-sharing mechanisms, supported by independent audits and escrow accounts, bolstered financial transparency and stakeholder confidence.

> *"The clear revenue-sharing mechanisms and independent audits ensured mutual trust between public and private entities."* – A key informant.

The PPP model's strengths lie in its ability to pool expertise and resources while effectively distributing risks. Global consultants from the Asian Development Bank (ADB) contributed significantly. As one participant reflected: *"Consultants with global experience shaped the project, making it financially viable and operationally efficient."*

A senior officer remarked: *"The PPP framework allowed for shared responsibility, ensuring that both entities had a vested interest in the project's success."* The success of this governance model has provided a replicable blueprint for future infrastructure projects, especially in regions with complex development needs.

However, challenges like communication gaps and law-and-order disruptions arose during implementation. The government was responsible for addressing security issues, but a lack of coordination at the district level sometimes created delays, a key informant shared.

Public Sector Learning

The HMDC project can become a template for future PPP projects in Sindh. It has demonstrated the viability of the PPP model for infrastructure development, offering insights into financial monitoring and operational efficiency. As one respondent put it, *"The lessons learned here are already being applied to other projects like the Malir Expressway and M5-M9 link road."*

One key innovation was expanding real-time access to project monitoring data, as explained by a respondent, *"We learned that the electronic toll and ticket management systems provide broader access, allowing project managers to monitor cameras and revenue remotely."*

Challenges and Risk Management

Despite its notable achievements, the project faced significant hurdles that required innovative risk management and adaptive strategies. Persistent community resistance to toll collection posed a recurring issue. This was mitigated through several awareness campaigns that highlighted the long-term benefits of improved infrastructure.

> *"Partnering with local administration was critical in managing crowds and community, flooding risks and encroachment issues."* - A key informant.

One of the key informants said that challenges like communication gaps and law-and-order disruptions arose during implementation phase due to unacceptance of toll charges by the community and they resist, as there was no inclusion of the relevant district government department in the planning phase after realizing the gap the concerned departments were included, The

government was responsible for addressing security issues, but a lack of coordination at the district level sometimes created delays, a key informant shared.

We engaged local influencers to explain how tolls fund better roads and services, explained a project manager, emphasizing the importance of trust-building. Another challenge was unauthorized road usage, which required enhanced monitoring and enforcement.

> *"Community outreach programs were essential in addressing misconceptions about tolls and demonstrating the tangible benefits of the project,"* - A key informant.

Natural disasters, such as flooding, compounded by economic shocks like inflation and COVID-19, tested the project's resilience. Collaborative efforts with local administration proved instrumental. Addressing encroachments during floods required close coordination with local authorities to prevent further damage, stated one informant. These experiences underscored the need for flexibility, timely interventions, and stakeholder collaboration in overcoming complex challenges.

> *"We had to recalibrate budgets multiple times to account for inflation and the economic fallout of COVID-19."* – A key informant.

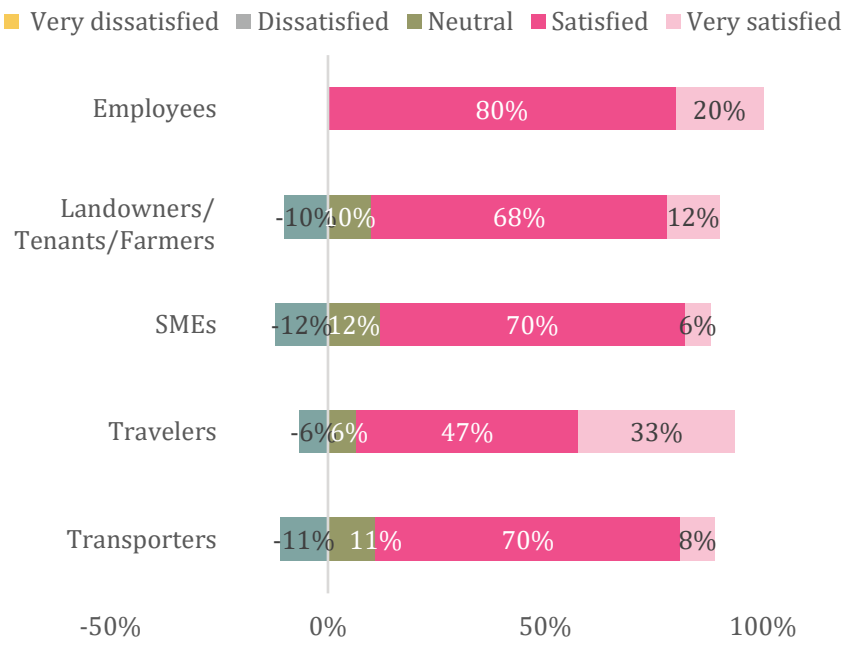
Satisfaction with the Overall Implementation of the HMDC Project under the PPP Model

The survey data showed a detailed assessment of satisfaction levels among different stakeholders regarding the overall implementation of the HMDC project under the PPP model. Employees demonstrated the highest levels of satisfaction, with 80% of respondents reporting that they were satisfied, and 20% indicating they were very satisfied. Landowners, tenants, and farmers similarly expressed significant satisfaction, with 68% being satisfied, and 12% stating they were very satisfied. Neutral responses from this group accounted for 20%.

SMEs also showed a positive response, with 70% indicating they were satisfied, while a smaller proportion, 6%, were very satisfied. However, 24% of SMEs remained neutral about the project. Among travelers, 47% reported being satisfied, and a notably higher percentage, 33%, expressed being very satisfied, which represents the highest proportion of very satisfied responses across all stakeholder groups. On the other hand, 12% of travelers remained neutral.

Transporters shared similar satisfaction levels with SMEs, as 70% reported being satisfied, but only 8% indicated they were very satisfied, while 22% of transporters provided neutral responses. Overall, the data highlights varying degrees of satisfaction among the stakeholder groups, with employees, landowners, and SMEs demonstrating the highest levels of contentment, whereas travelers and transporters, while largely satisfied, showed a more polarized distribution of responses.

Figure 29: Satisfaction with the HMDC under PPP



Source: Authors' calculations based on the study's primary survey data.

The Extent to Which the PPP Model Has Effectively Reduced Costs and Ensured Financial Efficiency in the HMDC Project

The data indicated differing levels of agreement among stakeholders regarding the effectiveness of the PPP model in reducing costs and ensuring financial efficiency in the HMDC project. Employees showed a strong positive response, with 73% reporting satisfaction with the financial efficiency of the PPP model, and 17% expressing strong approval by stating they were very satisfied. A smaller proportion of employees, 10%, remained neutral.

Landowners, tenants, and farmers demonstrated a high level of agreement, with 83% satisfied with the financial efficiency achieved through the PPP model, and 3% stating they were very satisfied. However, 14% of this group remained neutral, indicating some level of uncertainty or lack of direct impact on their experiences.

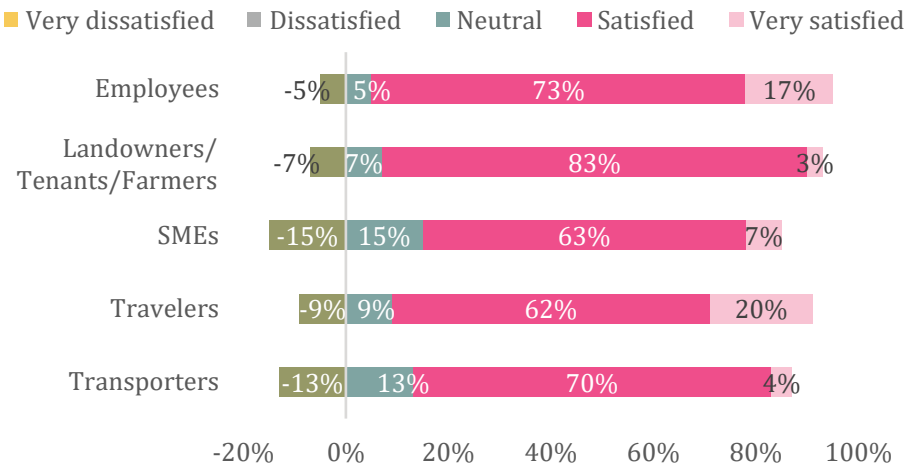
SMEs exhibited mixed perceptions. While 63% of SMEs reported satisfaction with the PPP model, only 7% expressed strong satisfaction, and a significant 30% remained neutral, suggesting cautious or uncertain views regarding the financial outcomes of the project.

Travelers reported a relatively high level of satisfaction, with 62% acknowledging the effectiveness of the PPP model in achieving financial efficiency, and 20% stating they were very satisfied. However, 18% of travelers remained neutral, indicating that some may not have observed or experienced direct financial benefits.

Transporters shared similar patterns with SMEs, with 70% reporting satisfaction and 4% expressing strong satisfaction. However, 26% of transporters remained neutral, which reflected a notable degree of uncertainty or indifference regarding the financial aspects of the project.

The results suggested that employees, landowners, and farmers were the most confident in the financial efficiency of the PPP model, while SMEs, travelers, and transporters displayed more diverse responses, with a significant proportion expressing neutral opinions.

Figure 30: Agreement with the Efficiency of the PPP Financial Model



Source: Authors' calculations based on the study's primary survey data.

Insights from KIIs and FGDs

The minimum revenue guarantee (MRG) acted as a safety net, ensuring stability during periods of uncertainty. We ensured financial sustainability with a revenue model and a minimum revenue guarantee to cover shortfalls even during economic downturns, said one informant. These measures showcased innovative approaches to mitigate financial risks.

> *"Minimum revenue guarantees (MRG) provided a much-needed cushion during periods of reduced traffic."* – A key informant.

Structured loan repayment mechanisms further strengthened financial credibility, enabling the project to meet obligations without compromising operational priorities. This robust framework demonstrated the importance of financial discipline in maintaining long-term viability.

The Extent of Agreement with the Current Maintenance and Operational Management of the HMDC Is Highly Effective in Ensuring Its Sustainability

The responses revealed varying levels of agreement among stakeholders regarding the effectiveness of the current maintenance and operational management of the HMDC in ensuring its sustainability. Employees exhibited the highest level of agreement, with 90% agreeing that the management was effective and 10% strongly agreeing. This indicates that employees were overwhelmingly confident in the operational and maintenance efforts.

Landowners, tenants, and farmers also showed strong agreement, with 75% agreeing and 15% strongly agreeing. However, 10% of this group remained neutral, suggesting a minor portion may have been uncertain about the sustainability measures.

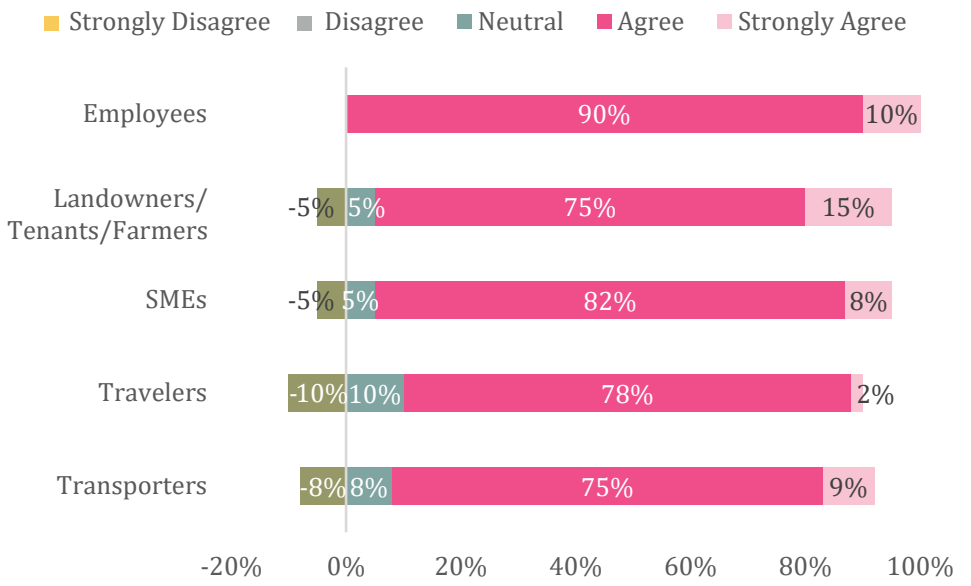
SMEs expressed a high level of confidence, with 82% agreeing and 8% strongly agreeing with the statement. Nevertheless, 10% of SMEs remained neutral, indicating some level of hesitation or uncertainty about the effectiveness of management.

Travelers demonstrated significant agreement, with 78% agreeing that the operational management was effective. However, only 2% strongly agreed, while 20% remained neutral, suggesting a notable proportion of travelers were either indifferent or unsure about the sustainability impact of the management.

Transporters displayed similar trends, with 75% agreeing and 9% strongly agreeing with the statement. Meanwhile, 16% of transporters were neutral, reflecting some uncertainty or limited direct benefits perceived by this group.

The results suggested that employees were the most confident in the maintenance and operational management of the HMDC, followed by SMEs and landowners. Travelers and transporters also expressed positive feedback, though with a slightly higher proportion of neutral responses, indicating some reservations or lack of direct awareness regarding sustainability efforts.

Figure 31: Extent of the Maintenance and Management of the HMDC



Source: Authors' calculations based on the study's primary survey data.

Insights from KIIs and FGDs

The financial model of the project also supports sustainability, with a user-pay system covering operational costs and loan repayments. A key informant remarked that *"The revenue model ensures long-term viability, and the government's initial equity support was crucial to attracting private investment."*

> *"Our proactive maintenance schedule ensured that minor issues were addressed before escalating, minimizing service disruptions."*
> – A key informant.

Sustainability formed a cornerstone of the project, focusing on long-term operational and environmental viability. Proactive maintenance schedules and daily inspections minimized infrastructure deterioration, ensuring uninterrupted service quality.

A key informant highlighted that they prioritized durable construction materials that not only extended the infrastructure's lifespan but also reduced the frequency of repairs.

Environmental sustainability was equally prioritized. Solar energy integration reduced operational costs and contributed to a lower carbon footprint. An official emphasized that incorporating renewable energy solutions was not just a cost-saving measure but a commitment to sustainable development. These efforts demonstrate how infrastructure projects can simultaneously address immediate operational needs and long-term environmental goals.

> *"Solar energy integration not only reduced operational costs but also highlighted our commitment to environmental sustainability."* A key informant.

Sustainability was integral to the project design, with provisions for a seamless transition at the end of the 30-year concession period. One participant explained that six months before contract completion, a handback activity would ensure the facility, including toll systems and equipment, is handed over in excellent condition.

Technological Innovations

Technology was a driving force behind the project's efficiency, transparency, and user-friendliness. The electronic toll and traffic management systems (ETTMS) revolutionized toll collection by automating processes and reducing human error.

> *"The electronic toll and traffic management system (ETTMS) was a game-changer in streamlining toll collection and ensuring revenue transparency."* –A key informant.

According to an officer, with ETTMS, they now have real-time revenue data, which ensures accountability and eliminates discrepancies, shared an officer. Other innovations, such as weigh bridges and advanced traffic management systems, further streamlined operations by minimizing congestion and improving vehicle flow.

Additionally, the use of machine-based road cleaning has optimized resources and reduced reliance on manual labor. A key informant noted that machine-based systems have not only improved efficiency but also enhanced safety and resource utilization. Collectively, these technological advancements elevated the project's operational standards and user experience.

Technology was a game-changer for the HMDC project. The introduction of the ETTMS and weighbridges enhanced efficiency and transparency. One of the key informants explained, ETTMS, implemented for the first time in Pakistan, not only streamlined toll collection but also provided real-time data on revenue and vehicle movement. Another added, Weighbridges ensured that vehicles complied with load limits, preserving road quality and safety. These advancements also offered lessons for future projects, such as broader access to real-time monitoring for stakeholders.

> *"Real-time monitoring has drastically improved accountability and decision-making."* – A key informant.

The quality of the construction under the Public-Private Partnership (PPP) model was widely praised, with many respondents noting that the road was built to a higher standard than government-managed projects. The majority of the participants commented that the road's build quality is the best under PPP. This sentiment reflects the success of the PPP model in ensuring high-quality infrastructure development.

> *"We worry that after the contract is over, maintenance will be neglected. The road needs regular upkeep to stay in good condition."* – FGD participants.

> *"The owner of the gobble cultivator should install tyres to protect the roads."* – An FGD participant.

Despite the praise for the initial construction, there were concerns about the road's long-term maintenance and sustainability. Some respondents feared that once the PPP contract ends, the road's quality might decline. A few participants feared that the quality would be maintained after the contract period ends. This raises important questions about the sustainability of the project and the need for continued investment in maintenance to preserve the infrastructure's quality.

Suitability of Toll Charges in Relation to the Accessibility and Quality of the HMDC

The findings about the fairness and reasonableness of the toll charges in relation to the accessibility and quality of the HMDC were diverse across different stakeholder groups. 90% of the employees who participated in the survey found the toll charges to be fair, while 10% were neutral. This indicates that employees generally viewed the toll charges as justified, considering the quality and accessibility of the road.

Landowners, tenants, and farmers showed a mixed response. While 56% found the toll charges fair, a notable 30% considered them unfair. Additionally, 14% were neutral, indicating some level of uncertainty or dissatisfaction with the toll fees. This suggests that while the road has brought benefits, a significant portion of this group felt that the toll charges were not reasonable in relation to the road's advantages.

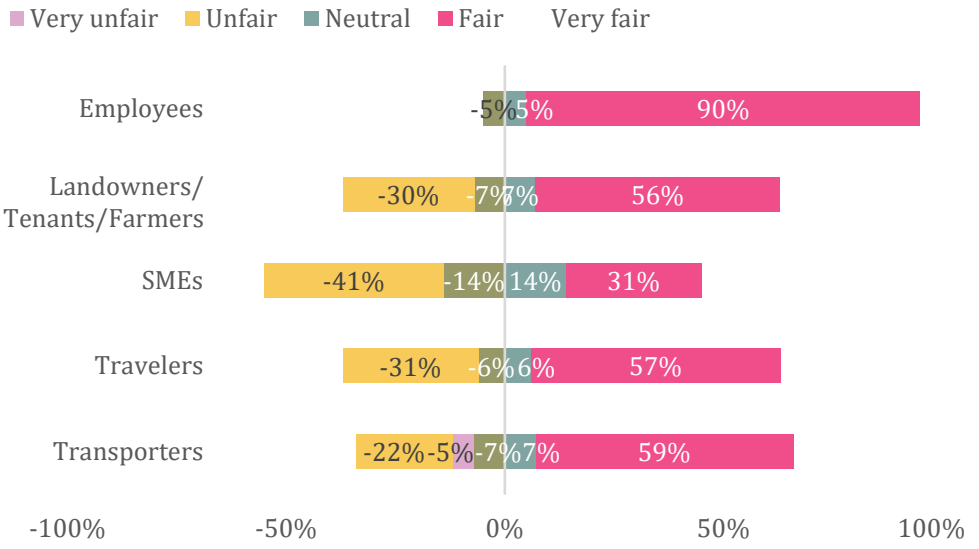
SMEs exhibited a more critical stance on the toll charges. Only 31% found the toll charges fair, with 41% considering them unfair, and 28% remaining neutral. This suggests that a large portion of SMEs either found the toll charges unreasonable or were unsure about their fairness, potentially reflecting concerns about the financial burden on businesses operating in the area.

Travelers had a balanced perspective, with 57% considering the toll charges fair, 31% finding them unfair, and 12% being neutral. This indicates that most travelers accepted the toll charges, but some still felt they were not entirely reasonable for the benefits provided by the road.

Transporters, similar to SMEs, had a more critical view, with 59% considering the toll charges fair, 22% finding them unfair, 5% very unfair, and 14% remaining neutral. While a majority deemed the charges reasonable, the proportion who found them unfair suggests that transporters were more sensitive to the financial implications of toll fees.

The results from the FGDs indicated that the majority of participants, along with most survey respondents, believed the toll charges were high.

Figure 32: Fairness of Toll Charges



Source: Authors' calculations based on the study's primary survey data.

Key Challenges That Still Need to be Addressed in Improving Transportation Infrastructure in the Hyderabad-Mirpurkhas Area

The findings highlighted several challenges identified by different groups of stakeholders regarding transportation infrastructure in the Hyderabad-Mirpurkhas area. The majority of the respondents 31% reported the traffic congestion during peak hours. Employees primarily emphasized traffic congestion during peak hours, with 30% of respondents highlighting this as a significant issue. Additionally, 21% of employees considered insufficient safety measures, particularly at accident-prone spots, as a pressing concern, while 17% pointed to improper maintenance of roads and bridges. A smaller proportion, 12%, raised concerns about high toll charges, and 9% mentioned the lack of facilities for pedestrians. Only 11% viewed the lack of adequate road networks as a challenge.

Landowners, tenants, and farmers shared similar concerns, with 42% identifying traffic congestion as a key issue. Improper maintenance of roads and bridges was cited by 17% of respondents in this group, while 20% noted inadequate safety measures at accident-prone locations. The lack of facilities for pedestrians and high toll charges were flagged by 10% and 17% of respondents, respectively. Only 8% mentioned the inadequacy of road networks as a challenge in this region.

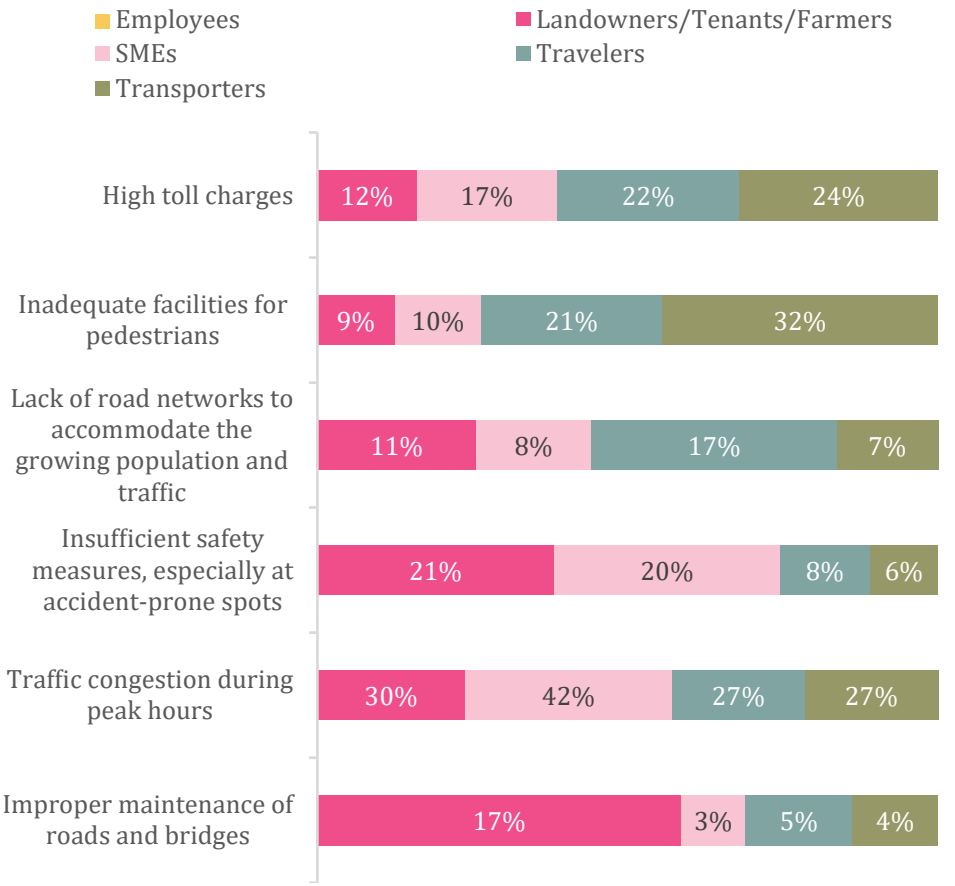
SMEs predominantly highlighted traffic congestion during peak hours, with 42% emphasizing this issue. Safety measures were a concern for 20% of respondents in this category, while 17% pointed to the lack of adequate road networks to accommodate growing traffic. Furthermore, 3% of SMEs noted the improper maintenance of roads and bridges, and 8% expressed concerns about high toll charges. Inadequate pedestrian facilities were identified by 21% of respondents as an area needing attention.

Travelers shared a broader range of concerns. Traffic congestion was highlighted by 27%, while 22% considered high toll charges to be a significant issue. Inadequate pedestrian facilities were a concern for 21% of travelers, and 8% mentioned insufficient safety measures at critical spots. Improper maintenance of roads and bridges was flagged by 5%, and 17% noted the lack of road networks to accommodate the growing population.

Transporters, who play a vital role in the area's logistics and economy, expressed notable concerns regarding inadequate pedestrian facilities, with 32% identifying this as a key challenge. High toll charges were highlighted by 24%, and 27% of transporters mentioned traffic congestion during peak hours. A smaller percentage, 6%, raised concerns about insufficient safety measures, while 4% mentioned improper maintenance of roads and bridges. Only 7% flagged the lack of road networks as an issue.

These findings collectively underline the diverse responses and perspectives of stakeholders on transportation infrastructure challenges in the Hyderabad-Mirpurkhas area, with traffic congestion during peak hours, high toll charges, safety measures, and pedestrian facilities, emerging as common concerns and challenges requiring immediate attention and actions.

Figure 33: Challenges that Still Need to be Addressed



Source: Authors' calculations based on the study's primary survey data.

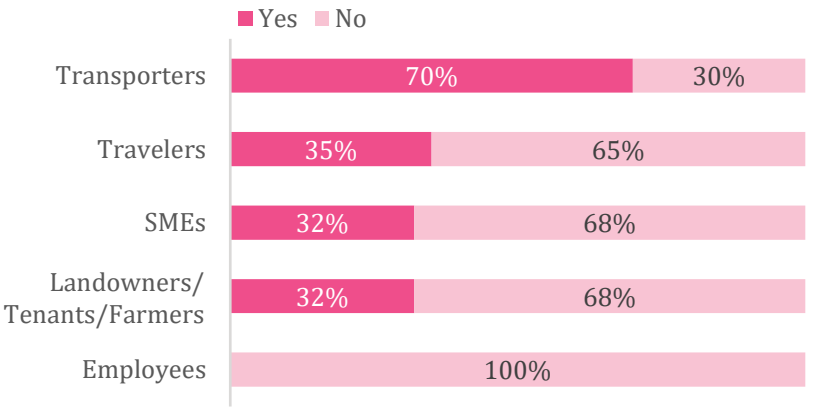
Additional Amenities or Facilities Required along the Hyderabad-Mirpurkhas Route to Enhance Commuters' Experience

The findings highlight the differing opinions among stakeholders regarding the need for additional amenities or facilities along the Hyderabad-Mirpurkhas route. Among employees, 100% expressed a desire for no additional amenities. Landowners, tenants, and farmers were predominantly against the need for additional amenities, with 68% responding negatively. Only 32% of respondents from this group indicated an interest in further enhancements along the route.

SMEs also showed a clear preference for maintaining the status quo, with 68% stating that no additional amenities were needed. Conversely, 32% believed that improvements would be beneficial to enhance the commuting experience. Travelers exhibited a similar trend, with 65% opposing the idea of additional facilities and 35% supporting it. This indicates that a significant portion of travelers felt the existing infrastructure met their needs.

Transporters stood out as the group most strongly in favor of implementing additional amenities, with 70% supporting the idea. Only 30% of transporters believed that no further improvements were necessary. This highlights transporters' unique concerns or challenges that might not be as apparent to other stakeholders.

Figure 34: Need for Additional Amenities



Source: Authors' calculations based on the study's primary survey data.

Type of Additional Amenities or Facilities Needed

The survey highlighted the preferences of various stakeholders for additional amenities along the Hyderabad-Mirpurkhas route. Rest areas with restroom facilities emerged as a priority for many, with 30% of landowners and farmers, 26% of SMEs, and 31% of travelers considering it an essential enhancement. Among transporters, however, only 16% identified rest areas as a significant need.

Service stations offering fuel, food, and other essentials were also a common preference, with 21% of landowners, 13% of SMEs, 22% of travelers, and 15% of transporters selecting this as a required facility. The installation of roadside emergency phones or helplines was favored by 11% of landowners, 18% of

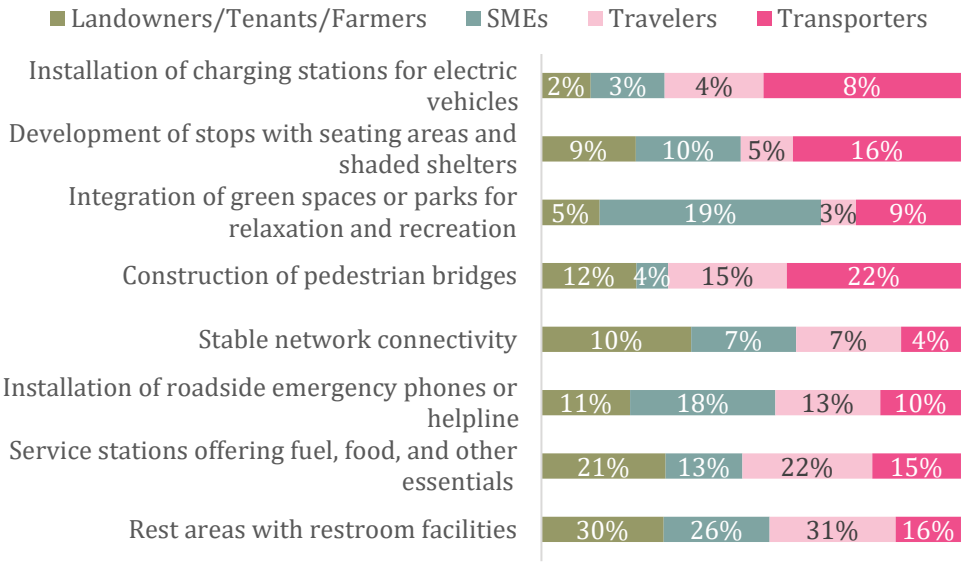
SMEs, 13% of travelers, and 10% of transporters, reflecting its perceived importance in ensuring safety and assistance in emergencies.

Stable network connectivity was seen as less critical, with only 10% of landowners, 7% of SMEs, 7% of travelers, and 4% of transporters emphasizing its necessity. Conversely, the construction of pedestrian bridges was a priority for 22% of transporters and 15% of travelers, while only 12% of landowners and 4% of SMEs expressed interest in this facility.

Green spaces or parks for relaxation were particularly appealing to landowners, with 19% selecting this option, compared to only 5% of travelers, 9% of transporters, and 3% of SMEs. Stops with seating areas and shaded shelters were favored by 16% of transporters, 10% of landowners, and smaller proportions of travelers (5%) and SMEs (9%). Charging stations for electric vehicles were seen as a relatively low priority, with only 2% of landowners, 3% of SMEs, 4% of travelers, and 8% of transporters supporting their installation.

Overall, 26% of the respondents stated the rest areas with restroom facilities and service stations were the most commonly preferred amenities across stakeholder groups, while specific needs, such as pedestrian bridges for transporters and green spaces for landowners, reflect diverse priorities depending on the nature of their engagement with the route.

Figure 35: Type of Additional Amenities Needed



Source: Authors' calculations based on the study's primary survey data.

5. CONCLUSION

The HMDC project, developed under a PPP framework, represents a landmark infrastructure achievement in Sindh Province, Pakistan. This research comprehensively assessed the project's socioeconomic, environmental, and operational impacts, revealing both transformative benefits and critical challenges.

The project has significantly enhanced transportation efficiency by reducing travel times, improving fuel efficiency, and lowering vehicle maintenance costs, thereby fostering economic growth and regional connectivity. It has stimulated the establishment of new businesses, increased land and property values, and improved market access for agricultural communities, contributing to the socioeconomic upliftment of Hyderabad, Tando Allahyar, and Mirpurkhas districts.

While the HMDC has had a positive environmental impact in the region, however, the communities are concerned about the reduced number of local species of trees. Social benefits such as job creation and improved livelihoods have been observed, but these gains remain limited by gender disparities and a lack of inclusivity in employment and entrepreneurship opportunities. High toll charges and insufficient commuter amenities are identified as persistent issues, affecting overall user satisfaction. Moreover, a large number of travelers, those who travel between Tando Allahyar and Tando Jam, do not pay tolls, which puts a burden on other stakeholders and end-users in achieving the revenue generation targets of the HMDC project. In addition to that, it was revealed by study participants that numerous road accidents occur due to high speed, uninterrupted vehicle movement, and the absence of pedestrian and overhead bridges at congested areas, such as Khwaja stop at Tando Allahyar resultantly resulting in deaths of people and livestock.

The findings underscore the importance of adopting a more inclusive and sustainable approach to infrastructure development. Addressing gender imbalances, enhancing employment diversity, strengthening road maintenance, and integrating advanced traffic management systems are essential to maximizing the project's long-term benefits. Furthermore, adopting ETTMS has been proven to be a successful experiment for real-time vehicle toll tax monitoring and computerized revenue report generation, which has been adopted and implemented by the government of Sindh under other PPP projects after the HMDC. Moreover, the study also highlights the HMDC's excellent build quality. The study's participants reported that the

concerned team of the Government of Sindh inspected the road 10 years after its completion. The team suggested overlaying the HMDC after more than 2 to 3 years, although it was due in the 10th year after its construction.

The HMDC project has laid a strong foundation for regional development, providing valuable lessons for future PPP initiatives. The project has the potential to fully realize its vision of fostering economic prosperity, social inclusivity, and environmental sustainability for the communities it serves.

6. LIMITATIONS AND CHALLENGES

- The research study team did not receive the necessary documents (e.g., progress and monitoring reports) required for the desk study/review from concerned stakeholders and departments.
- Due to the inaccessibility of relevant project documents, the study could not verify the number of direct jobs created as per the project target, i.e., "5,000 direct jobs to be created under the HMDC Project."
- Service user data (e.g., travelers and vehicles) commuting on the HMDC route was unavailable. Furthermore, there was a lack of segregated traffic flow data for peak hours and weekdays.
- A toll gate is absent in Tando Allahyar, leading to unpaid service usage by a large number of travelers between Rashidabad and Tando Jam.
- Traffic data regarding vehicles entering from Mirpurkhas/Tando Jam toll gates and exiting on the other side was unavailable. This limitation hindered the proper assessment of the road's complete economic benefit to the public.
- The absence of speed cameras and road studs along the HMDC contributed to an increase in road accidents.
- There was a lack of overhead bridges in several populated areas (e.g., Khuwaja Stop). Additionally, the jersey barrier (wall) interrupted frequent connectivity among families and communities living on both sides of the HMDC. The absence of overhead bridges and reduced visibility caused by the jersey barrier resulted in fatal road accidents.

- Limited support and influence were observed from the local administration and armed forces.
- Political influence affected staff hiring and vehicle toll tax collection processes.
- Right-of-way (ROW) protection was a challenge for the project since the road passes through populated cities and villages. Research participants reported limited support from the local government in this regard.

7. RECOMMENDATIONS AND WAY FORWARD

Based on the findings of the research study on the Hyderabad-Mirpurkhas Dual Carriageway (HMDC) Project, the following recommendations and way forward are proposed to maximize the project's socioeconomic benefits, address challenges, and ensure its sustainability:

I. The HMDC project, implemented under the DBFOT revenue model, demonstrates significant economic feasibility. Scaling this model for other road infrastructure projects across provinces will attract private investments, reduce public financial burdens, and accelerate economic development.

II. To improve data accuracy and assist in future studies, the installation of AI-driven cameras at both toll gates (Tando Jam and Mirpurkhas) should be implemented. These systems would provide precise traffic flow data and user demographics, which are vital for assessing the socioeconomic benefits and ensuring that the road infrastructure serves its intended purpose.

III. The HMDC project serves as a benchmark for future PPP road projects. The success of this initiative in its execution and revenue generation models should be shared as a guiding framework for future projects. Establishing clear policies and guidelines for PPP projects will help ensure consistent outcomes and long-term sustainability in the infrastructure sector.

IV. The dualization of the route has significantly reduced travel time and associated costs for end-users and improved fuel consumption. Beyond economic savings, this improvement has enhanced access to

vital services, such as education and healthcare, boosting human capital development and reducing opportunity costs for regional populations while boosting regional connectivity. Future infrastructure projects should prioritize dualization to achieve similar socioeconomic benefits.

V. The combination of effective finance and revenue models with the high-quality construction of the HMDC project has resulted in a successful partnership. These elements should be adopted as a standard for upcoming toll road projects. Regular quality inspections, maintenance schedules, and adherence to construction benchmarks will ensure long-term sustainability and cost efficiency. This model should be replicated for future toll road projects to guarantee sustainability and ensure adequate financing for the operation and maintenance of infrastructure.

VI. The ETTMS has enhanced revenue collection and reduced operational inefficiencies. The ETTMS should be implemented in similar future infrastructure projects to optimize operational efficiency, enhance financial transparency and enable data-driven decision-making.

VII. The inclusion of female toll gate operators at Tando Jam marks a significant milestone in promoting gender diversity and demonstrates socioeconomic inclusivity in infrastructure projects. This initiative should be replicated in future projects to ensure equal employment opportunities, foster gender inclusivity, empower women in traditionally male-dominated sectors and enhance gender equality in employment while boosting household incomes in the region.

VIII. Revenue sources such as toll taxes, weighbridges, and advertisement boards have proven essential for the financial viability of the HMDC project. The support of the Sindh government in terms of minimum revenue generation during the COVID-19 pandemic to meet revenue targets exemplifies an effective PPP revenue model. Similar diversified and adaptive revenue mechanisms should be incorporated into future projects to ensure financial resilience.

IX. Weighbridges not only serve as revenue-generating tools but also play a crucial role in maintaining the quality of the road infrastructure. They should be incorporated into future road projects as essential components for both revenue generation and quality assurance by enforcing axle load management to prevent overloading and protect infrastructure quality.

X. Considering the build quality and axle load management, the due overlay was forwarded for 2-3 years during its due inspection after 10 years of operation. It is also recommended for other ongoing and future projects that this practice should be implemented to maintain high build quality of roads.

XI. To ensure smooth connectivity and improved traffic management, appropriate measures should be taken to reduce congestion during peak hours. This can include enhancing traffic flow through the introduction of additional lanes, improving signaling systems, and optimizing toll gate operations. It will enhance economic productivity, saving businesses and commuters time and resources.

XII. A review of toll rates should be carried out periodically to ensure that they remain affordable for commuters while sustaining the financial viability of the PPP model. The review process should involve stakeholders to strike a balance between affordability and operational needs.

XIII. Align job creation initiatives with the skills and needs of local populations to maximize employment and ensure equitable economic opportunities.

XIV. While the Go-Green initiative in the HMDC project was commendable, it is essential to further evaluate its ecological impact, particularly regarding local biodiversity. The project included a large number of non-native tree species (i.e., Conocarpus), which may not contribute to local environmental conservation. Future projects should prioritize the planting of regionally appropriate, indigenous species to ensure the protection and enhancement of local ecosystems, as well as to reduce maintenance costs associated with non-native species.

XV. To enhance road safety and ensure inclusivity, clear road signs and road studs should be installed along the HMDC, studs should be installed along the HMDC to improve night-time visibility and guide drivers, particularly in low-light conditions. This will enhance safety for all road users and reduce the likelihood of accidents caused by unclear lane demarcations. These measures will improve navigation and safety for all road users, particularly pedestrians and differently abled persons. Additionally, pedestrian-friendly infrastructure such as footpaths, crossings, and signage should be incorporated to ensure equitable access to the road for all members of society, and this will enhance the road's social value.

XVI. To address the absence of speed enforcement mechanisms, speed cameras should be installed along the HMDC at critical points. These will help monitor and manage vehicle speeds, reduce the frequency of speeding violations, and lower the risk of road accidents.

XVII. Overhead bridges should be constructed at high-traffic and densely populated areas, such as the Khuwaja stop, to provide safe pedestrian crossings. These structures will improve connectivity for communities on both sides of the highway and reduce the number of pedestrian-related accidents.

XVIII. The jersey barrier along the HMDC, while essential for traffic management, has hindered connectivity between families and communities on either side of the road. To address this, appropriate connectivity solutions such as pedestrian underpasses or strategically located breaks in the barrier (with safe crossing points) should be implemented. This will restore accessibility and cohesion among communities while maintaining traffic flow.

XIX. A communication gap between the concerned line departments and other stakeholders was found since the planning phase of this road. The gap was overcome at some stages, but there was little support from the district government and armed forces. Therefore, the establishment of robust stakeholder mapping mechanisms and a comprehensive communication plan for all PPP initiatives is highly recommended, so that no communication gap arises and all risk factors can be addressed and mitigated timely and accordingly. This will help and encourage the private partners to invest and work smoothly on the project.

XX. Land acquisition and resettlement policies should be regularly reviewed to ensure they are fair, transparent, and inclusive. Policies should address any gaps in implementation and protect the rights of displaced communities.

XXI. Formalize partnerships with local governments to provide consistent support in ROW protection, land acquisition, and encroachment prevention. This collaboration should ensure proactive involvement in all stages of the project.

XXII. Introduce electric vehicle (EV) charging stations along the route to encourage the use of environmentally friendly vehicles.

XXIII. Encouraging comparative studies of similar infrastructure projects across different regions of Sindh and other provinces is critical for identifying best practices and lessons learned. These studies will provide valuable insights into the socioeconomic impacts, challenges, and success factors of different projects, contributing to the development of evidence-based policies for future projects. Policymakers can refine strategies and improve the implementation of future infrastructure developments across the country by learning from other regions.

XXIV. A centralized knowledge-sharing platform should be established to promote the exchange of best practices, lessons learned, and innovative approaches from past and ongoing infrastructure projects, including HMDC. This platform should be accessible to project developers, policymakers, and stakeholders across the country to facilitate collaboration, improve project outcomes, and enable continuous learning in infrastructure development.

These measures can create a more inclusive, efficient, and sustainable infrastructure development model that can serve as a blueprint for future projects across Pakistan.

REFERENCES

Ahmed, A., Choudhary, S., & Irfan, M. (2019). Post implementation evaluation of Lahore-Sheikhupura-Faisalabad Dual Carriageway-A Built Operate Transfer (BOT) project. *International Journal of Transportation Engineering and Technology, 4*(3), 59-64.

Chen, B. (2021). Public–private partnership infrastructure investment and sustainable economic development: An empirical study based on efficiency evaluation and spatial spillover in China. *Sustainability, 13*(15), 8146.

Cui, C., Liu, Y., Hope, A., & Wang, J. (2018). Review of studies on the public–private partnerships (PPP) for infrastructure projects. *International Journal of Project Management, 36*(5), 773-794.

EIB (European Investment Bank). (2023). The economic appraisal of investment projects at the EIB. 2nd Edition. https://www.eib.org/en/publications/20220169-the-economic-appraisal-of-investment-projects-at-the-eib

Government of Sindh. (n.d.). HMDC Project impact report. Public Private Partnership Unit, Finance Department, Government of Sindh. https://www.pppunit.gos.pk/Download/data/ProgressReport.pdf

Grimsey, D., & Lewis, M. K. (2004). *Public-private partnerships: The worldwide revolution in infrastructure provision and project finance.* Edward Elgar Publishing.

Guo, X., Chen, B., & Feng, Y. (2022). Public-private partnership transportation investment and low-carbon economic development: An empirical study based on spatial spillover and project characteristics in China. *Sustainability, 14*(15), 9574.

Haider, S. W. (n.d.). *Lahore-Islamabad Motorway (M-2) experience: Lessons and improvements for future projects* [Paper 232]. NHA. https://pecongress.org.pk/images/upload/books/Paper232.pdf

Hodge, G. A., & Greve, C. (2007). Public–private partnerships: an international performance review. *Public Administration Review, 67*(3), 545-558.

IIED (International Institute for Environment and Development). (n.d.) https://www.iied.org/

Llanto, G. M. (2012). *The impact of infrastructure on agricultural productivity* [Discussion paper]. PIDS discussion paper series No. 2012-12.

NHA (National Highway Authority). (n.d.). https://www.nha.gov.pk/

PPRC (Public-Private Partnership Resource Center), World Bank. (n.d.). https://ppp.worldbank.org/public-private-partnership

Riaz, M. T., Aaqib, S. M., Ahmad, S., Amin, S., Ali, H., Husnain, S., & Riaz, S. (2021, October). *The intelligent transportation systems with advanced technology of sensor and network* [Paper presentation]. 2021 International Conference on Computing, Electronic and Electrical Engineering (ICE Cube) (pp. 1-6). IEEE.

TRIS (Transportation Research Information Services). (n.d.). Karakorum Highway study. https://trid.trb.org/view/760024

An, S. H., Lee, B. H., & Shin, D. R. (2011, July). *A survey of intelligent transportation systems* [Paper presentation]. Third international conference on computational intelligence, communication systems and networks (pp. 332-337). IEEE.

InfraPPP. (2014, April 25). Pakistan M-2 toll road signed. https://www.infrapppworld.com/news/pakistan-m-2-toll-road-signed

PART II

SUSTAINABLE DEVELOPMENT

Policy Briefs

A COMPREHENSIVE ASSESSMENT OF CONVENTIONAL PRACTICES AND SUSTAINABLE PATHWAYS FOR SOLID WASTE MANAGEMENT: INTEGRATING PERSPECTIVES, PRACTICES, AND ENVIRONMENTAL IMPACT

Shoaib Muhammad, Taimur Mazhar Sheikh, and Musharib Khan

INTRODUCTION

Municipal solid waste is being generated at an alarming rate of 2 billion tons annually, and this rate is expected to double by 2050. While official statistics are not available for Pakistan, the country is estimated to generate 32 million tons per year, increasing annually by 2.4%. Typical waste treatment options such as incineration, composting or anaerobic digestion are absent, and there are also no functioning sanitary landfills in Pakistan. This leads to the open dumping and burning of manually collected waste, which releases cancer-causing chemicals, particulates, and other pollutants into the environment.

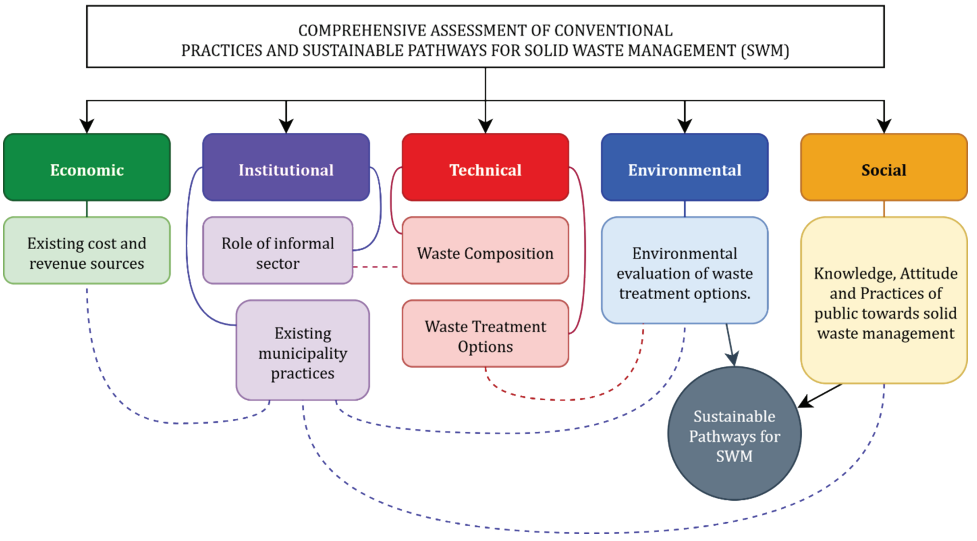
The dilapidated state of solid waste management (SWM) in Pakistan is due to political negligence, lack of resources, public awareness and behaviour, outdated regulatory framework, and administrative issues. Thus, there is an urgent need to correct the path and enact actionable and effective national waste management policies. However, the lack of official statistics and narrow assessment hinders good policy formulation. An effective policy needs a comprehensive, reliable, and site-specific assessment of the baseline situation of the various interconnected components of solid waste management.

Therefore, a research study was conducted to provide a broad-scoped, comprehensive and translatable assessment of solid waste management at an urban city in Pakistan. Multiple aspects of solid waste management were covered in this study using an interconnected approach, with consideration from all major stakeholders.

METHODOLOGY

The methodology aimed at analysing various components of SWM to gain a comprehensive understanding of the issues within each component and their interconnections. As illustrated in Figure 1, the technical component was first addressed by determining the composition of generated waste to understand residents' consumption behaviour and identify suitable waste treatment options. These options were further validated through expert opinions and assessed for environmental impacts, covering the environmental component of the SWM system. The institutional component focused on evaluating existing municipal practices and the role of the informal sector, a key but often understudied stakeholder. Issues faced by the informal sector were explored through semi-structured interviews, and potential methods for the integration of the informal sector with the formal sector were identified using the framework proposed by Velis et al. (2012). The social component involved uncovering residents' perspectives, including their knowledge, attitudes, and practices regarding SWM, through structured interviews. This component is linked to the institutional component, as residents' perspectives are shaped by municipal authorities' actions. Lastly, the economic component was examined by calculating the operational and management (O&M) costs and the revenue earned from selling recyclables, as revealed through the assessment of municipal practices.

Figure 1: Methodological Framework

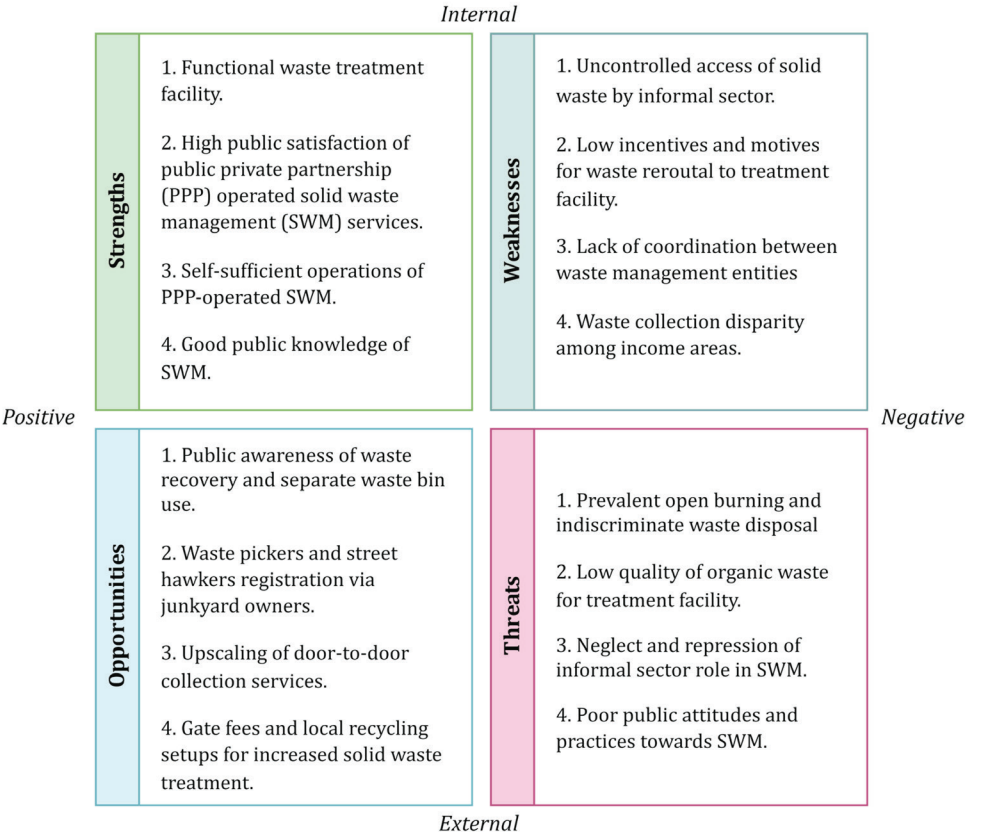


Source: Authors' illustration.

FINDINGS AND CONCLUSIONS

The assessment revealed some strengths but multiple shortcomings in each of the five aspects of the SWM. These are summarised as a SWOT analysis in Figure 2.

Figure 2: Summary of SWOT Analysis



Source: Authors computations.

The assessment also highlighted several prevalent issues of the SWM throughout Pakistan, such as administrative issues and a lack of public awareness. The administrative problems arise from the lack of coordination between the waste management organisations and the failure to implement easily actionable rules, such as registering informal sector workers and controlling access to dumpsites. The public, meanwhile, showed poor behaviour towards SWM. For instance, respondents understood the health and environmental risks of open burning and excessive plastic bag use, yet openly admitted to performing both practices.

The overall findings and conclusions are listed below.

1. More recyclable waste is found in door-to-door waste versus skip and tubs, which are collected by the informal sector. About 36% of waste is collected by the informal sector.

2. More than 5% of total daily waste comprises plastic bags, despite their light weight. Respondents were knowledgeable about the environmental harm posed by plastic bag use.

3. Composting and anaerobic digestion are potential waste treatment options based on high amounts of organic waste (55%) and yard waste (1.7 tons per day).

4. Sanitary landfill, material recovery facility (MRF)/ recycling, and incineration are other waste treatment options based on experts' opinions. Additionally, composting is preferred over anaerobic digestion as it is cheaper and easier to set up.

5. Two waste management entities operated in the city are a public-private partnership (PPP) and a public entity. The PPP provides door-to-door waste collection, supported by a treatment facility, an MRF, compost, and pellet lines. The public entity collects waste from skips and tubs and disposes of all waste at the dumpsite. The PPP maintained a regular collection schedule.

6. The PPP-managed door-to-door waste collection areas showed reduced incidents of open burning and dumping. This method also increases the recovery of recyclables, making it an effective and environmentally friendly collection mode.

7. A major challenge for the PPP in treating organic waste is its low quality, as residents do not segregate waste despite the provided separate bins. This highlights the need for active measures to improve organic waste quality, given its dominance in the waste stream.

8. The PPP has installed a weighing bridge at its facility to record the incoming waste from both the PPP and public entities. However, no waste limitation or gate fee is imposed, a practice recommended in the literature to encourage waste treatment.

9. Waste management services varied significantly across the city, with low-income areas and suburbs receiving fewer collection visits and

possessing fewer waste bins or skips, highlighting disparities with income levels.

10. Bureaucratic barriers exist between waste management entities, as the PPP is denied access to the public entity's waste for treatment.

11. There is no integration of services between the formal and informal sectors in solid waste management. Key issues for informal sector include lack of controlled access to waste, repression and neglect of the informal sector, absence of a database of waste-pickers and hawkers, public discrimination, inadequate authority support, lack of informed initiatives, child labour, no penalties for open burning, lack of recycling-friendly policies, minimal NGO advocacy, the absence of PPEs, poor healthcare access, and exploitation by recycling industries.

12. Despite a vast majority of the public knowing (90%) about the different aspects of waste, the attitude and practices do not match the high level of knowledge. There was a negative perception of waste and limited knowledge about key waste management practices like the 3Rs and segregation. Younger respondents were more knowledgeable, and those with higher education were more willing to pay for waste services. Social media was the preferred source for those with higher education, while TV was preferred by those with lower education. Respondents served by PPP reported higher satisfaction and more frequent waste collection than those served by the public entity, though they were less willing to pay. Practices like open burning and plastic use were concerning, given Pakistan's environmental challenges.

13. The cost-benefit analysis (CBA) indicates strong revenue potential of waste collection and disposal, as revenues (PKR 4,000,000) fell short of O&M costs (PKR 4,600,000) by just PKR 600,000. Revenues could rise significantly if waste segregation is practised by households, allowing compost to be sold.

14. Environmental evaluation of shortlisted waste treatment options showed positive results for the composting, anaerobic digestion, and MRF, two of which (composting and MRF) are currently operational in the study area.

KEY POLICY RECOMMENDATIONS

The following key policy recommendations are suggested following the findings:

1. The government must make composting and MRF setups mandatory for all municipalities throughout the country.

2. The PPP mode of operations is recommended for better quality of waste management services and higher satisfaction levels of the public.

3. There should be the maximum possible transition from skips and tubs to door-to-door waste collection to limit the informal sector's uncontrolled access to waste, reducing open burning incidents. This shift would also enable waste management entities to recover more recyclables.

4. Installation of separate bins (two bins, i.e., dry and wet waste instead of three bins) at the household level for simpler waste segregation.

5. Visually attractive and interactive awareness campaigns on social media and TV, and curriculum changes in educational institutions are recommended to ensure public understanding and practice of separate bin use for waste.

6. After installing weighing bridges, a gate fee should be introduced for the dumpsite to promote recycling and other management options.

7. Waste management services, including collection methods, frequency, and bin placement, should be standardised across the city. Priority should be given to low-income areas, ensuring inclusivity for underserved communities and informal sector stakeholders.

8. Integrating the formal and informal waste management sectors is crucial. Key policy measures include: i) providing controlled access to the informal sector at treatment facilities or dumpsites; ii) registering waste pickers and street hawkers by mandating already documented junkyards to purchase only from registered members; iii) supplying registered members with uniforms, ID cards, and large containers;, iv) enforcing strict action against unregistered members and child labour; v) involving informal sector stakeholders, like junkyard owners, in planning; vi) offering

affordable loans to registered workers; vii) incentivising parents of child waste pickers to enroll them in school; viii) promoting positive environmental contributions of informal sector workers to improve public acceptance; and ix) supporting unions and NGOs that advocate for their rights.

9. Strict fines must be imposed on indiscriminate waste disposal and open burning to ensure compliance.

SMART BIOTECHNOLOGICAL INDUSTRY– BIOFLOC'S ROLE IN SUSTAINABLE AQUACULTURE

Aima Iram Batool, Muhammad Fayyaz Ur Rehman, Naima Huma Naveed, and Muhammad Mustaqeem

INTRODUCTION

The aquaculture industry is an emerging source of quality food for the human population all over the globe. Aquaculture has been playing a vital role in supplying 50% fish for human consumption for the last three decades to address the rising demand for protein-rich diets. Despite its contributory role in food provision and economic boost, traditional aquaculture faces many challenges, such as water scarcity, high fish feed cost, waste management, environmental degradation, and disease outbreaks, particularly in resource-limited countries like Pakistan. Biofloc Technology (BFT) is the best transformative solution to these challenges, turning simple and traditional fish farming into a biotechnological industry.

Biofloc farming is not just a method; it's a movement towards an aquaculture renaissance. Its potential benefits extend beyond the water tanks—it promises a ripple effect of economic strength, ecological sustainability, food provision and wise resource conservation. Practical application has yielded enhanced growth rates, improved survival, and cost-effectiveness, making BFT a gateway to agricultural innovation. BFT enables continuous nutrient recycling with minimal or zero water exchange, relying on in-situ microorganism production. Traditional aquaculture systems consume approximately 16.9 cubic meters of water per kilogram of fish.

Pakistan, facing a steady decline in per capita water availability since its inception, can benefit greatly from adopting such forward-thinking technologies. This downward trend is ascribed to factors such as exponential human population growth, inefficient water use, overextraction of groundwater, inflexible government policies, and the increasing challenges of climate change. In this context, Biofloc Technology (BFT) offers a win-win situation for all stakeholders.

METHODOLOGY

Large and small biofloc setups in almost all parts of Punjab, Pakistan, were part of the study. The Faisalabad region can be considered a hub of BFT, comprising hundreds of small and large private setups. Only 3 biofloc setups have been established under the Punjab Fisheries Department of Pakistan, which mainly rely on these setups for fish seed production. Out of all the biofloc setups, only one setup was being successfully run by a female, while all others were under the ownership of males.

Both qualitative and quantitative data were collected using a semi-structured questionnaire. The questionnaire included sections on demographic information, farm characteristics, investment details, compliance with regulations, operational challenges, and growth strategies. Farmers were randomly selected from the study areas. The selection criteria ensured a diverse representation of biofloc fish farms in terms of size and operational scale. The study was executed in three phases: preparatory phase, data collection phase and analysis & reporting phase. Consultations with biofloc farmers, consultants and tool development take place during the first phase. Data collection was focused on surveys, in-person interviews, and focus group discussions, refined tools and identifying target areas. The collection of data focused on early adopters. Quantitative data was analysed statistically, while qualitative data was categorised into thematic insights.

FINDINGS

Demographics of Biofloc Farmers

The study indicates that biofloc farming is a relatively new practice, with 58% of farmers having less than five years of experience. Formal training is lacking for 60.2% of farmers, resulting in a reliance on self-learning or informal networks. Most setups are small-to-medium scale, with 76% operating 1–10 tanks, reflecting cautious investment due to financial constraints or limited technical expertise. The primary species farmed are tilapia and pangasius, dominating over 90% of operations, while ornamental species (5.1%) and others (3.0%) are rare, indicating limited diversification.

Economic and Productivity Advantages

BFT offers significantly higher profitability, with net profits of PKR 1.5–3.3 million after two cycles compared to a net loss of PKR 500,000 for traditional systems. Lower operational costs (PKR

66,000 vs. PKR 175,000 per crop) and higher yields (3,000 kg vs. 1,000 kg annually) underscore its efficiency. Enhanced feed conversion reduces feed costs to PKR 17,000 per crop versus PKR 80,000 in traditional aquaculture, and water costs are minimised (PKR 10,000 annually vs. PKR 55,000). These factors make Biofloc a more cost-effective and sustainable model.

Environmental Sustainability

Emergy analysis highlights Biofloc's superior environmental performance, with a lower environmental loading ratio (1.5 vs. 2.5) and a higher Sustainability Index (0.000771 vs. 0.000204). This reflects reduced ecological impact, efficient resource use, and better alignment with sustainable aquaculture practices.

Thematic Analysis

Thematic analysis identified biofloc adoption enablers and challenges. Economic viability of the biofloc system was attributed to low feed and water cost, increased growth and production of fish. The analysis further revealed that government policies and support are required in terms of biofloc set-up material, seed and feed availability and electrical subsidies to make this more economically feasible.

Lack of formal training (60.2% of farmers are untrained), high setup costs, and technical complexity are the main identified challenges. Awareness campaigns and training programmes are essential to address these issues. Collaboration with research institutions can further enhance productivity and disease management.

CONCLUSION

BFT represents a paradigm shift in aquaculture, addressing critical issues like resource efficiency, environmental sustainability, and economic viability. In Pakistan, where aquaculture is still developing, BFT offers a pathway to overcome resource constraints and boost productivity. The findings of this study underscore the importance of strategic investments in training, financial support, and regulatory frameworks to accelerate BFT adoption.

Policymakers, investors, and aquaculture practitioners must collaborate to unlock the full potential of biofloc systems. By addressing the identified challenges and implementing the recommended policies, Pakistan can position itself as a leader in sustainable aquaculture, contributing to food security, economic growth, and environmental conservation.

POLICY RECOMMENDATIONS

No previous policy related to biofloc fish farming exists in Pakistan. Based on the findings of the current study, the following recommendations are suggested to make biofloc technology friendly, economical, and attractive for farmers, investors, and all stakeholders.

National Biofloc Database: The Government should create a comprehensive national biofloc farming database that includes key information related to the species that can be cultured, their growth and development information, feeding habits, water quality in biofloc set up, disease prevalence, feed availability and seed availability centres.

Seed and Feed Availability: Fish seed availability and seed availability centres for biofloc farming should be established, where healthy fish seed should be available at lower rates. Feed quality should be ensured, especially related to crude protein level, which plays an important role in fish growth and health.

Subsidies and Financial Support: The Government should introduce subsidies for initial capital costs, including tanks, aerators, and monitoring equipment, as well as on electricity bills, particularly to those farmers who have small setups and want to expand their setup. Most farmers expressed concerns that government subsidies and reforms are typically announced for large farm holders, leaving small-scale farmers excluded. The government should also direct banks to establish low-interest or interest-free loan programmes for biofloc investments, enabling scalability and system expansion.

Capacity Building: The government should arrange training for traditional fish farmers and stakeholders in adopting BFT, focusing on building their skills for sustainable and efficient aquaculture practices. Efforts should be made to support farmers in transitioning from conventional methods to cost-effective and productive Biofloc systems. These programmes should address critical aspects such as microbial floc management, water quality control, feed optimisation, and disease prevention specific to Pakistan's climatic and resource conditions. Training should be delivered in local languages and supported by easy-to-understand manuals, ensuring accessibility for farmers with limited formal education.

Value Addition: Supporting infrastructure for biofloc end products: fish fillet and ready-to-eat meat should be provided by the government. More to this, encouraging access to high-value markets, including exports, through targeted programmes and tax

benefits should be provided. The government should provide easy loans and tax-free access to solar power equipment, power generators, aerators, and automated feeders to reduce the labour cost.

Awareness Campaigns: Most farmers lack awareness of biofloc profitability over traditional aquaculture. To enhance the importance and benefits: financial, structural and environmental, of biofloc technology, awareness seminars, workshops, and hands-on training should be organised by the government and NGOs.

Electricity Cost: Soaring electricity costs is one of the major challenges in biofloc adoption. The government should invest in electrification and provide subsidised energy to help farmers reduce high power costs.

Infrastructure Development for Inputs and Markets: The Profit level of local farmers can be improved by establishing cold storage facilities and efficient transportation networks to connect them with urban and export markets. The government should take the initiative to establish supply chains for quality seeds, feed, and probiotics, especially in rural areas, which will not only make availability easier for farmers but will also reduce the additional cost of seed, feed, and probiotics transportation.

Policy Incentives for Sustainability: Farmers complained about the heavy tax on the import of biofloc equipment, feed and new fish seed, which is a hurdle in the adoption of this technology. The government should exempt tax for those farmers who want to incorporate innovations in their biofloc setups. Additionally, clear regulatory frameworks should be established to ensure environmental compliance and provide farmers with well-defined guidelines for adopting Biofloc technology.

Target Technical and Cultural Resistance: Most of the farmers were hesitant in adopting biofloc farming due to misinformation regarding biofloc complexity and cost. The government should take the initiative to disseminate correct information and awareness regarding establishing and working with BFT. Training programmes in a simple and local language should be planned. Technical information should be disseminated through a brochure and local newspapers, making it easier for farmers to adopt the system. A community-based discussion forum should be established in each rural area with potential for biofloc farming to address cultural and local resistance.

Supportive Policies for Scalability: Farmers holding small setups should be provided with financial and

technical support through the development of flexible policies. Additionally, insurance schemes should be introduced to safeguard farmers' investments against risks like disease outbreaks and environmental disasters, ensuring long-term sustainability and growth in Biofloc aquaculture.

Promoting Diversification in Aquaculture: Biofloc farmers don't have much awareness regarding fish species that can be cultured under this setup, so more than 90% use to culture only limited types of fish species (tilapia & pangasius). Policies should encourage the farming of other nutritious and ornamental fish species by offering incentives and technical support.

Water Quality and Feed Quality Testing Labs: One major issue raised by biofloc farmers was the unavailability of testing labs to check the quality of water and feed used for biofloc farming. Most of the feed available in the market contains less crude protein, which affects the fish growth negatively. Governments should establish testing labs at the district level.

EVALUATING THE SOCIOECONOMIC IMPACT OF THE HYDERABAD-MIRPURKHAS DUAL CARRIAGEWAY ON REGIONAL DEVELOPMENT UNDER PPP INITIATIVES

Hira Hussain and Ayaz Ali

INTRODUCTION

This policy brief presents the findings of a comprehensive study on the Hyderabad-Mirpurkhas Dual Carriageway (HMDC) project, which systematically estimates the direct and indirect benefits accruing to end users and communities through improved infrastructure. The study assessed the comprehensive socioeconomic impacts of the HMDC project on regional development, which has been completed under Public-Private Partnership (PPP) initiatives. As the first study of its kind, it systematically addressed research gaps, highlighting the lessons learned and challenges encountered throughout the HMDC project. The research aimed to fill a significant research gap by providing evidence on how such projects impact local economies, businesses, and communities under a Public-Private Partnership (PPP) model.

The HMDC project, inaugurated with the significant objectives of mitigating traffic congestion and facilitating efficient connectivity between Hyderabad and Mirpurkhas, represents a monumental infrastructure endeavor spearheaded by the Works & Services Department of the Government of Sindh. This visionary initiative, conceived as a strategic response to the escalating demands for improved regional infrastructure, entails the extensive enhancement of the existing two-lane road, spanning a substantial 58.7 kilometers from a single road. The transformative upgrades were poised to yield significant enhancements in travel efficiency and safety, promising an elevated experience for all end-users along this vital corridor under the PPP initiative.

Commencing its trajectory in December 2008, the HMDC project emerged as a response to the

pressing infrastructural needs of the region. Adopting a design, build, finance, operate, maintain, and transfer (DBFOT) Revenue model within a PPP framework, the project reflects a meticulously crafted strategy for execution and long-term sustainability. A pivotal milestone was achieved on November 11, 2009, marked by the execution of the concession agreement establishing the special purpose vehicle (SPV), entrusted to the preferred bidder, Deokjae Connecting Roads (Private) Limited.

A robust financial framework supported the HMDC project, with a blend of equity, bank loans, and subordinated debt. The 26.1% equity comprised 18.4% from the private partner and 7.7% from the GoS, indicating a collaborative financing approach. The 37.3% bank loan, 31.3% GoS subordinated debt, and 5.3% developer equity collectively underlined a well-structured financial model.

Beyond the tangible infrastructure outcomes, the HMDC project envisioned substantial social impacts. Reduced travel time and enhanced safety were anticipated benefits, along with the creation of 5,000 direct and 22,000 indirect job opportunities. The project was poised to uplift land values, facilitate the major agricultural belt of Sindh, and provide local communities with opportunities for employment and businesses, contributing to improved law and order in the area.

The HMDC project achieved substantial completion of construction works in August 2012. A noteworthy aspect was its reliance on local lenders, the National Bank of Pakistan (NBP) and Summit Bank, for project financing. The successful retirement of bank loans in December 2020 and the commencement of subordinated debt repayments to the GoS from March 2021 underscore the project's financial viability. The implementation of the electronic toll and traffic management (ETTMS) reflects a commitment to technological innovation in project execution.

The HMDC was the first-ever road dualization project initiated by the Government of Sindh under a PPP. The study revealed significant socioeconomic contributions of the project in the region. The project has resulted in reducing the average travel time from 15-20 minutes for the majority of travelers, which has led to less fuel consumption. Moreover, it has supported in improving the productivity of travelers, which has resulted in improved economic benefits for them in the form of indirect savings of PKR 6,553 to PKR 30,584 per year. In addition, the surge in private and agricultural land value from PKR 3 to PKR 4 million per acre signifies the

direct impact on regional economic development and overall provincial and national economic contribution through relevant tax collection based on improved property value.

Moreover, this study finds that the project has expanded and improved market access of the region's business community from Mirpurkhas, Tando Allahyar, and Hyderabad. Now it is easier for the businessmen in this region to gain market access to other parts of the province. This improvement signifies a direct benefit to local growers, landowners, the business community, and increased economic contribution in the national and provincial economy through toll tax and other applicable taxes. Weighbridges and billboards are other sources of revenue generation for this project for the loan repayment of the HMDC project.

METHODOLOGY

The study employed a mixed-methods approach for data collection, integrating quantitative and qualitative techniques including the desk study. Quantitative data were collected through surveys of 40 transport owners (20 public transport, 20 goods transport), 90 commuters/travelers, 90 from landowners, tenants, and farmers, 60 shopkeepers/SMEs owners, and 20 project employees. The sample was drawn from 3 districts, namely, Hyderabad, Tando Allahyar, and Mirpurkhas in Sindh. The source of qualitative data was five key informant interviews (KIIs) and focus group discussions (FGDs). The key informants included two Deokjae project officials and one representative each from Sindh's Finance Department, Works & Services Department, and the PPP Unit. The FGDs were held with 60 community members, including farmers, tenants, social workers, businessmen, faculty, officials, etc. An extensive questionnaire was developed for the surveys, and structured interview guides were prepared in advance for both KIIs (specified to stakeholder requirements) and FGDs protocols or guides to ensure consistency and depth across discussions. Survey data were analyzed using SPSS for descriptive statistics on SPSS, while thematic analysis was used to analyze KIIs and FGDs on Atlas.ti.

KEY FINDINGS

The analysis of the HMDC project highlighted several key lessons, including the successful attraction of private investment, the dualization of the road to improve fuel efficiency and reduce travel time, enhanced regional connectivity, and a positive impact on agricultural growth. The integration of innovative technologies, such as the electronic toll and traffic management system (ETTMS) and axle load management,

along with the creation of employment opportunities for women, further underscores its value as a pioneering infrastructure initiative.

However, certain gaps limited the project's potential to fully serve as a model for sustainable and inclusive infrastructure development. These include insufficient safety measures, such as the absence of speed cameras and road studs, inadequate overhead bridges in populated areas, and challenges in protecting the right-of-way (ROW). Addressing these gaps is essential to maximizing the project's long-term impact and serving as a benchmark for future initiatives.

1. A major shortfall in the HMDC project was the limited engagement of local communities during the planning and construction phases. As outlined in the PPP Policy 2017 (Section 11, Subpoint iv), the government is expected to provide the public with information about the roles and obligations of both the private sector and the government. However, this was not sufficiently implemented, leading to resistance against the toll tax during the construction phase and resulting in law-and-order issues. It became evident that the local government was not actively involved in the early stages of the project. Although this gap has since been addressed by including local government stakeholders, the lack of initial communication affected public acceptance.

2. Despite efforts to raise awareness, resistance to toll collection and unauthorized use of the road highlights significant deficiencies in the outreach strategies. The absence of a toll gate at Tando Allahyar has resulted in many people using the road without paying the toll. Furthermore, a majority of the study participants consider the toll tax to be high. The exclusion of these groups from the planning process worsened the situation, reducing public acceptance and ownership of the project. This finding reveals a gap vis-à-vis the PPP Policy 2017 (Section 11, Subpoint v), which mandates that tolls and charges be set at an affordable level.

3. While the project has resulted in safer travel with reduced travel time, improved fuel efficiency, and a better law and order situation, the number of road accidents has increased. These accidents have led to severe injuries and fatalities, particularly of livestock and people crossing the road. This finding reveals a gap against

the PPP Policy 2017 (Section 11, Subpoint ii), which ensures the health and safety of the public.

4. The HMDC project has made some progress in terms of sustainability, such as the adoption of solar energy. However, these efforts are limited in scope. There is a lack of a comprehensive ecological impact assessment and the integration of broader green infrastructure principles. Although a green belt and a small park have been established, the majority of the trees planted are non-native species (e.g., Conocarpus), and the number of trees planted is fewer than the trees that were removed during the project.

5. While the HMDC project has created employment opportunities for women as toll gate operators, the number of positions available is limited. This is a notable achievement as it marked the first road project where female operators have been appointed. However, the study could not find reliable data on the total number of jobs created under the project, such as the anticipated 5,000 direct jobs.

6. There is a significant issue of traffic congestion during peak hours, a concern reported by the majority of research participants. This congestion impacts the efficiency of the road, causing delays and reducing the overall benefits of the project.

7. The project revealed a significant infrastructure gap, particularly the lack of overhead bridges in populated areas (e.g., Khuwaja stop). Furthermore, the presence of jersey barriers disrupts connectivity between families and communities living on both sides of the HMDC route, leading to reduced visibility and contributing to fatal road accidents.

8. A significant gap in the project is the challenge of protecting the right-of-way (ROW), as the road passes through densely populated cities and villages. Research participants reported limited support from the local government in maintaining and securing the ROW, leading to encroachments and challenges in ensuring the integrity of the road corridor.

9. The PPP governance framework has demonstrated strengths. For example, the implementation of the ETTMS has significantly improved transparency, accountability,

and real-time monitoring of the revenue-sharing process.

10. The HMDC project has significantly contributed to socioeconomic development by increasing agricultural and property land values and stimulating regional economic activity. The establishment of new SMEs and the creation of indirect employment opportunities have further bolstered local economic growth. Improved access to markets, healthcare, and educational services has enabled individuals to pursue new ventures, driving prosperity and enhancing the overall quality of life in the region.

POLICY RECOMMENDATIONS/ POLICY IMPLICATIONS

To address these gaps and align future infrastructure projects, the following recommendations are proposed:

I. It is recommended for the concerned department for all PPP projects that local communities be engaged from the planning stages to avoid any unwanted situations. This includes ensuring that stakeholders such as district local governments are actively involved from the outset, and that communication about the roles and responsibilities of all parties is transparent and widespread. Additionally, government and private sector obligations should be clearly communicated to the public for trust building and mitigating resistance to key project elements such as toll taxes.

II. Private partners must install AI-driven cameras at toll gates to gather real-time data on traffic flow, commuter headcount, and vehicle movement. This will help assess the economic benefits and operational efficiency of road projects.

III. The Electronic Toll and Traffic Management Systems (ETTMS) enhanced revenue collection and reduced operational inefficiencies in the HMDC project. The ETTMS should be incorporated in the PPP policy for similar road dualization projects to optimize operational efficiency, enhance financial transparency and enable data-driven decision- making.

IV. PPP must thoroughly review toll tariffs to ensure affordability for all end users and align them with the principles of the PPP Policy of 2017. It is recommended that a strategic location be envisioned for the installation of toll gates to collect toll tax fairly.

Install toll gates at strategic locations (such as Tando Allahyar in the HMDC project), to prevent unauthorized road use and revenue loss.

V. It is recommended that the concerned line departments and private partners incorporate pedestrian-friendly infrastructure, including a maximum number of overhead bridges, road studs, and clear road signage, in the project plan and install speed cameras, to ensure the safety of pedestrians, eliminate the risk of fatal road accidents and ensure road safety.

VI. The minimum revenue guarantee model of the HMDC project should be adopted for future projects to eliminate financial risks and maintain fiscal sustainability during crises.

VII. Weighbridges must be included in road dualization initiatives to ensure and monitor axle loads to prevent road damage and safeguard long-term build quality. As the HMDC project proved the model to be as successful as the initial overlay after 10 years was extended for 2-3 years.

VIII. The concerned government line departments must establish clear guidelines and enforcement mechanisms to protect the ROW, especially in populated areas. Foster collaboration between local governments and project stakeholders to ensure timely support in addressing encroachments and maintaining the integrity of the road corridor in future projects.

IX. PPP unit must develop stakeholder mapping frameworks and comprehensive communication plans to ensure effective communication among departments, private partners, and local authorities, thereby addressing risks proactively.

X. Expand the road network, like HMDC, to promote regional development, reduce travel time, improve fuel efficiency, and enhance economic growth at the local level, which will contribute to boosting the national economy.

Implementing the proposed recommendations will enhance project outcomes and align them with international best practices. Pakistan can pave the way for equitable growth and sustainable development, ensuring that future projects deliver long-term benefits for all by embedding resilience, inclusivity, and transparency into the core of infrastructure planning and execution.

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