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Microplastics in Particulate Matter from Kitchen Air: A Comparison of Rocket and Traditional Stoves

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Abstract

Indoor air pollution in rural and resource-constrained households is primarily caused by the use of biomass fuel in cookstoves, a significant risk factor for morbidity and mortality throughout the world. This study uniquely investigates indoor microplastic pollution from cookstove emissions in Pakistani slums, as plastic has been identified as one of the major tertiary fuels used to start cookstoves, addressing a major research gap. Unlike previous local studies focused on outdoor air, this study identifies and characterizes polymeric particles in PM_{10} and $PM_{2.5}$ from 2 different cookstoves, using FTIR and Raman spectroscopy, offering first-time molecular evidence in this context. Particulate matter (PM) samples were collected both from the traditional and the locally manufactured rocket biomass cookstove kitchens, within H-11 and F-11 slums in Islamabad, Pakistan. Two analytical techniques, Raman and Fourier Transform Infrared Spectroscopy (FTIR), were employed to identify and characterize microplastics in PM_{10} and $PM_{2.5}$ samples. The detected polymers included polypropylene, polyvinyl chloride, polystyrene, polyolefins, and polyurethanes. At Site 2, LDPE, polyolefins, and polypropylene were identified. Results from the comparative analysis of traditional and rocket stoves in PM_{10} and $PM_{2.5}$ samples revealed a significant difference in the concentration of particulate matter contamination at both sites. The findings from this study indicate that the rocket stove had a lower concentration of particulate matter in PM_{10} and $PM_{2.5}$ samples as compared to the traditional stove, which may suggest that microplastic concentration was also lower, thereby offering enhanced potential health benefits for users, as inhalation and continuous exposure to microplastics are associated with adverse health effects. Overall, ICS reduced PM_{10} concentrations by 38.73% and $PM_{2.5}$ concentrations by 34.75% across both monitored sites. This study emphasizes the importance of using rocket stoves as they offer a superior alternative to traditional stoves by reducing particulate matter and microplastic exposure, making them a cleaner and safer cooking option in slum areas.

Keywords: Traditional stoves; Improved stoves; Microplastics; Startup fuels; Indoor air pollution

1. Introduction

Indoor Air Pollution (IAP) may pose a significant health threat to people, hundreds of times greater than outdoor air pollution (Smith and Mehta, 2003). Current estimates suggest that IAP causes approximately 4 million premature deaths worldwide each year, and millions more suffer from serious health conditions (Kim et al., 2011). This problem is critically significant in slums or informal settlements where over a billion people live worldwide (Cosgrove, 2020). Due to factors including their proximity to factories, the dust from unpaved roads, improper waste disposal, burning of trash, and their significant reliance on solid fuels like wood, plastic, agricultural residues, cow dung, etc., slum settlements are likely to have elevated levels of indoor and ambient air pollution than non-slum areas.

According to Wu (2021), using solid fuels for cooking is dangerous and can have an instantaneous detrimental effect on one's health. According to McLean et al. (2019), indoor air pollution from incomplete combustion of biomass fuels for cooking has been linked to about 0.5 million deaths in Asia and approximately 3.8 million deaths globally (Balmes, 2019). This issue is especially critical in developing countries that rely heavily on non-renewable energy sources (Nadimi et al., 2018).

Another growing concern in both rural and urban areas is the emission of microplastics, due to the burning of traditional solid fuels, especially plastics. The stove's igniting or 'startup' procedure could be a key aspect in understanding cookstove emissions and associated health effects. During the cookstove startup procedure, a quick-burning material such as consumer product waste or plastic waste is frequently utilized to ignite the primary fuel. This practice could be especially relevant for human health because the cookstove user is often extremely close to the stove during the startup period, potentially resulting in high personal exposures. Several laboratory studies have shown that the startup phase contributes significantly to overall emissions, though the contribution varies depending on the startup fuel type, method of ignition, and main fuel (e.g., Arora et al., 2014; Carter et al., 2014; Lask and Gadgil, 2017; Wathore et al., 2017).

Several studies recorded that the consumption of secondary fuels, such as huge plastic bags and consumer product waste, is common to ignite traditional stoves. The combustion of these plastic-based materials is especially worrying since it not only releases toxic compounds but also adds to the emission of microplastics into the atmosphere. Because of their tiny sizes and hues, the scientific community has recently been increasingly concerned about the presence, distribution, and movement of microplastics (Cole et al., 2011). However, the research in Pakistan remains limited, particularly regarding microplastic emissions and indoor air pollution in low-income or informal settings through household combustion activities. Most available local studies address outdoor ambient air quality or solid fuel use patterns without assessing the presence of microplastics in indoor air particulates. Therefore, this study aims to address this gap by determining the concentrations of PM_{10} and $PM_{2.5}$ sampled from traditional and improved cooking environments and through the identification of the molecular composition of the Particulate Matter (PM) to determine the presence and nature of polymeric (plastic-based) particles. This has developed a comparison of traditional cooking stoves and Rocket stoves as improved cooking stoves, not only for PM concentrations but also for the microplastic types present in them.

2. Methodology

2.1. Study Area

The focus of the study was to conduct an extensive investigation of indoor fuel combustion, particularly the use of different cookstoves in a marginalized and vulnerable community. The chosen slums of Islamabad present the true picture of these requirements. The first slum site (S1) is located at coordinates 33°38' north latitude and 73°01' east longitude. The second slum site (S2) is from 33°40' north latitude to 72°58' east longitude, as illustrated in Figure 1. Both sites are located in the federal capital of Pakistan.

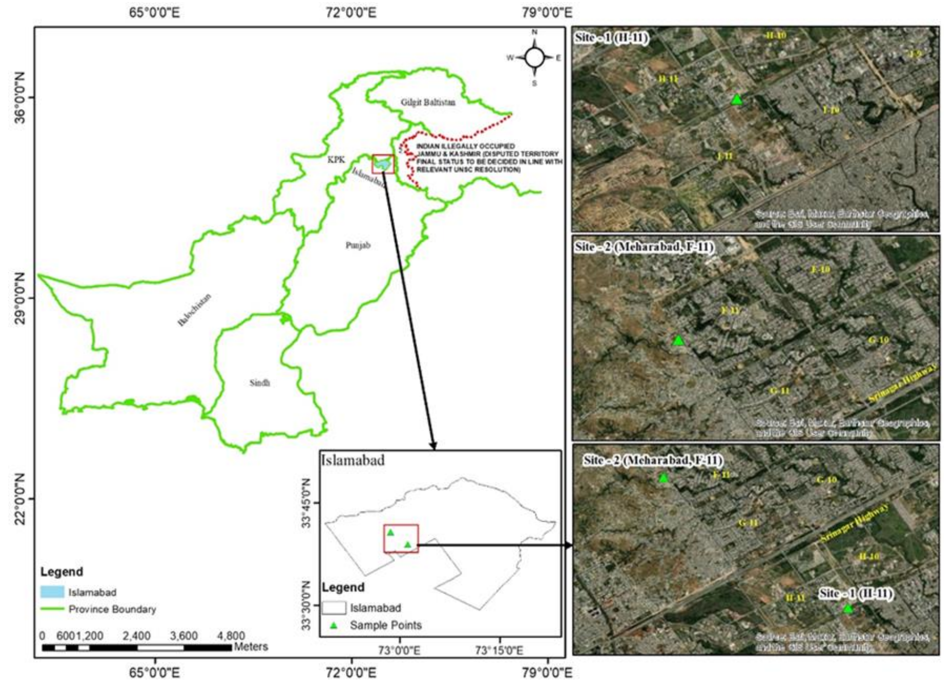

Fig. 1. Study area of Islamabad, Pakistan

2.2. Sampling

The overall methodology has been summarized in Figure 2. The sampling for traditional and improved cooking stoves was conducted over 12 hours, spanning from morning to evening, in September. A two-head low-volume sampler (LVS) was turned on before breakfast and turned off after dinner to collect concentrations of $PM_{2.5}$ and PM_{10} samples. This round of sampling was conducted in households that continued to burn biomass fuel in traditional cookstoves, often known as mud stoves.

The two-head low-volume sampler was positioned 1.5 meters above the chief cook's breathing zone (Cao et al., 2017). To collect PM, 47-mm diameter pre-weighed (W1) quartz fiber filters were used on both heads. The sampler's flow rate was kept constant at 15 Liters per minute (LPM) throughout the sampling duration (Chen et al., 2020; Beaurepaire et al., 2021; Wright et al., 2021; Sharaf Din et al., 2024). The 12-hour sampling window was intended to incorporate all indoor cooking activities that a family would take part in. From each location, a total of eight samples were collected. Table 1 presents an overview of the various types of cookstoves and fuels that were being used in the study areas.

2.3. Gravimetric concentration of particulate matter (PM)

Filters were weighted (W2) and refrigerated following sampling to prevent thermal degradation. The mass of the blank filter paper (W1) was subtracted from the mass of the sample-laden filter paper (W2) to compute the gravimetric mass of the PM. The PM concentration on each filter was subsequently determined using Equation 1 (Araújo et al., 2014).

$$C = \frac{m}{Q \times T} \quad (1)$$

where C is the particulate concentration (mass/volume), m is the net mass collected on the filter (mass), Q is the volumetric flow rate (volume/time), and T is the duration (time) of sampling. The calculations for the gravimetric concentration of particulate matter (PM) for both PM_{10} and $PM_{2.5}$, including initial mass, flow rate, sampling duration, and the resulting concentration values in micrograms per cubic meter (µg/m³) across different sites, are shown in Table 2.

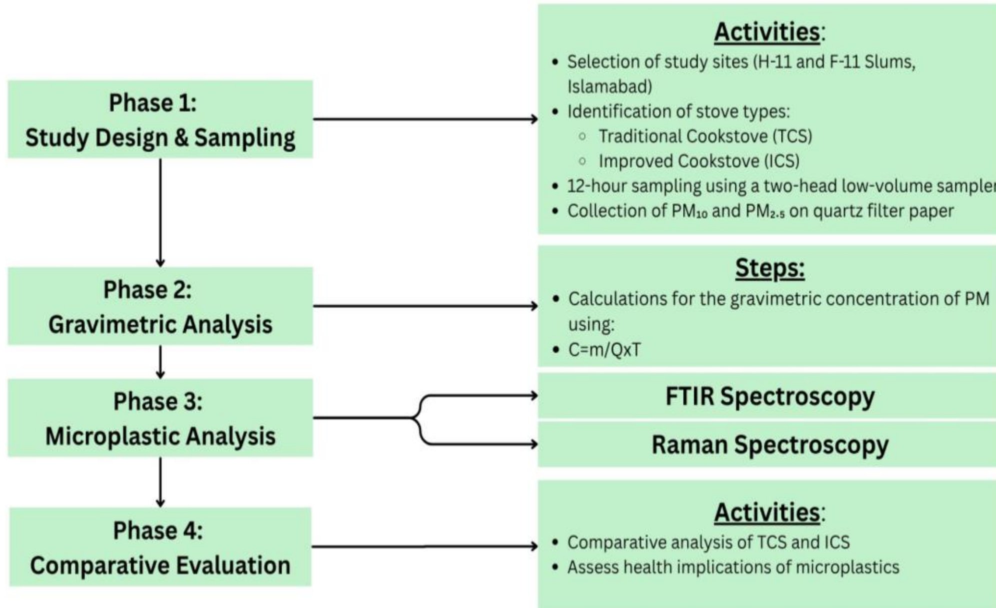

Fig. 2. Flowchart of the research methodology

Table 1: Types of Cookstoves and Fuels used in the research

Study	Stove Type	Fuel Type
TCS Site 1	Traditional Cookstove-TCS (mud stove) Tandoor Iron stoves like a drum	-Firewood -Stylophorum diphyllum (Poppy Plants) -Paper/Petrol
ICS-Site 1	Rocket Biomass Stove (Improved Cookstove-ICS)	-Firewood -Stylophorum diphyllum (Poppy Plants)
TCS-Site 2	Traditional Cookstoves-TCS (mud Stoves) Iron Stoves like a drum	-Cow-dung cakes -Plastic Wrapper, bags -Kerosene oil
ICS-Site 2	Rocket Biomass Stove (Improved Cookstove-ICS)	-Cow-dung cakes -Plastic Wrapper, bags -Kerosene oil

To identify the microplastics in PM_{10} and $PM_{2.5}$ samples collected from both Traditional and improved cookstoves, Fourier Transform Infrared (FTIR) spectroscopy and Raman spectroscopy were employed for molecular-level characterization and confirmation of polymeric components of the particulate matter.

2.4. Detection of Microplastics in PM Samples

To identify and confirm the presence of microplastics in PM_{10} and $PM_{2.5}$ samples, a total of eight samples were subjected to both Fourier Transform Infrared (FTIR) spectroscopy and Raman spectroscopy.

2.4.1. FTIR spectroscopy analysis

FTIR analysis was used to identify functional groups indicative of different types of microplastics. The FTIR spectroscopy results of particulate matter (PM_{10} and $PM_{2.5}$) samples obtained from both TCS and ICS indicate noteworthy discoveries about the presence of microplastics and the health problems they cause. Determining the polymer composition is highly helpful because different samples have distinct chemical structures, which result in varied spectra (Pervez et al., 2020; Günzler and Gremlich, 2002).

Table 2: Calculations for the gravimetric concentration of PM

Sites	Sample Code	Concentration in the air ug/m-3
TCS Site 1-PM_{10}	S1	16.667
TCS Site 1-$PM_{2.5}$	S2	16.111
ICS Site 1-PM_{10}	S3	9.444
ICS Site 1-$PM_{2.5}$	S4	6.667
TCS Site 2-PM_{10}	S5	96.667
TCS Site 2-$PM_{2.5}$	S6	155
ICS Site 2-PM_{10}	S7	60
ICS Site 2-$PM_{2.5}$	S8	105.56

2.4.2. Raman spectroscopy analysis

Raman spectroscopy was used to analyze and describe the various types of microplastics found in PM_{10} and $PM_{2.5}$ samples taken from both traditional cooking stoves (TCS) and improved cooking stoves (ICS). The Raman spectroscopy approach has several benefits, including its non-destructiveness, minimal sample volume requirement, potential for high-throughput screening, and environmental friendliness. For the analysis and characterization of MPs, these are noteworthy benefits over other approaches (Elert et al., 2017; Ribeiro-Claro et al., 2017). Raman spectroscopy operates on the principle of observing the shift in an incident radiation beam due to inelastic interactions with the molecules in the sample (Baeten and Dardenne, 2002).

Raman is best suited to analyze these particles since it can analyze micro-sized particles of up to 1 µm in length. Both techniques are sophisticated, efficient, and costly (Beaurepaire et al., 2021; Enyoh et al., 2019).

3. Results and Discussion

Based on a comprehensive assessment of the impact of these stoves on indoor air quality, Figure 2 and Table 2 illustrate that the particulate matter (PM_{10} and $PM_{2.5}$) emissions from the Rocket biomass stove are significantly lower in the study area compared to traditional stoves. Rocket biomass stoves are an excellent option because their use is effective in lowering the amount of hazardous particulate matter released into the atmosphere.

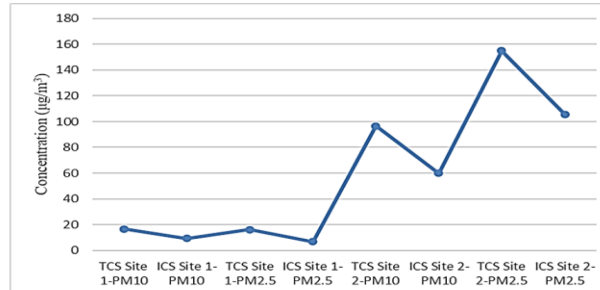

Fig. 2. Average indoor PM_{10} and $PM_{2.5}$ concentrations from TCS and ICS at both sites

The findings are highly relevant to environmental sustainability and public health since elevated levels of PM_{10} and $PM_{2.5}$ are known to have detrimental effects on respiratory health and overall air quality. The data shows that in these kinds of communities, these stoves are a good option for a more affordable and ecologically responsible cooking method that satisfies the demands of slum residents while still staying within their means.

3.1 Microplastic identification using FTIR

3.1.1. Microplastic Presence in Traditional Cook Stove (TCS)

In sample S1-TCS-PM_{10}-Site-1, where the wood fuel is used as a primary fuel, polypropylene (PP) at a wavenumber of 1681.93 cm^{-1} was detected, which is associated with carboxylic acid (C=O) functional groups, indicating the release of microplastics from traditional stoves. Polypropylene is linked to respiratory damage, restrictive impairment, and pulmonary function impairment (Fedeli et al., 2019; Mattsson et al., 2017; Goodman et al., 2021). Its presence in PM_{10} indicates that the community's practice of using plastic material as a secondary fuel during the ignition process significantly contributes to microplastic emission in the surrounding environment, raising major health concerns for users.

However, no microplastics were found in the $PM_{2.5}$ sample (S2-TCS-$PM_{2.5}$-Site-1), showing that microplastic particles are predominantly found in the larger PM_{10} fraction, which is important for understanding the particle size distribution and its related potential inhalation risk.

In contrast to Site 1, at Site 2, no microplastics were detected in the PM_{10} sample (S5-TCS-PM_{10}-Site-2). However, the $PM_{2.5}$ sample (S6-TCS-$PM_{2.5}$-Site-2) revealed the presence of linear low-density polyethylene (LDPE) with a -CH_2 functional group, detected at 719.45 cm^{-1}. Exposure to LDPE is known to cause respiratory system irritation (Sapuan et al., 2022), highlighting the health impacts associated with solid fuel use in traditional stoves. The absence of microplastics in the PM_{10} fraction at this site highlights the heterogeneity in microplastic emissions, which may be impacted by factors such as fuel type and combustion conditions.

3.1.2. Microplastic Presence in Improved Cooking Stove (ICS)

Sample S3-ICS-PM_{10}-Site-1 from the improved stove showed the presence of polyvinyl chloride (PVC) at 794.67 cm^{-1}, associated with the Si-O-Si functional group. PVC is a toxic polymer that has been linked to serious health hazards such as liver damage, angiosarcomas, and hepatocellular carcinomas (Fedeli et al., 2019). Its presence in particulate matter generated by ICS highlights the risks of access usage of non-biomass fuels or mixed waste materials. Similarly, no microplastics were observed in the $PM_{2.5}$ fraction (S4-ICS-$PM_{2.5}$-Site-1), underlining the particles' broader size range.

The ICS PM_{10} sample (S7-ICS-PM_{10}-Site-2) also contained polypropylene (PP) at a wavenumber of 1454.33 cm^{-1}, associated with C-N functional groups, consistent with the Site-1 results. The presence of PP in both stove types highlights the prevalence of plastic use in cooking environments, as well as the larger issue of microplastic pollution, which has been linked to respiratory damage and pulmonary function impairment (Fedeli et al., 2019; Mattsson et al., 2017; Goodman et al., 2021). No microplastics were found in the $PM_{2.5}$ sample (S8-ICS-$PM_{2.5}$-Site-2), supporting the size distribution findings.

3.2. Microplastic Identification Using Raman Spectroscopy

3.2.1. Microplastics in Traditional Cooking Stoves (TCS)

At Site 1, the sample (S1-TCS-PM_{10}-Site-1) contained polystyrene at the wavelength of 1604 cm^{-1}, which is linked to negative health outcomes such as cell damage, decreased metabolic activity, and slower cell proliferation (Fedeli et al., 2019; Mattsson et al., 2017; Goodman et al., 2021).

S2-TCS-$PM_{2.5}$-Site-1 detected polypropylene (PP) at 1150 cm^{-1}, indicating respiratory injury, restrictive limitation, and pulmonary function impairment. This sample also detected polyurethane (PUR) at 2252 cm^{-1}, which has been associated with fish mortality and intestinal injury (Ebrahimpour et al., 2021). The presence of these microplastics indicates significant inhalation risks and probable health consequences from TCS use. At Site 2, the sample (S5-TCS-PM_{10}-Site-2) revealed no microplastics, indicating a decrease in plastic pollution or a lack of relationship between microplastics and small particulate matter. S6-TCS-$PM_{2.5}$-Site-2 identified LLDPE at 1284 cm^{-1}, which is responsible for the respiratory discomfort (Sapuan et al., 2022). This finding raises new health concerns about indoor air quality.

3.2.2. Microplastics in Improved Cooking Stoves (ICS)

The ICS samples from Site 1 produced significant findings, particularly S3-ICS-PM_{10}-Site-1, which found polyvinyl chloride (PVC) at 2900 cm^{-1}.

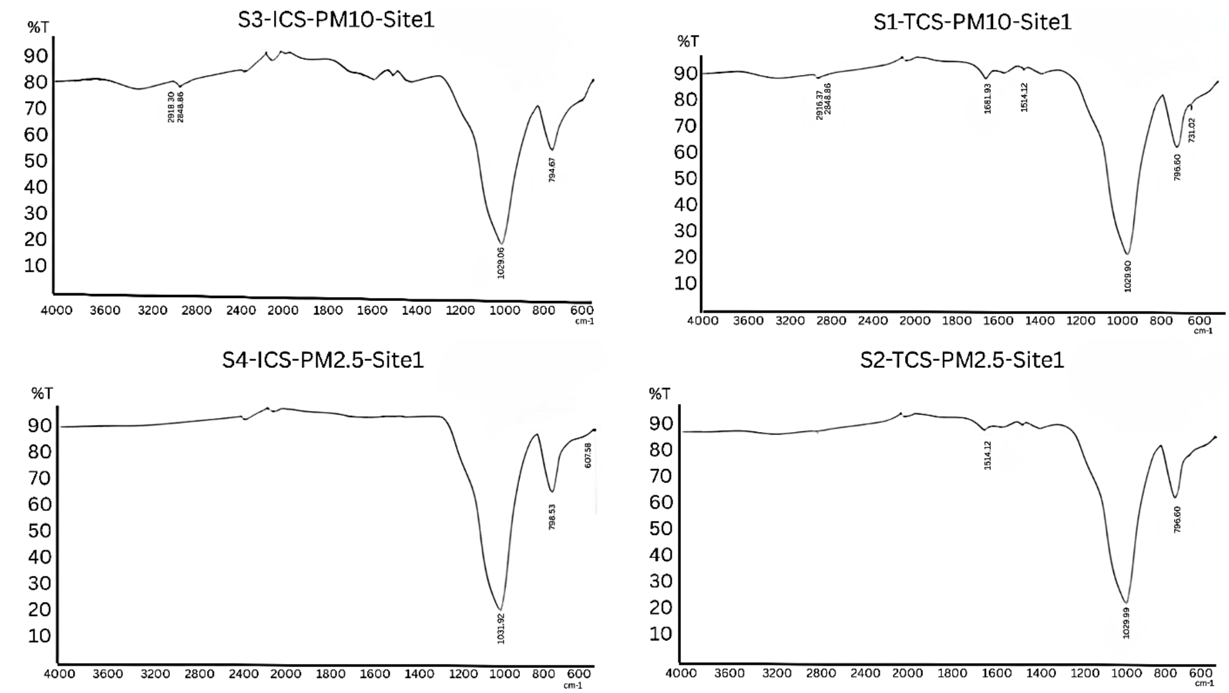

Fig. 3. FTIR spectroscopy graphs site 1.

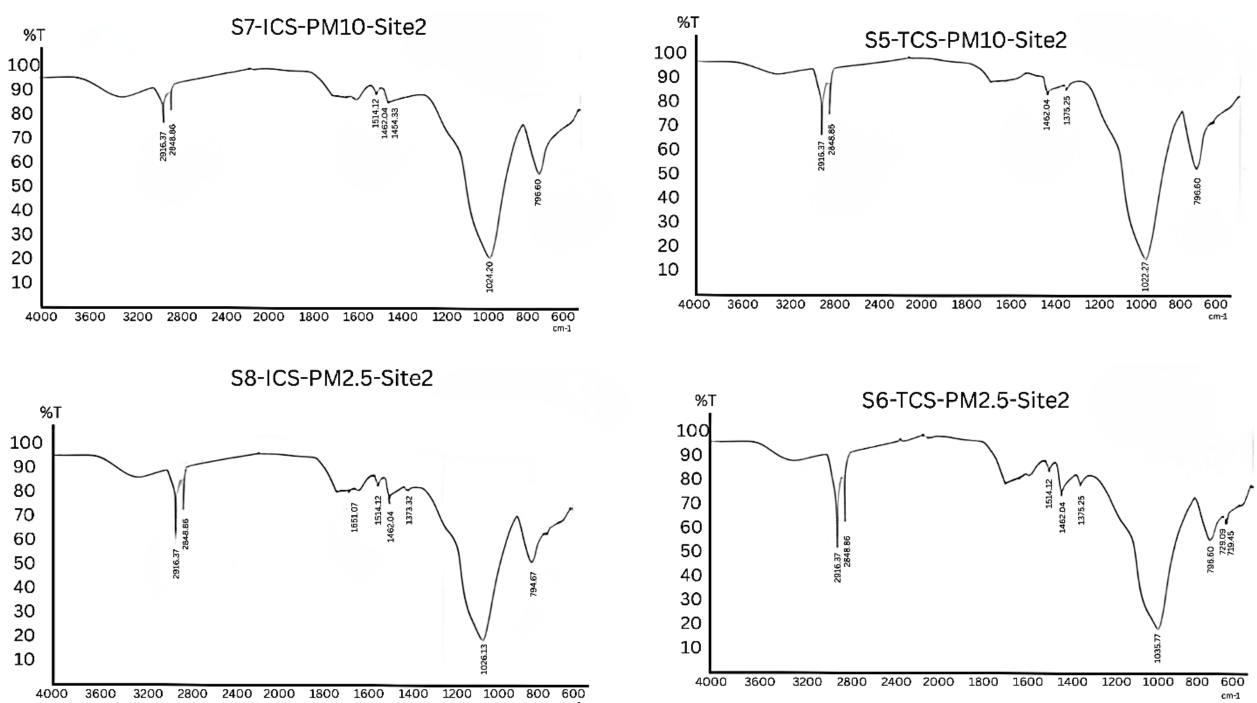

Fig. 4. FTIR spectroscopy graphs site 2.

This chemical has been related to major health risks, including liver damage, angiosarcomas, hepatocellular carcinomas, and decreased cell viability and ATP levels (Zarus et al., 2023). In contrast, S4-ICS-$PM_{2.5}$-Site-1 found no microplastics, signaling better interior air quality or less use of plastic as a secondary fuel.

At Site 2, (S7-ICS-PM_{10}-Site-2) identified polypropylene (PP) at 972 cm^{-1}, indicating respiratory concerns (Fedeli et al., 2019). Similarly, S8-ICS-$PM_{2.5}$-Site-2 found no microplastics, underscoring the importance of continuing to monitor indoor air quality.

Table 3: FTIR spectroscopy results

Samples	Wavenumber (cm^{-1})	Functional Group	Microplastic Type	Possible Health Effects and References
S1-TCS-PM_{10}-Site-1	1681.93	Carboxylic Acid (C=O)	Polypropylene (PP)	*Respiratory Damage, Restrictive impairment, Pulmonary function impairment* (Fedeli et al., 2019; Mattsson et al., 2017; Goodman et al., 2021)
S2-TCS-$PM_{2.5}$-Site-1				**No Microplastic Found**
S3-ICS-PM_{10}-Site-1	794.67	Si-O-Si	Polyvinyl Chloride	*Liver damage, Angiosarcomas, Hepatocellular carcinomas, Decreased cell viability and ATP levels* (Fedeli et al., 2019)
S4-ICS-$PM_{2.5}$-Site-1				**No Microplastic Found**
S5-TCS-PM_{10}-Site-2				**No Microplastic Found**
S6-TCS-$PM_{2.5}$-Site-2	719.45	$-CH_2$	Linear Low-density Polyethylene (LDPE)	*Irritation of the respiratory system* (Sapuan et al., 2022)
S7-ICS-PM_{10}-Site-2	1454.33	C-N	Polypropylene (PP)	*Respiratory Damage, Restrictive impairment, Pulmonary function impairment* (Fedeli et al., 2019; Mattsson et al., 2017; Goodman et al., 2021)
S8-ICS-$PM_{2.5}$-Site-2				**No Microplastic Found**

Table 4: Raman spectroscopy results

Samples	Wavenumber (cm^{-1})	Material	Plastic Pollution category	Possible Health Effects and References
S1-TCS-PM_{10}-Site-1	1604	polystyrene	polystyrenes (polyphenylethene, methyl styrene)	*Cell damage, Decrease in Metabolic activity, Decline in the rate of cell proliferation* (Fedeli et al., 2019; Mattsson et al., 2017), (Goodman et al., 2021)
S2-TCS-$PM_{2.5}$-Site-1	1150	Polypropylene (PP)	polyolefins (polyalkenes)	*Respiratory Damage, Restrictive impairment, Pulmonary function impairment* (Atis et al., 2005)
	2252	Polyurethane (PUR)	polyurethanes (isocyanates)	*Fish mortality, Intestinal Damage* (Ebrahimpour et al., 2021)
S3-ICS-PM_{10}-Site-1	2900	Polyvinyl Chloride	polyhaloolefins (vinyl halides)	*Liver damage, Angiosarcomas, Hepatocellular carcinomas, Decreased cell viability, and ATP levels* References: (Zarus et al., 2023)
S4-ICS-$PM_{2.5}$-Site-1				**No Microplastic Found**
S5-TCS-PM_{10}-Site-2				**No Microplastic Found**
S6-TCS-$PM_{2.5}$-Site-2	1284	Linear Low-density Polyethylene (LLDPE)	polyolefins (polyalkenes)	*Irritation of the respiratory system* References: (Sapuan et al., 2022)
S7-ICS-PM_{10}-Site-2	972	Polypropylene (PP)	polyolefins (polyalkenes)	*Respiratory Damage, Pulmonary function impairment* References: (Fedeli et al., 2019)
S8-ICS-$PM_{2.5}$-Site-2				**No microplastic found**

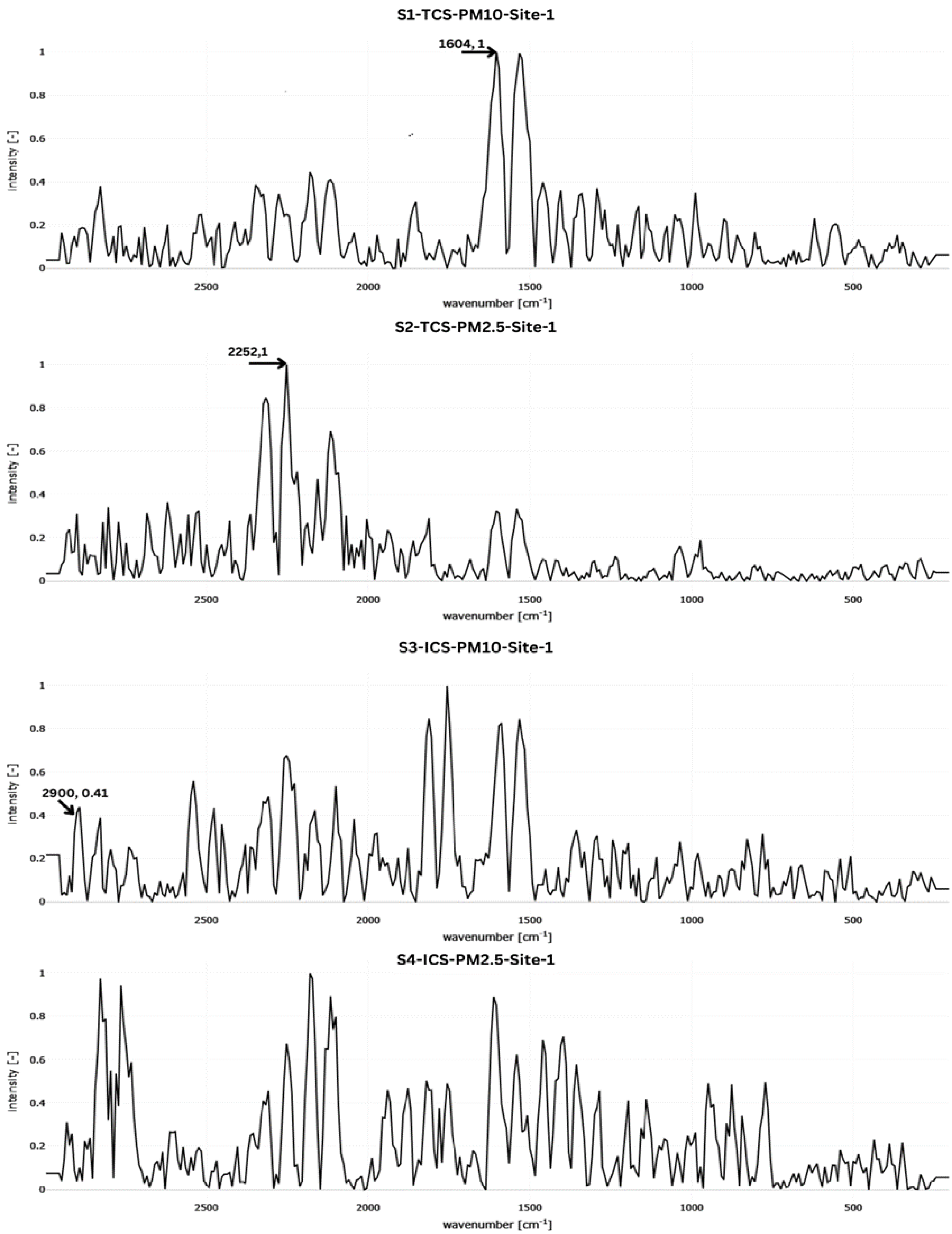

Fig. 5. Raman Spectroscopy graphs site 1.

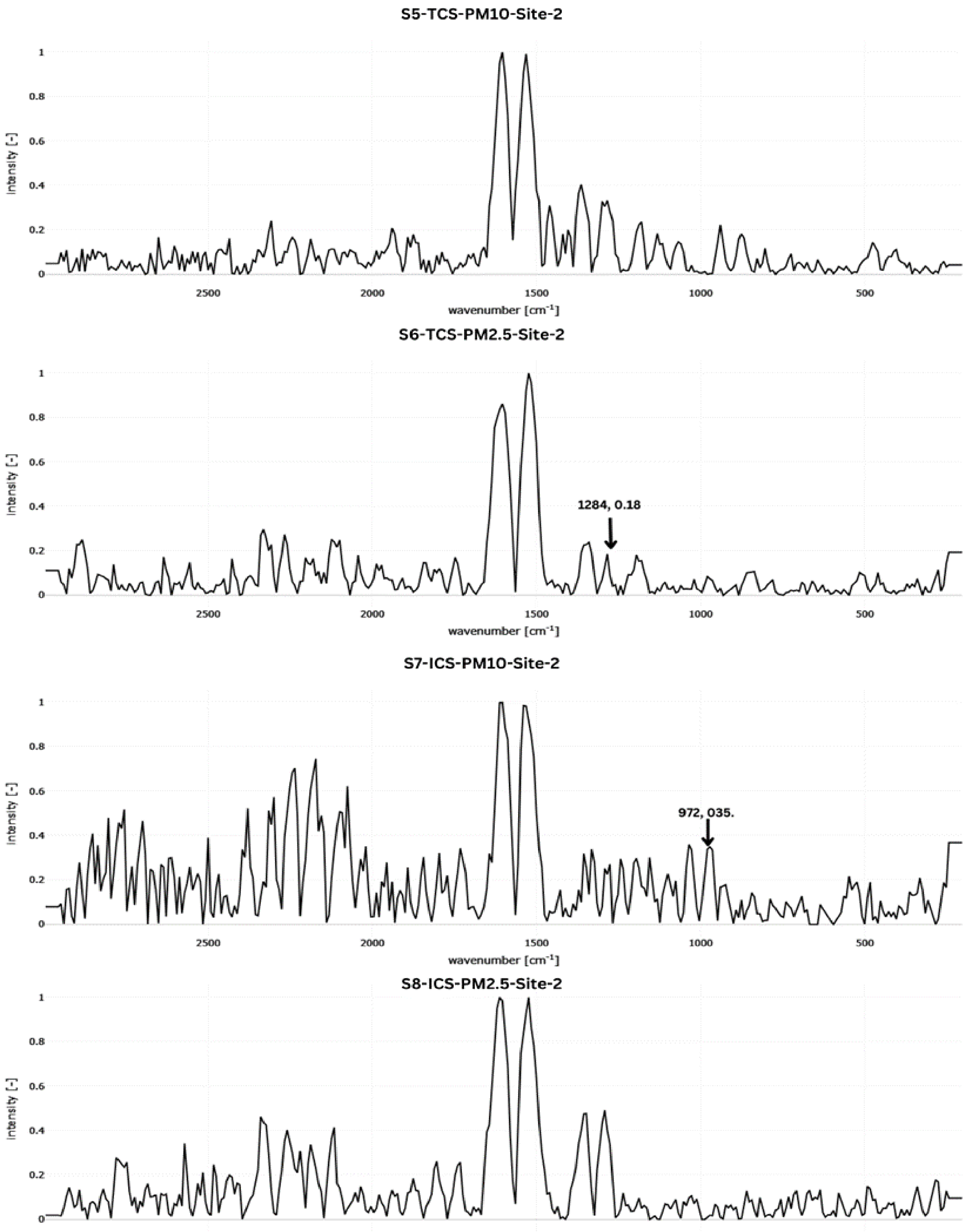

Fig. 6. Raman Spectroscopy graphs site.

Microplastics are most commonly associated with bigger particulate matter (PM_{10}), as seen by the presence of PVC and PP in PM_{10} samples. This shows that microplastics may represent significant inhalation dangers due to greater particle sizes, whereas smaller fractions, such as $PM_{2.5}$, have a reduced prevalence of microplastics. The difference in particle size distribution emphasizes the necessity for targeted monitoring and intervention measures to combat microplastic pollution in indoor air.

Overall, the findings from both TCS and ICS samples highlight the critical need for effective mitigation techniques to reduce microplastic pollution and protect public health, particularly in light of the respiratory and metabolic health hazards associated with these materials

3.3 Comparative analysis of TCS and ICS

A comparison of particulate matter (PM) concentrations and the presence of microplastics in samples collected from two sites using both traditional cook stoves (TCS) and improved cook stoves (ICS) provides significant insights into the effectiveness of these stoves in reducing air pollution.

3.4 Reduction in particulate matter using Improved Cook Stoves (ICS)

The gravimetric study showed that when the improved cook stoves (ICS) were used instead of the traditional cookstoves (TCS), the concentrations of PM_{10} and $PM_{2.5}$ were significantly lower. The average indoor PM_{10} and $PM_{2.5}$ values for TCS at Site 1 were 16.66 µg/m³ and 16.111 µg/m³, respectively, while the ICS had lower concentrations of 9.44 µg/m³ and 6.66 µg/m³. Site 2 showed a more significant difference, with TCS having PM_{10} and $PM_{2.5}$ levels of 96.66 µg/m³ and 155 µg/m³, respectively, while ICS had levels of 60 µg/m³ and 105 µg/m³. The data shown in Figure 2 highlights the noteworthy decrease in PM emissions obtained through the utilization of upgraded cookstoves.

3.5 Health implications and environmental impact of TCS and ICS

The samples show that there are microplastics in indoor air, which raises questions regarding the health effects on those who are exposed to these particles. Inhaling microplastics over extended periods can be hazardous to one's respiratory health. Certain microplastics that have been found, such as polystyrene and polypropylene, are known to contain hazardous compounds that can make health problems worse. Research has indicated that breathing in microplastics may result in heightened lung inflammation and possible neurotoxic consequences, underscoring the significance of mitigating exposure.

According to a study, the Polystyrene microplastics (PS-MPs) with a diameter of 1 and 10 µm were introduced to cultured human alveolar A549 cells to investigate the possible toxicological effects of microplastics on human cells. Both sizes showed minimal cytotoxicity but significantly reduced cell growth, alterations in the structure of cells (Goodman et al., 2021). According to the findings of a study by Hwang et al. (2019), direct interaction between PP particles and cells may have the ability to harm human health by triggering immune cells to produce cytokines.

Ebrahimpour et al. (2021) conducted a study on the effects of MP exposure on fish, which showed increased fish mortality along with hepatic and gill damage, behavioral changes, and intestinal damage such as epithelial detachment, gut wall weakening, and villi lesions.

Exposure to PVC may decrease cell viability, accompanied by an increase in ROS concentrations and a decrease in ATP (Mahadevan and Valiyaveettil, 2021). Polyethylene shows no negative health impacts; however, dust from the raw material might irritate the respiratory system if inhaled (Sapuan et al., 2022).

The improved cook stoves (ICS) can decrease indoor airborne microplastic concentrations in addition to lowering particulate matter concentrations. To mitigate the health concerns associated with exposure to PM and microplastics, this reduction is essential. Adoption of ICS can greatly enhance indoor air quality, giving inhabitants of impoverished areas a healthier place to live.

4. Conclusions

The particulate matter (PM) concentration analysis revealed a significant reduction in PM levels while using Improved Cookstoves (ICS) as compared to Traditional Cookstoves (TCS). At Site 1, the PM_{10} and $PM_{2.5}$ concentrations from TCS were 16.67 µg/m³ and 16.1111 µg/m³, respectively, while the ICS recorded lower concentrations of 9.44 µg/m³ (PM_{10}) and 6.67 µg/m³ ($PM_{2.5}$). This trend was sustained at Site 2, where TCS showed significantly higher PM_{10} levels of 96.67 µg/m³ and $PM_{2.5}$ levels of 155 µg/m³, compared to ICS values of 60 µg/m³ (PM_{10}) and 105.56 µg/m³ ($PM_{2.5}$). These findings underscore the potential of ICS to markedly reduce indoor air pollution.

Additionally, microplastic examination employing Fourier Transform Infrared (FTIR) and Raman spectroscopy revealed the presence of numerous hazardous polymers in PM samples, including polystyrene, polyurethane, polyvinyl chloride (PVC), linear low-density polyethylene (LLDPE), and polypropylene. The presence of these microplastics, which have been linked to negative health outcomes like as respiratory harm and carcinogenic hazards, raises severe concerns about indoor air quality in TCS-using families.

This study was limited by its small sample size and restricted geographic focus within Islamabad's slums, which may affect the accuracy of the results. Additionally, the analysis did not consider seasonal variation in indoor air quality or quantify long-term exposure effects. The cost and availability of equipment also constrained the scope and frequency of microplastic characterization.

These findings illustrate the environmental and health advantages of choosing ICS over TCS. Future studies should concentrate on further lowering particle and microplastic emissions in interior settings by employing economical and improved cooking technologies, as well as investigating alternative ways to improve air quality.

Author Contribution

Ukasha Ali and Mirza Agha Muhammad Taqi contributed to data analysis and article drafting. Amara Dar and Fiza Sarwar devised the research idea and supervised the study. Syed Umair Ullah Jamil formulated the study plan and ensured the execution. Hina Ishaque contributed to onsite data collection.

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Conflict of Interest

The authors declare that they have no conflicts of interest.

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