Design and Experimental Evaluation of a Packed-Bed Wet Scrubber System for Brick Kiln Emission Control

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Abstract

Conventional brick kilns contribute substantially to atmospheric pollution in South Asia, highlighting the need for practical emission-control technologies suitable for existing kiln infrastructure. This study aimed to design, fabricate, and experimentally evaluate a ground-mounted packed-bed wet scrubber for reducing gaseous emissions under simulated brick-kiln combustion conditions. The prototype incorporated coarse aggregate packing and fine-mist water spraying to promote gas–liquid contact. Flue gases generated from the combustion of coal, wood, and rubber were directed through the scrubber, and carbon monoxide (CO), nitrogen oxides (NO_x), and sulfur dioxide (SO_2) concentrations were measured before and after activation of the water-spray system. The results showed concentration reductions of 27.60% for CO, 28.57% for NO_x, and 25.53% for SO_2. A visible change from dense grey smoke to a lighter vaporous plume was also observed. However, particulate matter was not quantitatively measured; therefore, this observation provides only qualitative evidence of reduced smoke opacity and possible particulate capture. The ground-mounted configuration offers accessibility for operation and maintenance without imposing additional equipment loads on existing kiln chimneys. These preliminary findings provide a technical basis for further prototype optimization and full-scale evaluation under actual brick-kiln operating conditions.

Keywords: Packed-Bed Wet Scrubber, Brick Kiln Emission Control, Sulfur Dioxide Removal, Nitrogen Oxide Reduction, Flue Gas Cleaning, Air Pollution Mitigation, Laboratory-Scale Evaluation

Introduction

Brick production is an integral part of the construction industry in many developing countries. But at the same time, brick making is considered one of the major sources of pollution because of poor fuel

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consumption techniques and lack of control systems for emissions (Weyant et al., 2014). Thus, the South Asia Region (SAR) is the second in the world in brick production after China, with about 21% of the global share (Eil et al., 2020), as shown in Figure 1. There are several types of kilns; however, FCBTK and other types of trench kilns are still popular because of their lower capital investment and simpler technology (Guttikunda and Khaliquzzaman, 2014).

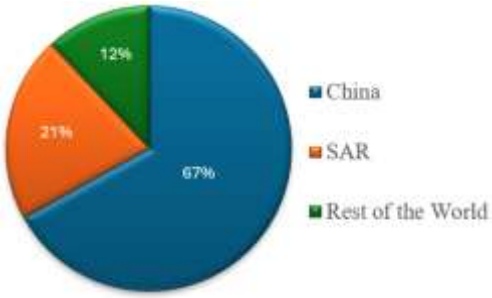


Figure 1: Distribution of Brick Production Globally (Eil et al. 2020)

The ecological and social risks associated with brick kiln operations have attracted increasing research interest over the last ten years. Each FCBTK normally emits 250-500 tons of particles and 1,500-3,000 tons of carbon dioxide per year in South Asia (Maithel et al., 2012). The brick business in Nepal is a major contributor to national $PM_{2.5}$ emissions, where the black carbon concentrations are the highest during the dry winter production seasons. It directly affects the quality of air and the health outcomes of people living in cities (Sadavarte et al., 2019). When low-grade coal is mixed with industrial wastes and abandoned materials, it creates a complex mix of pollutants, which include $PM_{2.5}$, PM_{10}, SO_2, CO, NOx, and black carbon (Bachmann, 2009). Likewise, in Pakistan, traditional brick kilns using low-quality coal and toxic materials such as scrap tyres are significant contributors of particulate matter and sulfur dioxide (SO_2), which contribute to significant deterioration of air quality and public health issues in the major urban centers during the winter season, with an estimated number of around 20,000 brick kilns (Ahmad et al., 2024; Iram et al., 2025).

The city of Peshawar, which is the capital of Khyber Pakhtunkhwa province, Pakistan, has serious air quality issues, and the presence of the brick kiln clusters of peri-urban nature can be blamed for this. Sources of fuel in local kilns include mainly coal, waste materials from factories, and rubber, which lead to high concentrations of pollutant emissions (Hasnain et al., 2026). Mean PM_{10} and $PM_{2.5}$ concentrations of 480 $\mu g/m^3$ and 172 $\mu g/m^3$, respectively, have been recorded in areas around kilns, which are

9.6 and 6.9 times greater than the World Health Organization (WHO) 24-hour limits, respectively (Alam et al., 2015). The stack emission monitoring at the Sorezai and Pandu kiln site, located in Badhber Tehsil of Peshawar District in Khyber Pakhtunkhwa, revealed that the presence of SO_2 and CO emissions was 1045-1214 mg/Nm^3 and 5672 mg/Nm^3, respectively, during mixing of coal with rubber and tires, which were much higher than the National Environmental Quality Standard (NEQS) (Hussain et al., 2022).

Health effects of prolonged exposure to the emissions of the brick kiln are devastating and well-reported. Fine/ultra-fine particulate matter is directly linked to the development of respiratory diseases, cardiovascular diseases, pulmonary diseases, and malignancy (Nicolaou et al., 2024; Rafiq and Khan, 2014). Along with these health issues, the building industry has begun to consider recycling brick waste to minimize the impact on the environment. It has also been shown that waste brick aggregate can be used in alkali-activated mortar composites with excellent mechanical and durability properties, and lightweight recycled brick aggregate concrete can be used with waste materials as a sustainable way to produce masonry units (Hameed et al., 2025). In the village of Baghbanan, a local study was carried out in an area with a population of 60 families and 486 residents, which found that 68% of families have an illness related to pollution, and the measured concentration of PM_{10} was 306 μg/m^3, which is above the standard of 180 μg/m^3 (Rahim, 2016).

The application of technology for emission reduction has focused primarily on the design of the kiln, for example, the change from FCBTK kilns to Zig-Zag kilns. Although in combustion, Zig-Zag technology improves combustion efficiency (10-20%) and reduces fuel consumption, the technology is not as effective at removing acidic gases (SO_2) and fine PM (Hameem et al., 2025; Hasnain et al., 2026). This weakness calls for an end-of-pipe solution that is complementary and can treat the entire range of pollutants.

Wet scrubbing technology is an appealing technology to concurrently eliminate gaseous and particulate pollutants. Venturi scrubbers have been used in industries with high efficiency for particle and soluble gas removal, for example, in the cement industry with a removal efficiency of over 95% in the power generation sector (Ali et al., 2013). The use of reduced-scale wet scrubber designs with gravel beds has been confirmed as having specific potential, with the flue gases passing through an anti-current flow of water and the high-surface-area media, which encourages flue gas interaction with the media and the absorption of the gases (World Bank Group, 1999). Recent research indicates that properly constructed wet scrubbers are capable of reducing hydrocarbons by 97.8%,

CO_2 by 98.5%, and CO by 99% in the case of a brick kiln (Getahun et al., 2024).

The scrubber has been proven to work, but there are several practical concerns, including the use of water, the need to remove used sludge, and the effects of the back pressure on the natural kiln draft, which must be taken into account to ensure that the scrubber does not have an impact on the combustion rate and quality of the bricks. Economic studies indicate that co-benefits, such as recovery of unburnt carbon to be used in recycling the fuel and less component wear in the kiln, make scrubber adoption financially viable (Thakuri et al., 2024). Favorable policy enablers, monetary incentives, and employee training interventions play a role in effective implementation as well, as reflected by brick and profitability improvements and more than 20% emission reductions that resulted from interventions (Co et al., 2009).

Although wet scrubbing is an established emission control technology, it proves difficult to adapt to the practicalities of traditional brick kilns due to issues with water and sludge management, draft resistance, maintenance requirements, and limitations of existing kiln chimneys. The reviewed literature fails to provide substantial evidence regarding the development of simplified ground-mounted packed-bed scrubbers, which were specifically designed to address retrofit constraints. The present prototype addresses the aforementioned limitations through a design that uses a ground-level scrubber column, coarse aggregate packing, and an upward flow of flue gas, which is treated with downward fine-mist water spraying. Unlike some other approaches, which attempt to address the retrofit limitations by focusing on the kiln geometry or using more sophisticated industrial scrubbers, the present technology is aimed at providing an accessible configuration that can be serviced from a ground level.

Accordingly, the present work aimed at designing, developing, and experimentally evaluating a low-flow ground-type packed bed wet scrubber under laboratory high-emission combustion conditions simulating the brick-kiln operations. The prototype of the scrubber consists of coarse aggregate packing and fine mist water spray, and the performance of the prototype scrubber was evaluated by measuring concentrations of CO, NO_x, and SO_2 before and after the action of the water-spray system. The developed prototype scrubber is ground-type, implying that the additional equipment of the scrubber is not mounted on the chimney of the brick kiln, but rather is located at ground level and is accessible for operation and maintenance. The present study is a laboratory-scale preliminary proof-of-concept study, which allows for further design optimization and field-scale validation trials.

Materials and Methods

Scrubber Design Criteria

The wet scrubber was a laboratory-scale wet scrubber designed to be similar to the flow rate of a conventional zig-zag brick kiln of 75,000 bricks/day. Real flow behavior was recreated under laboratory conditions using an approximately 1:80 gas-flow capacity ratio relative to the reference kiln. The scaling parameters are given in Table 1.

Table 1: Scaling criteria for prototype design

S. No.	Parameter	Full-Scale Kiln	Reduced-Flow Prototype
1	Bricks Production per day	75,000	937
2	Gas flow rate	1.94 m^3/s	0.023 m^3/s
3	Chimney diameter	1.22–1.52 m	0.61 m
4	Scrubber height	4.57–6.10 m	1.52 m
5	Flue gas velocity	6.6–7.0 m/s	0.079 m/s

Design Calculations

The design calculations establish the principal geometric and operating parameters used for the reduced-flow prototype. In Table 2, all calculated parameters are summarized. The cross-sectional area has been determined based on the given inner diameter, applying Equation 1**,** and is equal to 0.292 m². This parameter forms the starting point for further calculations of velocities and residence times.

$$A = \frac{\pi D^2}{4} \quad (1)$$

The prototype gas-flow rate was selected at approximately 1:80 of the estimated full-scale gas-flow rate. This ratio represents a reduction in nominal flow capacity and does not imply strict geometric or dynamic similarity with the full-scale kiln system.

Using the prototype gas-flow rate and scrubber cross-sectional area, the superficial gas velocity was calculated as 0.079 m/s using Equation 2.

$$V = \frac{Q}{A} \quad 2)$$

The nominal gas residence time, estimated from the scrubber height and superficial gas velocity using Equation 3, was 19.3 s.

$$T = \frac{H}{V} \quad (3)$$

A water flow rate of approximately 3 L/min was used during testing, corresponding to the calculated liquid-to-gas ratio reported in Table 2. This flow rate was selected to provide continuous wetting of the packing material during operation. The liquid-to-gas ratio is calculated by applying Equation 4.

$$L/G = \frac{0.00005}{0.023} = 0.0022 \quad (4)$$

Table 2: Prototype design parameters and calculated values

Parameter	Symbol	Value	Unit
Diameter	D	0.61	m
Height	H	1.52	m
Cross-sectional area	A	0.292	m^2
Full-scale flow rate	Qfull	1.94	m^3/s
Prototype flow rate	Qproto	0.023	m^3/s
Gas velocity	V	0.079	m/s
Residence time	T	19.3	s
Water flow rate	Qwater	0.00005	m^3/s
Liquid-to-gas ratio	L/G	0.0022	-

Prototype Fabrication

The scrubber column was made of mild steel sheet and consisted of a cylinder 0.61 m in diameter and 1.52 m in height. A mild-steel angle frame was provided to resist stresses induced by thermal and flow forces. The joints were gas-welded to be leak-free at the air inlet and outlet. The gas inlet duct was connected near the lower section of the column, while the gas outlet was positioned at the top, producing upward gas flow counter to the downward water spray and thereby promoting gas–liquid contact. Figure 2 shows a schematic of the full prototype, including the cylindrical chamber, packing medium, spray nozzle arrangement, and water supply/drainage system.

Internal packing used coarse aggregate layers in contact with a high-surface-area steel plate (perforated). The perforated steel support plate contained holes approximately 12.7 mm in diameter. In engineering applications, similar methods with the utilization of reconstructed brick aggregate as packing material and filtration material have proved that the efficiency of contact can be improved (Hameed et al. 2025). For the upper part, a fine-mist spray nozzle (100-200 μm droplets) was mounted, and the spray was directed downwards. A 250 L water reservoir (water drum) that was dependent on a submersible pump formed the water supply system.

Experimental Procedure

Testing Standards and Equipment

All experimental testing was performed in compliance with ASTM D-6522, which is a standard test method for the determination of nitrogen oxides and carbon monoxide concentrations in emissions from natural gas-fired reciprocating engines, combustion turbines, and other stationary sources. All measurements were made using a portable, battery-operated gas analyzer fitted with electrochemical sensors. Pollutant concentrations (CO, NOx, and SO_2) were continuously measured by the instrument, so that the composition of the flue gas could be monitored in real time, both before and after the scrubbing process.



Figure 2: Schematic diagram of the prototype

Aggregate Layer Preparation and Sieve Analysis

The coarse aggregate that was used as a packing medium was screened before loading into the scrubber to enhance the homogeneity of the packed bed. The nominal aggregate size was approximately 31.75 mm, and a 25.4-mm sieve was used as a lower size limit, as seen in Figures 3 and 4. The aggregate particles remained on the sieve and were used for packing, while the smaller particles were rejected. The coarse aggregate was chosen to minimize pressure loss, plugging, and non-uniformity of pores in the packed bed. The selected coarse aggregate was placed by hand above the perforated steel support plate to form a porous packing layer that would enhance gas distribution and gas-liquid contact while minimizing channeling.

Fuel Mixture Preparation

A heterogeneous fuel mixture was prepared to represent a high-emission combustion condition that could arise when uncontrolled burning practices are used. The main fuel included coal, wood, and pieces of tire rubber. Shredded low-density polyethylene and additional rubber pieces were introduced as high-emission components that constitute approximately 10% of the total fuel mass. A small amount of petrol was used to ignite the fuel. There were two main reasons for using this kind of fuel in the experiment. First, it helped ensure that the combustion process of the heterogeneous fuel started quickly. Second, it ensured that there was a stable flame throughout the experiments. It lowered the temperature and

emission variation levels during combustion. The composition of the fuels in terms of the different emissions of PM, SO_2, and CO is shown in Figure 5.



Figure 3: 25.4-mm sieve used for screening the coarse aggregate



Figure 4: Screening of coarse aggregate used as packed-bed material.

Combustion and Flue Gas Flow

The fuel mixture prepared was fed into a combustion chamber with controlled combustion, where primary and secondary airflow were manipulated by adjusting the air inlet. Once ignited, the combustion was allowed to stabilize for about five minutes, during which flame temperature and smoke production were observed to be steady. After stabilization, the produced flue gas was led through a horizontal 101.6 mm diameter (circular cross section) inlet duct made of galvanized steel. The duct was used to direct the hot flue gas into the main scrubber vessel. The gas stream was immediately subjected to a layer of 12.7 mm diameter holes in circular steel plates inside the scrubber. The stream was then placed on top of the perforated steel plate, which was itself covered with coarse aggregate, also layered. This combination provided two purposes: firstly, it would lower the linear velocity of the gas, and secondly, it would

cause the residence time of the flue gas to be much longer in the scrubbing zone, due to an extended contact time between the gas and the then-injected water spray. Residence time was determined using the gas velocity in the empty tower and the packed bed height, ranging from 5 seconds to 19.3 seconds for the baseline system configuration.

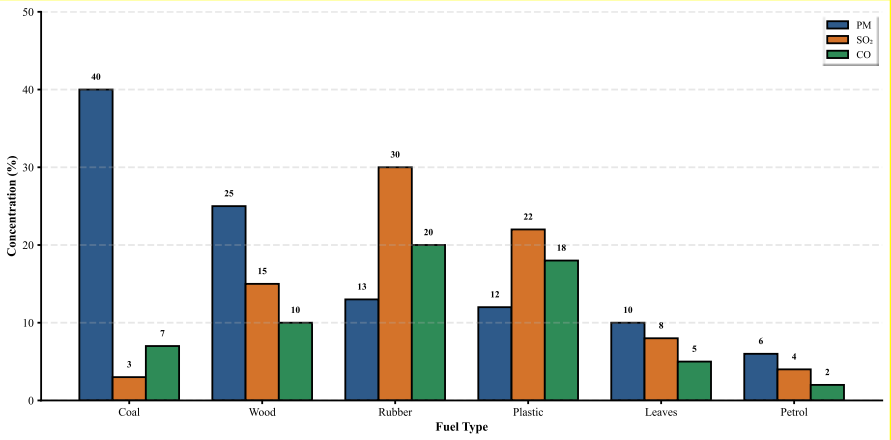


Figure 5: Estimated concentration of each fuel type

Baseline Measurements

Baseline emission measurements were obtained with the water-spray system switched off. During this stage, the flue gas only went through the perforated steel plate and coarse aggregate setup with no injection of any liquid. Measurements of baseline parameters were obtained over a period of 2-3 minutes after the confirmation of combustion stabilization. The dry baseline readings were used to ascertain the pre-treatment concentration of pollutants (CO, NOx, and SO_2) as shown in Figure 6, and the subsequent wet scrubbing efficiencies have been calculated with respect to the pre-treatment concentrations. The baseline data also incorporated any initial reduction that occurred only because of the packing material itself (inertial impaction and/or gravitational settling of larger particulates), so that any additional reduction that occurred during wet operation was considered to be directly due to the water spray and associated gas-liquid interaction.

Wet Scrubbing Operation

The water supply was turned on immediately after baseline measurements were completed. Water was pumped from the 250-litre water reservoir to the pipe by a submersible pump, and then the pipe was connected to several nozzles arranged in a circular sequence at the top of

the scrubber vessel, around 2 ft above the perforated steel plate and coarse aggregates mixture. The nozzle assembly was made up of spray nozzles that were distributed in a way that covered the entire cross-sectional area of the scrubber. The water was broken up into very small droplets (diameter ~ 100–200 μm). It was operated continuously in the once-through (non-recirculating) mode. This resulted in the water being sent to the nozzles from the reservoir being continuously used, while the water that had been used was pumped out to a collection tank without being recycled. This once-through basis was designed to avoid any contamination issues that may arise with recirculated water, which would artificially improve or diminish removal efficiencies over time by the addition of solids, gases, and/or pH changes. A constant water flow rate of around 3 L/min was maintained throughout each test run. The test was run, and a visualization of the smoke is displayed in Figure 7.



Figure 6: Visual representation of the baseline smoke

Data Collection and Observation

During the wet scrubbing phase, the outlet emissions were sampled continuously in real time using the gas analyzer. The gas analyzer calculated concentration values for CO, NOx, and SO_2 every second, and these real-time data were recorded for subsequent analysis. In addition to quantitative gas measurements, two qualitative observations were systematically recorded. First, the appearance of the emitted smoke was visually assessed. The smoke's color transitioned from dark gray to whitish in appearance. Second, changes in the spray appearance, clarity of water drainage, and wetness of the packing were visually assessed. Post-treatment readings were compared to pre-treatment (dry) readings to assess the efficiency of pollutant removal. In other words, Pollutant removal efficiency was determined by subtracting the post-activation concentration from the pre-activation concentration, dividing the

difference by the pre-activation concentration, and multiplying by 100. The comparison helped not only to quantify scrubber efficiency but also to qualitatively assess the system's efficiency in clarifying exhaust.



Figure 7: Visual representation of the smoke after running the test

Performance Evaluation

Pollutant removal efficiency was calculated using the conventional emission control device Equation 5:

$$\eta(\%) = \frac{C_{\text{before}} - C_{\text{after}}}{C_{\text{before}}} \times 100 \quad (5)$$

Where, C_{before} is the average pollutant concentration in raw flue gas before sprinkler activation (mg/Nm³) and C_{after} is the average pollutant concentration after sprinkler activation (mg/Nm³).

Results

Pre-Activation Emission Profile

Before turning on the water-spray system, the scrubber outlet released a thick dark-grey smoke plume that could be seen as dense, as shown in Figure 8. Since the amount of particulate matter was not measured, the visual appearance of the plume is presented as a qualitative observation only and should not be taken as a quantitative indication of the amount of PM.

Post-Activation Emission Profile

Activation of the water-spray system produced a clearly visible decrease in smoke opacity (the exhaust plume changed from a dense dark-grey plume into a lighter whitish plume, see Figure 9). This change in the visual appearance of the smoke plume was mainly attributed to the formation of water vapor when the hot flue gas came into contact with the

scrubbing water. Although this effect suggests that there was a reduction in the amount of smoke opacity and possible removal of particulate matter, particulate matter was not quantitatively measured in this study, and thus no numerical particulate-removal efficiency can be derived from these observations.



Figure 8: Smoke before Activation of Sprinkler System



Figure 9: Smoke after the Activation of the Sprinkler System

Pollutant Concentrations and Removal Performance

Table 3 summarizes the measured gaseous pollutant concentrations before and after activation of the water-spray system. The measured CO concentration decreased from 5,870 to 4,250 mg/Nm³, corresponding to a removal efficiency of 27.60%. NO_x decreased from 154 to 110 mg/Nm³, corresponding to a removal efficiency of 28.57%, while SO_2 decreased from 940 to 700 mg/Nm³, corresponding to a removal efficiency of 25.53%. Under the tested experimental conditions, the measured NO_x and SO_2 concentrations were below the cited NEQS numerical limits, whereas the measured CO concentration remained above

the cited numerical limit. The NEQS values are provided only for numerical regulatory context and should not be interpreted as a complete regulatory compliance assessment.

Table 3: Measured pollutant concentrations before and after scrubber activation, cited NEQS numerical limits, and removal efficiencies

Pollutant	Pre-Activation (mg/Nm^3)	Post-Activation (mg/Nm^3)	Cited NEQS Limit (mg/Nm^3)	Removal Efficiency (%)
CO	5,870	4,250	800	27.60
NO_x	154	110	400	28.57
SO_2	940	700	1,700	25.53

Discussion

Pollutant Removal Mechanisms

Several physicochemical processes can occur within the wet scrubbing systems, and these processes can be used to explain the resulting emission cuts. For SO_2, it is highly soluble in water, and the gaseous pollutant is directly absorbed and then converted to sulfurous acid (H_2SO_3), which transports the gaseous pollutant to the liquid phase (Veal, 2021). The SO_2 removal efficiency of 25.53% is classified as moderate, but it reveals the potential of pure water scrubbing without the use of chemical additives, where the alkaline reagents may have a great effect on the removal of the acid gas (Talaie et al., 1997).

The removal of nitrogen oxides (28.57%) is more complicated. As one might expect, insoluble nitric oxide (NO) oxidizes to nitrogen dioxide (NO_2) and reacts with water to form nitric acid (HNO_3) and nitrous acid (HNO_2) (Lee et al., 1990). The water spray also helps to cool exhaust gases and causes gaseous oxides to condense in liquid form. That two-fold action makes obvious the same removal capacity for SO_2 despite the fact that generally NOx is less water-soluble than SO_2.

The mechanism responsible for the observed decrease in CO concentration cannot be determined conclusively in the present experiment. Because CO has relatively low water solubility, direct aqueous absorption is unlikely to account for the observed reduction. Variations in combustion conditions, gas temperature and moisture, gas–liquid interactions, and measurement variability may also have contributed. Further controlled experiments are needed to identify the dominant mechanism (Cooper and Alley, 2010).

Figure 10 shows the theoretical relationship between gas-residence time and pollutant-removal-efficiency extrapolated from the measured performance of the prototype. The values of removal efficiency at residence times beyond the experimentally evaluated operating condition are not measured directly but are included to show how pollutant

removal could potentially improve with increased gas-liquid contact time; therefore, these extrapolated values should not be interpreted as experimentally measured removal efficiencies. Additional controlled experiments at different gas-residence times are needed to evaluate the relationship between gas residence time and removal efficiency.

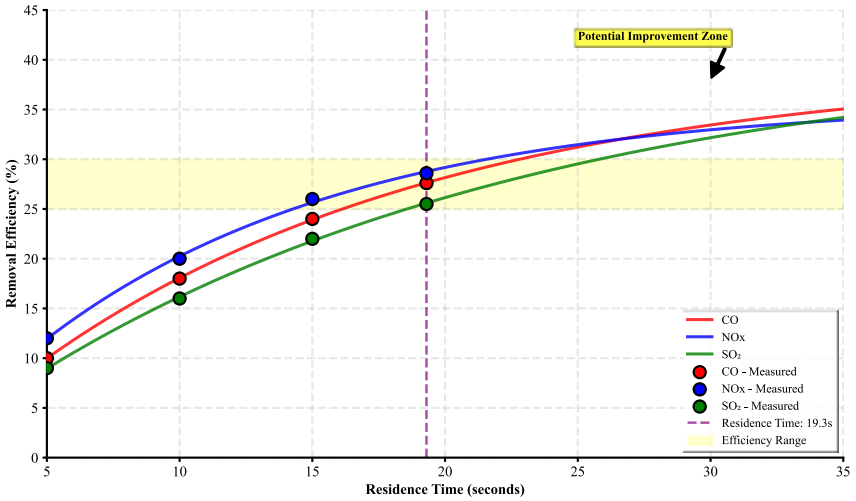


Figure 10: Conceptual extrapolation of the possible relationship between gas residence time and pollutant removal efficiency

Comparison with Previous Studies

Obtained removal efficiencies, although small in the context of optimized industrial scrubbers (>95%), are consistent with those of a first-generation prototype with untreated water and with less complex construction (Twigg, 2018). The efficiency in such cases is significantly improved because of optimized scrubber designs, chemical reagents used, and the increased contact time (hydrocarbons – 97.8%, CO2 - 98.5%, and CO – 99%) (Getahun et al., 2024). In addition to this, research on the venturi scrubber shows that more than 95% of particles can be removed (Ali et al., 2013).

Nonetheless, comparative analysis must take into account situational differences. In the current experiment, the worst-case fuel scenarios (coal, rubber, petrol mixture) were deliberately used to model unregulated fuel (combustion) practices prevalent in South Asian brick kilns, but controlled experiments normally use standardized fuel mixtures (Rajarathnam et al., 2014). The observed 27.60% reduction in measured CO concentration demonstrates that the prototype influenced the outlet CO concentration under the tested high-emission combustion conditions,

although further replicated experiments are required to establish the robustness of this effect.

Comparison With Cited NEQS Numerical Limits

Under the tested experimental conditions, the measured post-activation NO_x concentration of 110 mg/Nm³ and SO_2 concentration of 700 mg/Nm³ were lower than the cited NEQS numerical limits of 400 and 1,700 mg/Nm³, respectively. Meanwhile, the measured CO concentration declined from 5,870 to 4,250 mg/Nm³ but still stayed above the cited numerical limit of 800 mg/Nm³. These results suggest that the prototype reduced the measured concentrations of all three gaseous pollutants, though the reduction of CO was insufficient to reduce its measured concentration below the cited numerical limit. Since the experiments were conducted with a laboratory-scale prototype under controlled conditions, these comparisons should be seen as numerical regulatory context, rather than evidence of full-scale brick-kiln regulatory compliance (Saha et al., 2020).

Potential Improvements for CO Control

The obtained concentration of CO was found to be higher than the NEQS numerical limit even after the scrubber had been turned on. Due to the low solubility of CO in water, other measures should be taken to ensure that the concentration of CO is reduced to acceptable levels. Further research can be done to find ways to reduce the emission of CO. For instance, combustion parameters should be optimized to minimize CO production, and the use of appropriate fuel and air should be considered. Mechanical draft can also be considered to help reduce the amount of CO emitted. Oxidation methods such as chemical and catalytic oxidation can also be explored. Since these measures were not tried, their operating conditions, removal efficiency, cost, and applicability should be considered before they are deployed.

Qualitative Performance Indicators

The qualitative performance indicators were identified when the water spray was turned on. This was demonstrated by a difference in the color emitted from the stack, from dense black smoke to a whitish steam vapor cloud. Black smoke generally indicates high particulate loads (Burtscher, 2005). This visual change indicates reduced smoke opacity and suggests possible particulate capture; however, it does not provide quantitative evidence of PM removal. Because PM was not quantitatively measured in this study, the observed change should be interpreted as a qualitative indicator rather than a confirmed particulate removal

efficiency. The remaining whitish plume was mainly associated with water vapor produced by contact between hot flue gas and the cooler scrubbing liquid. This aesthetic value has enormous implications for community relations since the level of smoke opacity is the major measure of pollution to the surrounding communities (Saha et al., 2021).

Design Advantages for Brick Kiln Applications

The ground-level installation strategy solves structural limitations of the current kiln systems that are highly critical. Old-fashioned chimney-top scrubbers put high weight burdens on old stacks, which may collapse. The design prevents this risk by diverting exhaust to a ground-based unit, with easier access for maintenance and having a greater, sturdier water-sump capacity. This is both retrofit-friendly and especially useful in small factories and existing kilns that cannot support heavy equipment that is mounted on the top.

Operational Challenges

Several operational considerations were observed during the test. Packing media and internal baffle pressure drops sometimes hindered natural draft and led to the smoke escaping periodically out of the combustion chamber, as shown in Figure 11. Such a phenomenon, as it is also reported by earlier researchers (Thakuri et al., 2024) requires mechanical draft support to ensure uniform performance.



Figure 11: Escaping of Smoke from the Combustion Chamber during Testing.

In the regions of high heat, thermal degradation of protective layers was observed, as depicted in Figure 12, which shows that in future designs, industrial-grade heat-resistant material is necessary. The degrading environment formed by joint heat and aqueous scrubbing also

indicates that a corrosion-resistant alloy (e.g., stainless steel 304/316) would increase long-term service.



Figure 12: Degradation of non-thermal coating from the areas in contact with high heat.

Practical and Scalability Considerations

While the prototype utilized a mechanically simple ground-based configuration, further studies are needed to evaluate the viability for large-scale implementations. This work did not attempt a formal techno-economic assessment. The considerations for a full-scale implementation would include a detailed evaluation of capital and operating expenditures, water usage and recycling, sludge treatment and disposal, materials resistant to corrosion, packing maintenance, pressure losses, mechanical draft requirements, and system longevity. Such parameters should be evaluated at a field scale to determine the feasibility of this system for the intended purpose.

Study Limitations

This study was performed on a laboratory-scale, proof-of-concept basis, under only a few combustion and operating conditions. The prototype was not tested at a large-scale operating brick kiln, and so the removal efficiencies found should not be extrapolated to commercial kiln performance. Particulate matter was not quantified, and so the observed change in smoke opacity can only provide qualitative evidence of potential particulate capture. Pressure drops across the packed bed was also not quantified, though temporary smoke escape from the combustion chamber

suggests that draft resistance could be important during scale-up. Furthermore, effects like packing fouling, corrosion, water recirculation, sludge generation, system durability, and sustained operating performance were not evaluated. Finally, the reduced-flow prototype does not necessarily establish strict geometric or dynamic similarity with a full-scale kiln. Future work should include testing over a wider range of conditions, quantification of PM and pressure-drop measurements, system optimization, and full-scale validation under actual brick-kiln operating conditions.

Conclusion

This study demonstrated the technical feasibility of a simplified wet scrubber prototype for reducing emissions from brick-kiln flue gases through reduced-scale experimental testing. Using untreated water without chemical additives, the reduced-flow prototype achieved removal efficiencies of 25.53% for SO_2, 27.60% for CO, and 28.57% for NO_x. Under the tested experimental conditions, the post-activation NO_x and SO_2 concentrations were below the cited NEQS numerical limits, whereas the measured CO concentration, although reduced, remained above the cited numerical limit.

A visible change from a dense dark-grey smoke plume to a lighter vaporous plume was observed after scrubber activation. However, particulate matter was not quantitatively measured; therefore, this observation should be interpreted only as qualitative evidence of reduced smoke opacity and possible particulate capture. Quantitative PM measurements are required in future studies to determine particulate-removal efficiency. In addition, the idea of placing the wet scrubber at the ground level has great practical value in terms of overcoming the physical constraints in the current design of brick kiln chimneys.

Despite the efficiency figures being limited by the design of a first-generation prototype, the findings make an interesting starting point for future enhancements. Improvements could include better packing materials, efficient spray distribution, mechanical draft, corrosion protection of the materials used, water recirculation, water treatment, and even chemical or catalytic enhancements for better carbon monoxide control. Overall, the prototype provides a preliminary technical basis for further optimization and full-scale evaluation under actual brick-kiln operating conditions.

Competing Interests: *The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.*

Author Contributions: *Emad Khan (Software, methodology, data analysis, visualization, and writing—original draft; Anshrah Faisal (Writing—review and editing); Muhammad Aarish Shah (Writing—review and editing); Umar Aziz (Writing—review and editing); Khan Shahzada (Conceptualization, validation, supervision, review, and editing)*

Acknowledgement: *The authors gratefully acknowledge the Directorate of Science and Technology, Khyber Pakhtunkhwa, Pakistan, for providing funding for this study.*

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