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Review article

Brick kiln pollution and its impact on health: A systematic review and meta-analysis

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ABSTRACT

Brick kiln emissions adversely affect air pollution and the health of workers and individuals living near the kilns; however, evidence of their impacts remains limited. We conducted a systematic review of brick kiln pollution (emissions, source contributions and personal exposures) and its effects on health. We extracted articles from electronic databases and through manual citation searching. We estimated pooled, sample-size-weighted means and standard deviations for personal exposures by job type; computed mean emission factors and pollutant concentrations by brick kiln design; and meta-analyzed differences in means or proportions for health outcomes between brick kiln workers and controls or for participants living near or far away from kilns. We identified 104 studies; 74 were conducted in South Asia. The most evaluated pollutants were particulate matter (PM; n = 48), sulfur dioxide (SO_2; n = 24) and carbon monoxide (CO; n = 22), and the most evaluated health outcomes were respiratory health (n = 34) and musculoskeletal disorders (n = 9). PM and CO emissions were higher among traditional than improved brick kilns. Mean respirable silica exposures were only measured in 4 (4%) studies and were as high as 620 $\mu g/m^3$, exceeding the NIOSH recommended exposure limit by a factor of over 12. Brick kiln workers had consistently worse lung function, more respiratory symptoms, more musculoskeletal complaints, and more inflammation when compared to unexposed participants across studies; however, most studies had a small sample size and did not fully describe methods used for sampling or data collection. On average, brick kiln workers had worse health outcomes when compared to unexposed controls but study quality supporting the evidence was low. Few studies reported silica concentrations or personal exposures, but the few that did suggest that exposures are high. Further research is needed to better understand the relationship between brick kiln pollution and health among workers, and to evaluate exposure mitigation strategies.

1. Introduction

Approximately 1500 billion bricks are produced every year, and ~90% are produced in Asia (Eil et al., 2020; Mitra and Valette, 2017). South Asia is the second largest brick-producing region after China and has an estimated annual production of 310 billion bricks (Eil et al., 2020). India, Pakistan, Bangladesh and Nepal are the biggest producers in this region, accounting for nearly 25% of global brick production (Eil et al., 2020). The brick kiln industry in low- and middle-income countries (LMICs) is labor-intensive, and most kilns are energy inefficient and highly polluting (Eil et al., 2020; Mitra and Valette, 2017; Maithel and

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Abbreviations and acronyms

Pollutants

Ace	Acenaphthene
Acy	Acenaphthylene
Ant	Anthracene
B[b]A	Benzo[b]anthracene
B[b]F	Benzo[b]fluoranthene
B[b+k]F	Benzo[b+k]fluoranthene
B[k]F	Benzo[k]fluoranthene
B[ghi]P	Benzo[g,h,i]perylene
B[a]P	Benzo[a]pyrene
B[e]P	Benzo[e]pyrene
BC	Black carbon
BrC	Brown carbon
Chr	Chrysene
CO	Carbon monoxide
CO_2	Carbon dioxide
Cor	Coronene
D[ah]A	Dibenzo[a,h]anthracene
EC	Elemental carbon
Fl	Fluorene
Fth	Fluoranthene
HCl	Hydrogen chloride
He	Helium
HF	Hydrogen fluoride
HCN	Hydrogen cyanide
Ind	Indeno[1,2,3-cd]pyrene
Nap	Naphthalene
NH_3	Ammonia
NMVOC	Non-methane volatile organic compound
NO	Nitrogen oxide
NO_2	Nitrogen dioxide
NO_x	Nitrogen oxides
OC	Organic carbon
PAH	Polycyclic aromatic hydrocarbon
Phe	Phenanthrene
Py	Pyrene
PM	Particulate matter
SO_2	Sulfur dioxide
SO_3	Sulfur trioxide
TSP	Total suspended particulate
VOC	Volatile organic compound
WSOC	Water-soluble organic carbon

Kilns

BTK	Bull's trench kiln
CK	Clamp kiln
DDK	Downdraft kiln
FCBTK	Fixed chimney Bull's trench kiln
FDZ	Forced-draft/induced-draft zigzag kiln
HK	Hoffmann kiln
MK	Marquez brick kiln
MK2	Double-dome version of the original Marquez kiln
MCBTK	Movable chimney Bull's trench kiln
NDZ	Natural draft zigzag kiln
NS	Not specified
TCK	Traditional-campaign kiln
TFK	Traditional-fixed kiln
TIK	Traditional-improved kiln
TK	Tunnel kiln
VSBK	Vertical Shaft Brick Kiln
ZZK	Zigzag kiln

Heierli, 2008). Mechanised and efficient technologies are limited in number, making up <1% of the 150,000 kilns in South Asia (Eil et al., 2020; Mitra and Valette, 2017; Maithel and Heierli, 2008; Schmidt, 2013). Compounding this problem, many brick kilns operate in the informal sector with little or no regulation by local governments on labor or kiln emissions (Eil et al., 2020; Mitra and Valette, 2017).

Brick manufacturing involves a number of processes, typically starting with digging or mining of topsoil, mixing and molding of wet clay, and sun-drying of the green bricks (Shaikh et al., 2012). Once dried, green bricks are carried, usually on the head or back, stacked inside the kiln, and fired. Fired, or red, bricks are then manually carried out of the kiln. Bricks are primarily fired using coal or biomass, but other fuels such as rubber tires, motor oils, trash and plastic are also common (Nepal et al., 2019; Nasir et al., 2021; Beard et al., 2022; David et al., 2022). Throughout the brick making processes, workers are exposed to various airborne pollutants. Clay and brick dust contains high concentrations of silica, while the smoke emitted during brick firing contains particulate matter (PM) and gaseous pollutants including sulfur dioxide (SO_2), carbon monoxide (CO), and nitrogen oxides (NO_x). An estimated 16 million workers in South Asia alone are exposed to these hazardous pollutants (Eil et al., 2020). Brick kilns are also a major contributor to ambient air pollution and are responsible for up to 91% of total PM emissions in some cities (Eil et al., 2020). The most widely used technology across South Asia is the fixed chimney Bull's trench kiln (FCBTK) (Eil et al., 2020), one of the most polluting technologies due to poor heat transfer and high fuel consumption (Hamid et al., 2023). Government agencies and international organizations are promoting the transition to more modern, less polluting, technologies and many brick kiln owners have opted to retrofit conventional FCBTKs to zigzag kiln (ZZK) technology, which is easy and inexpensive, and can reduce fuel costs significantly due to the improved energy efficiency (Abbas et al., 2022; Bashir et al., 2023).

Reports from the 2016 Global Burden of Disease highlight the burden of chronic respiratory diseases caused by occupational exposures, namely chronic obstructive pulmonary disease (COPD), asthma, and pneumoconioses such as silicosis and asbestosis (GBD 2016 Occupational Chronic Respiratory Risk Factors Collaborators, 2020). Among high-risk occupations, those that involve increased exposure to both smoke and dust place workers at the highest risk for developing chronic respiratory symptoms and illnesses, as is the case with brick kiln workers (Boschetto et al., 2006).

Despite the contribution of the brick kiln industry to ambient air pollution and community-wide respiratory illness, data on kiln pollution remains limited (Schmidt, 2013). Most reports on the consequences of brick kiln pollution have been based in urban areas in South Asia. This review expands the evaluation of brick kiln emissions and their health impacts globally, with particular focus on LMICs. We synthesize existing evidence on the effects of brick kiln emissions on the environment and health, identify current gaps in the literature, and discuss implemented interventions to lower brick kiln emissions.

2. Methods

2.1. Search strategy and data sources

Sources were extracted from electronic databases including MEDLINE (via PubMed), Embase, Web of Science, SciELO, WHO Global Index Medicus, Cochrane Database of Systematic Reviews, and World Bank eLibrary, as well as reference lists from identified studies and reviews. The full search strategies used for each database are provided in the supplementary material. Manual and electronic searches were conducted between December 2020 and October 2022 and an updated electronic search was conducted in July 2023. Languages were restricted to English, Nepali, Spanish, Italian, and French. No date limits were applied. Sources identified from electronic databases were combined, duplicates removed, and articles screened for relevance based on title and abstract by two reviewers (LN and FS). Disagreements between the two reviewers were adjudicated by a third reviewer (WC). Our protocol was registered in PROSPERO (CRD42020221833). We followed the protocol as registered with one minor modification: after the literature search, we decided to exclude impacts on agriculture to focus on health outcomes.

2.2. Data extraction

The full text was acquired for all sources identified as potentially relevant. Studies were included if they provided (1) quantitative data on brick kiln pollutants, including concentrations, emission factors and source contributions to ambient air pollution; or (2) health outcomes among brick kiln workers or community members living near brick kilns; or (3) a comparison between brick kiln exposed and unexposed participants. Studies were excluded if they were conference abstracts or proceedings; provided data on pollution that does not directly impact human health (e.g., relevant to soil health or climate change); did not provide concrete data on health outcomes, pollutants at kiln sites or contribution of brick kiln emissions to the surrounding air pollution (e.g., ambient pollutant concentrations measured in the vicinity of kilns; source apportionment where brick kiln emissions are lumped together with other sources); reported modeled, rather than measured, exposures or outcomes (e.g., estimates of brick kiln emissions using existing emissions inventories and atmospheric dispersion modelling or cancer risk assessment using the incremental lifetime cancer risk approach); or were case reports, reviews and studies with duplicate data. In case of disagreement between reviewers, articles were adjudicated by the third reviewer. Articles were then sorted by categories (Pollution, Health, Pollution and Health) and summary tables were created including the following details for pollutant-related studies: region, sampling dates, measurement type, sampling location, sample size, number and duration of measurements, and pollutant(s) reported. Summary tables for health outcomes studies included region, dates, study design, characteristics of the study population (age, gender, sample size, inclusion criteria), and outcome(s) reported.

2.3. Methodological quality assessment

For studies reporting health outcomes, we assessed methodological quality using the Newcastle-Ottawa scale, which provides a standardized approach to grade the quality of nonrandomized studies. The Newcastle-Ottawa scale consists of eight criteria across three domains including selection of the study groups, comparability of the study groups, and ascertainment of the exposure or outcome for case-control and cohort studies, respectively (Wells et al., 2000). Since a validated risk of bias tool for exposure studies does not exist, we developed a 6-item scale to assess the quality of papers reporting pollution data. Two of three reviewers (LN, KL, WC) scored the studies independently and disagreements were resolved by the third if they failed to reach consensus.

2.4. Statistical methods

Analyses for emission factors, pollutant concentrations, and personal exposures were performed on natural-log transformed data. We estimated pooled, sample-size-weighted means and standard deviations for personal exposures by job type and then back-transformed the values to obtain geometric means and confidence intervals (Higgins et al., 2008). For emission factors and concentrations, the sampling intervals were too variable and as a result variances were not on the same time scales. Therefore, we computed simple means of the natural-log transformed data by brick kiln design and back-transformed to obtain the geometric mean. We categorized clamp (CK), downdraft (DDK), fixed chimney Bull's trench (FCBTK), movable chimney Bull's trench (MCBTK), traditional-campaign (TCK), traditional-fixed (TFK) and traditional-improved (TIK) kilns as traditional, while forced-draft zigzag (FDZ), Hoffmann (HK), Marquez (MK) and double-domed Marquez (MK2), natural draft zigzag (NDZ), tunnel (TK) and vertical shaft (VSBK) kilns were classified as improved designs. In additional analyses included in the Supplement, we computed the mean emission factors and pollutant concentrations for FCBTKs vs ZZKs (including NDZ and FDZ).

Emission factors and concentrations below the limit of detection (LOD) were assigned a value equal to the $\frac{LOD}{\sqrt{2}}$. We converted results reported in ppm to mg/m^3 using mg/m^3 = ppm $\frac{MW}{V_m}$, where MW is the molecular weight (g/mol) and V_m is the molar gas volume (L/mol). Assuming a pressure of 1 atm and a temperature of 25 °C, $V_m = 24.465$ L/mol for ideal gases. For VOCs, which were measured using an Aeroqual 500, we applied the device's conversion factor of 2.5 to determine concentrations in mg/m^3. (PPM to mg) For studies that did not report the modified combustion efficiency (MCE), we estimated it as MCE = $\Delta CO_2/(\Delta CO_2+\Delta CO)$, where ΔCO_2 and ΔCO are the total amounts of CO_2 and CO emitted, respectively. Non-physical and inconsistent data (e.g. CO_2 emission factors >3667 g/kg fuel [Nasim and Sharif, 2020]; higher MCE in fugitive than flue gas emissions [Chen et al., 2017]) were flagged and excluded from the meta-analysis. Emission factors and pollutant concentrations used in our analyses are shown in Tables S4 and S5.

We computed study-specific proportions of respiratory symptoms and diseases or the mean (and standard deviation) of lung function values for each study among brick kiln workers and control groups or for participants living near and far away from the brick kilns. For lung function data, we provided study-specific means and absolute mean differences in lung function. We calculated an overall mean difference for lung function values between brick kiln workers and controls. We used a fixed effects meta-analysis to summarize mean differences across studies. We also summarized lung function data stratified by both brick kiln worker exposure and tobacco smoking status and provided mean percent predicted values for both brick kiln workers and controls. We calculated the average proportion of respiratory symptoms and disease for brick kiln workers using the reciprocal of variances as weights. We also calculated risk differences (i.e., the absolute difference in proportions) of respiratory symptoms between brick kiln workers and controls or for participants living near and far away from the brick kilns using a fixed effects meta-analysis.

Analyses were conducted in R version 4.2.1 alias Funny-Looking Kid (R Core Team, 2022).

3. Results

3.1. Literature search

We identified 1089 references through electronic searching and 6 through manual searching. After removing duplicates, screening of titles and abstracts, and evaluation of full-text articles, we identified 104 studies for review (Fig. 1). Fifty-eight (56%) reported data on brick kiln pollution (Co et al., 2009; Hussain et al., 2022; Kamal et al., 2016; Khanoranga, 2019; Le and Oanh, 2010; Rajarathnam et al., 2014; Rauf et al., 2022; Suksuwan et al., 2023; Tabinda et al., 2019; Thygerson et al., 2019; Weyant et al., 2014; Ying et al., 2021; Zhang et al., 2020; Zhou et al., 2014, 2015; PPM to mg), 25 (24%) on health (Shaikh et al., 2012; Ali et al., 2013; Biswas et al., 2018; Das, 2014, 2019a, 2019b; David et al., 2020; Erdim et al., 2020; Goel et al., 2015; González et al., 2021; Gupta et al., 2019; Kaushik et al., 2012; Kazi and Bote, 2019;

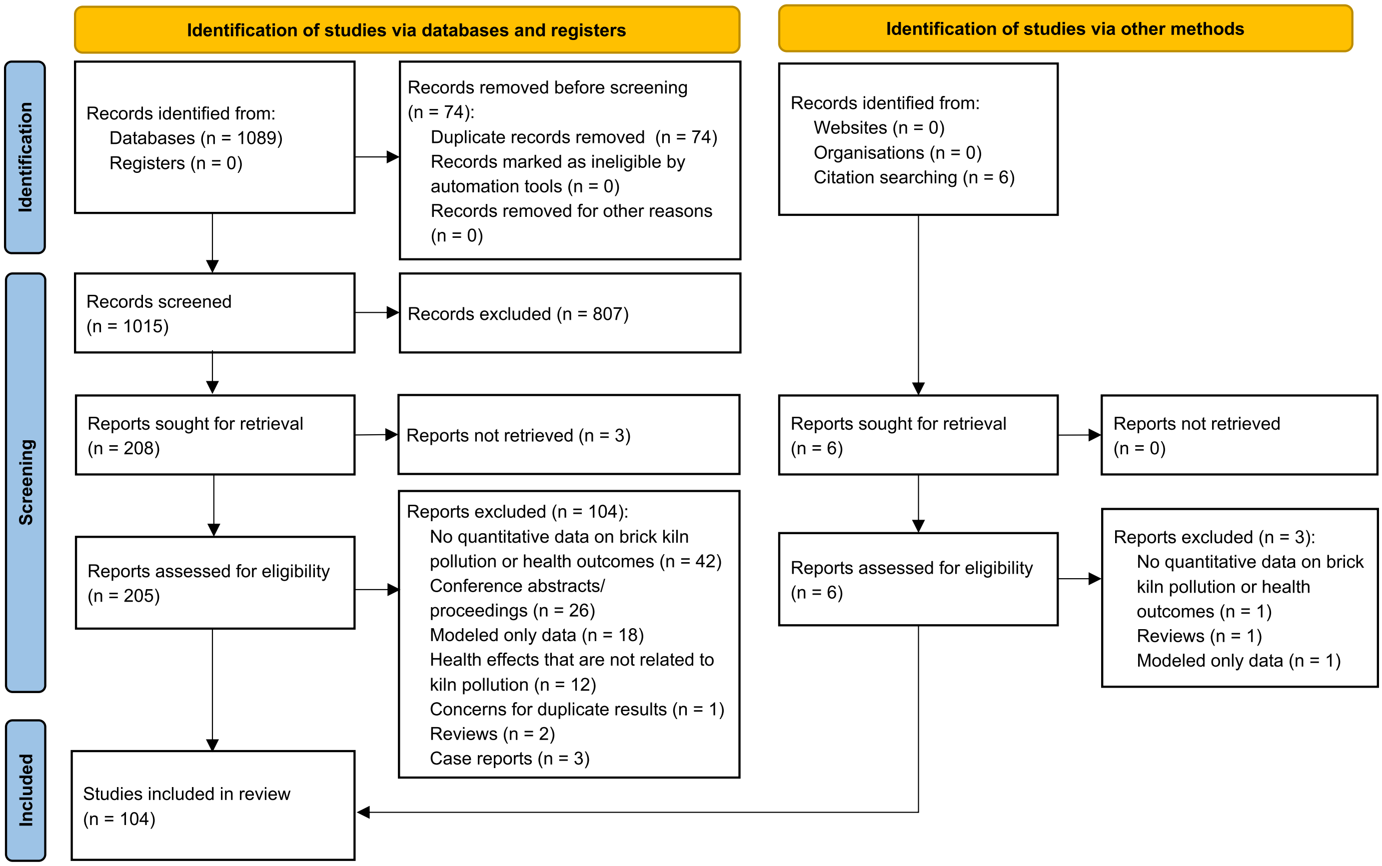

Fig. 1. Selection process for identifying original articles for the systematic review of brick kiln pollution and its impact on human health.

Khisroon et al., 2018; Rahman et al., 2013; Raza et al., 2018; Raza and Ali, 2022; Roshania et al., 2022; Saldaña-Villanueva et al., 2023; Sherris et al., 2021; Sheta and El Laithy, 2015; Shrestha et al., 2021; Sinaga et al., 2022; Srivastava et al., 2002; Subhanullah et al., 2022; Thomas et al., 2015), and 21 (20%) on both pollution and health (Nasir et al., 2021; David et al., 2021, 2022; Hamid et al., 2023; Sanjel et al., 2016, 2017; Khan et al., 2019; Ahmad et al., 2020; Akram et al., 2022; Berumen-Rodríguez et al., 2023; Berumen-Rodriguez et al., 2021; Jahan et al., 2016; Joshi and Dudani, 2008; Kamal et al., 2014a, 2014b; Love et al., 1999; Raza et al., 2014; Raza and Ali, 2021; Vaidya et al., 2015; Zawilla et al., 2014). We mapped countries where brick kiln research was conducted in Fig. 2. Most were in South Asia (Online Supplement).

3.2. Brick kiln pollution

Seventy-nine studies reported data on brick kiln pollutants or toxic exposures (Table S1). Overall study quality was low (Table S2). The Kappa value for agreement with consensus between two reviewers was 0.59. We report on study characteristics in Table S1 and summarize type of pollutant data, pollutants measured and measurement locations in Table S3. The most measured pollutants were PM, SO_2 and CO, and most studies performed measurements at kiln sites (n = 65, 82%), including flue gas and in-stack sampling, samples collected at various locations within the kiln site, and measurements of personal exposures and exposure biomarkers in brick kiln workers and children living at the site

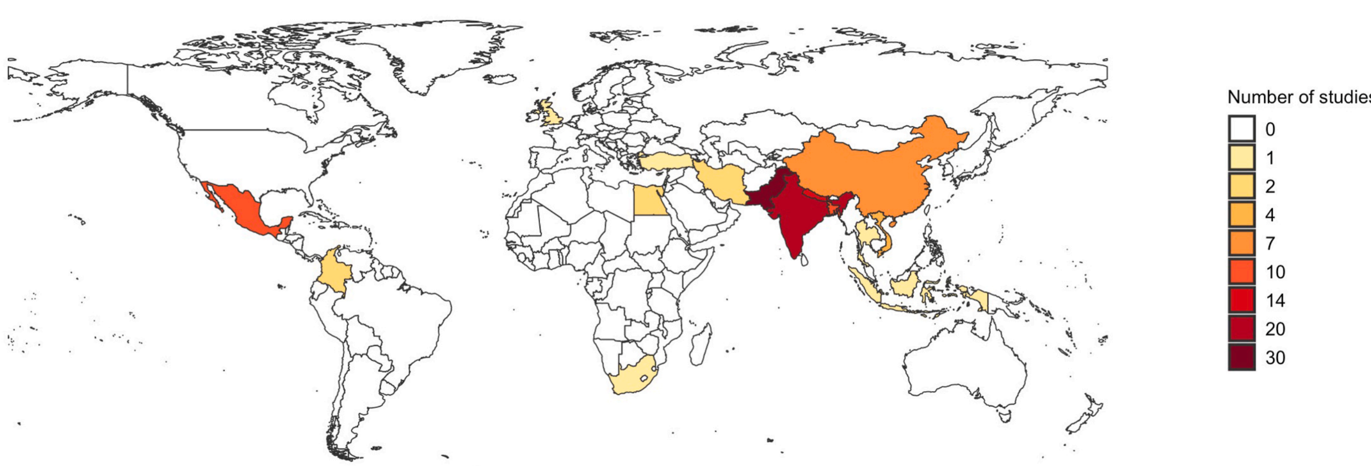

Fig. 2. Number of studies per country included in this systematic review.

(Table S3).

3.3. Pollutant emission factors from brick kilns

PM and NOx were the most reported emission factors (Online Supplement). Emission factors for PM, BC, EC, and OC were higher for traditional when compared to improved brick kilns (Fig. 3). Kilns using coal had higher SO_2 emissions, but lower CO_2, CO and TSP compared to those using biomass (Fig. 4). Emissions of OC were considerably larger than EC across all studies (Table S4).

Among gaseous pollutants, CO_2 was the largest emission and was similar in both traditional and improved kilns (Fig. 3). Emission factors of NO, NO_2 and NO_x were low across both traditional and improved kilns. Emission factors of SO_2 displayed a large variability across studies. In general, brick kilns using biomass had lower SO_2 emission factors than those using coal. As expected, due to the lower combustion efficiency of traditional kilns, CO emission factors were higher among traditional vs improved kilns (mean MCEs were 0.96 ± 0.02 and 0.98 ± 0.01 for traditional and improved kilns, respectively). This trend held true when further stratifying by fuel type (Tables S7–S9). CO emission factors decreased with increasing MCE (Fig. S1).

We identified five studies that reported various VOC emission factors (Christian et al., 2010; Haque et al., 2018; Hu et al., 2019; Stockwell et al., 2016; Zavala et al., 2018), and found that VOCs were lower in brick kilns than in food or pharmaceutical factories. Some studies reported higher VOC emissions in improved kilns when compared to traditional kilns; however, VOC emissions depend not only on kiln design but also on fuel type (Haque et al., 2018). We summarize findings on VOC emissions from all five studies in the Online Supplement.

Three studies reported PAH emission factors (Chen et al., 2017; Goetz et al., 2018; Jayarathne et al., 2018). Emission factors of PAHs and other incomplete combustion products were lower in stack gas than fugitive emissions due to the longer reaction time along the chimney (Chen et al., 2017). The most abundant PAHs from a clamp kiln were chrysene, benz(a)anthracene, benzo(e)pyrene, and 1-methylcrysene (Jayarathne et al., 2018). Low levels of PAHs were observed from a zigzag kiln, reflecting relatively complete combustion of the coal (Goetz et al., 2018; Jayarathne et al., 2018). We summarize findings from each study in the Online Supplement.

3.4. Pollutant concentrations at brick kiln sites

We report on the types of pollutant concentrations measured at the brick kiln sites in Table S4. Traditional kilns emitted higher concentrations of PM, BC, EC, OC and CO, similar concentrations of VOCs and SO_2, and lower concentrations of NO_x when compared to improved brick kilns (Fig. 5). High concentrations of VOCs, CO_2, CO and SO_2 were measured in-stack among both traditional and improved kilns (Fig. 5a). Mean out-of-stack concentrations of CO, SO_2 and NO_2 in traditional kilns were above the WHO recommended limits for 24-h mean exposures but below the National Institute for Occupational Safety and Health (NIOSH) time-weighted average recommended exposure limit for up to a 10-h workday (Fig. 5b). Mean PM_{10} and $PM_{2.5}$ concentrations from traditional kilns were both higher than the WHO limits, whereas mean $PM_{2.5}$ from improved kilns was below the recommended limit. In contrast with the emission factor data, kilns using only coal had lower mean SO_2 and similar CO_2 concentrations compared to kilns using biomass (Fig. 6). Concentrations of TSP and BC were higher when biomass was used.

We identified six studies reporting various PAH concentrations (Bruce et al., 2007; Iqbal et al., 2013; Jan et al., 2014; Saikia et al., 2018; Wang et al., 2022; Kamal et al., 2014a). We summarized findings of the individual studies in the Online Supplement. Briefly, we identified that the type and concentration of PAH depends on type of fuel used and type of sample (soot or soil). The most common PAHs identified were acenaphtylene, phenanthrene, chrysene, and fluorene.

Six studies reported metal concentrations (Hamid et al., 2023; Bruce et al., 2007; Mondal et al., 2017; Pangtey et al., 2004; Ravankhah et al., 2017; Ubaque et al., 2010). We summarized findings of the individual studies in the Online Supplement. Briefly, heavy metals such as mercury, lead, barium, zinc, chromium and cadmium were commonly identified at the kiln sites. Most studies reported that heavy metal concentrations per gram of sample tested exceeded background levels or national or international regulatory levels.

Surprisingly, only one study reported silica concentrations (Beard et al., 2022). In this study, pollutant concentrations, including respirable silica, were measured inside and outside 16 brick kiln worker homes across four brick kilns in Bhaktaphur, Nepal. The geometric mean silica (quartz) concentration across all 32 samples collected was 6.22 $\mu g/m^3$, while concentrations of silica in the form of cristobalite and tridymite were all below the limit of detection. These results suggest that silica concentrations are typically low at on-site worker housing and that silica exposures among brick kiln workers are likely to occur predominantly during work hours.

3.5. Contribution of brick kiln emissions to surrounding ambient air pollution

Sixteen studies reported the contribution of brick kiln emissions to the surrounding ambient air pollution in South Asia (Table S3). We report on data from individual studies in the Online Supplement. Brick kilns appear to contribute to ambient $PM_{2.5}$, PM_{10} and BC anywhere in the range of 20%–41%, up to 28% and 6%–91%, respectively, depending on the location and model used (Begum et al., 2005, 2009, 2011, 2013; Begum and Hopke, 2013, 2019; Gupta et al., 2023; Werden et al., 2022, 2023). Brick kilns are also primary contributors to EC (40%) (Kim et al., 2015) and NMVOCs (10%) (Sarkar et al., 2017) in some settings. Source apportionment studies in and adjacent to the Kathmandu valley, Nepal, showed that coal combustion in brick kilns accounted for 9–17% of the organic material in ambient PM_1 (Werden et al., 2022, 2023).

In India and Nepal, ambient BC, $PM_{2.5}$, PM_{10} and TSP were reported to be 70–180% higher in the winter season when the kilns are operational compared to the monsoon season when kilns are not operational (Arif et al., 2018; Joshi and Dudani, 2008). Sites near kilns are also associated with higher levels of ambient pollution. In Pakistan, for example, ambient PM_{10}, SO_2 and NO_2 was 500%, 28% and 270% higher, respectively, in an area where brick kilns were operational compared to an area where kilns were not operational (Khan et al., 2019). Similarly, another study in Pakistan found that $PM_{2.5}$ and PM_{10} concentrations were 4.6 times higher within 3 km of kilns compared to >3 km from the kilns (Nasir et al., 2021).

3.6. Personal exposures of brick kiln workers

There were 6 (8%) studies that reported personal exposures to pollutants among brick kiln workers (Table S3). Data collected for brick kiln workers across five different job types, or similar exposure groups (SEGs), in 16 brick kilns in Kathmandu Valley, Nepal, revealed that average exposures to total suspended particles (TSP), respirable suspended particles (RSP) and silica were highest among red brick loaders (Fig. 7; Sanjel et al., 2017, 2018). Green brick molders had the lowest exposures to RSP and silica, while TSP exposures were lowest among firemen. On average, exposures to respirable silica exceeded the NIOSH recommended exposure limit of 50 $\mu g/m^3$ in all job types, with mean exposures 1.4 to 6.6 times higher than the limit.

Similar levels of silica exposure were observed in a study among 12 workers across 2 brick kilns in the Mazandaran province in Iran (Fig. 7; Rokni et al., 2016). In brick and tile works in England and Scotland, mean quartz concentrations across 23 different work groups ranged between 40 $\mu g/m^3$ for those with no direct exposure (office, canteen), to 620 $\mu g/m^3$ for kiln demolition workers (SDs missing so not included in meta-analysis) (Love et al., 1999). Exposures to RSP were similar to

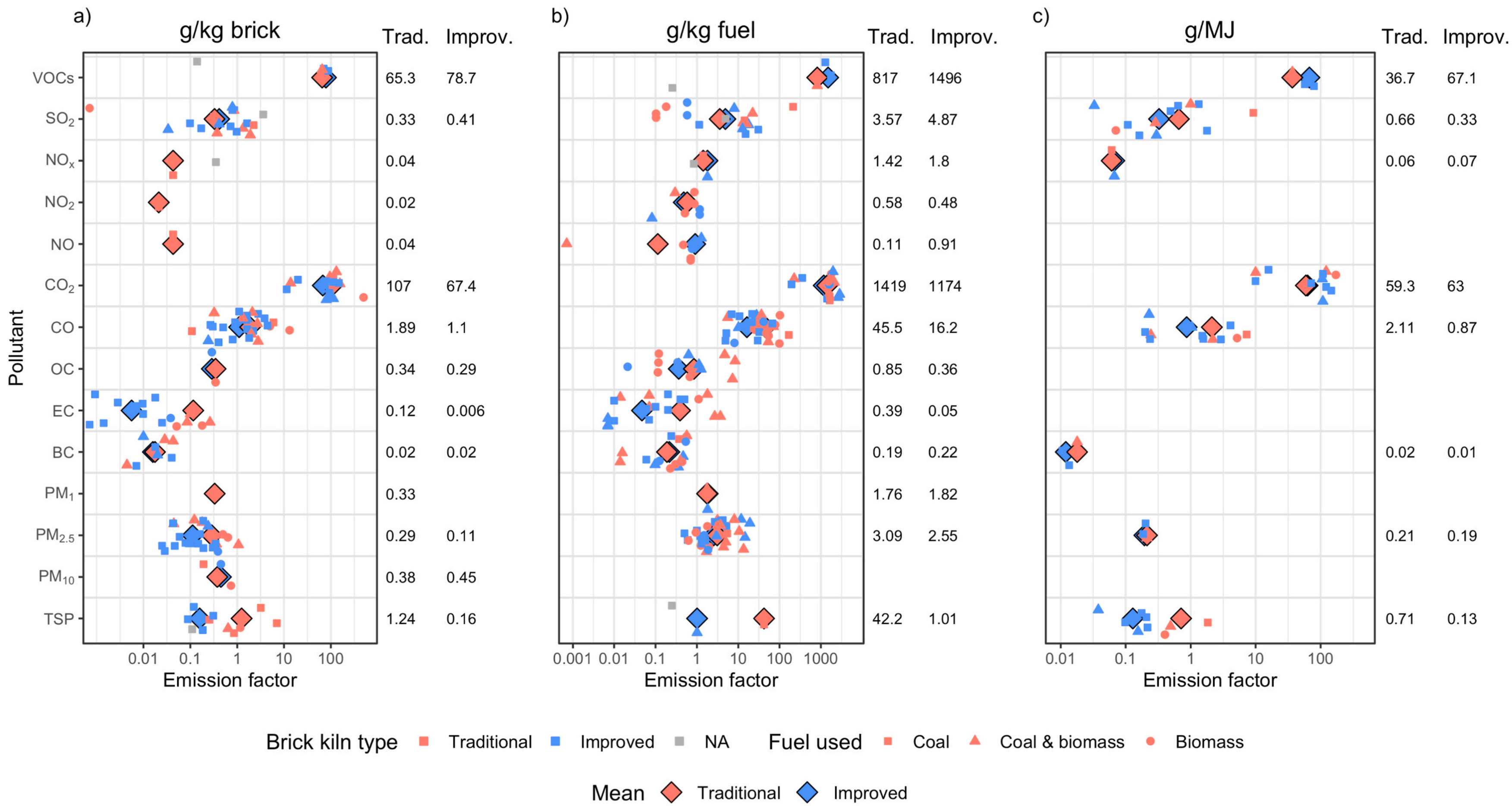

Fig. 3. Geometric mean emission factors and means by brick kiln design in (a) g/kg brick, (b) g/kg fuel, and (c) g/MJ. We plot geometric mean emission factors for multiple pollutants, categorized by brick kiln design and fuel used. Symbols in red and blue represent kiln types categorized as traditional and improved, respectively. Symbols in grey represent kilns whose type was not specified. Brick kilns that used coal only are shown as squares, those that used coal and biomass are shown as triangles, and those that used biomass only are shown as circles. Means for traditional and improved kiln designs are shown in the red and blue diamonds, respectively. Values displayed on the right of each plot represent the mean geometric mean emission factors for traditional vs improved kiln designs.

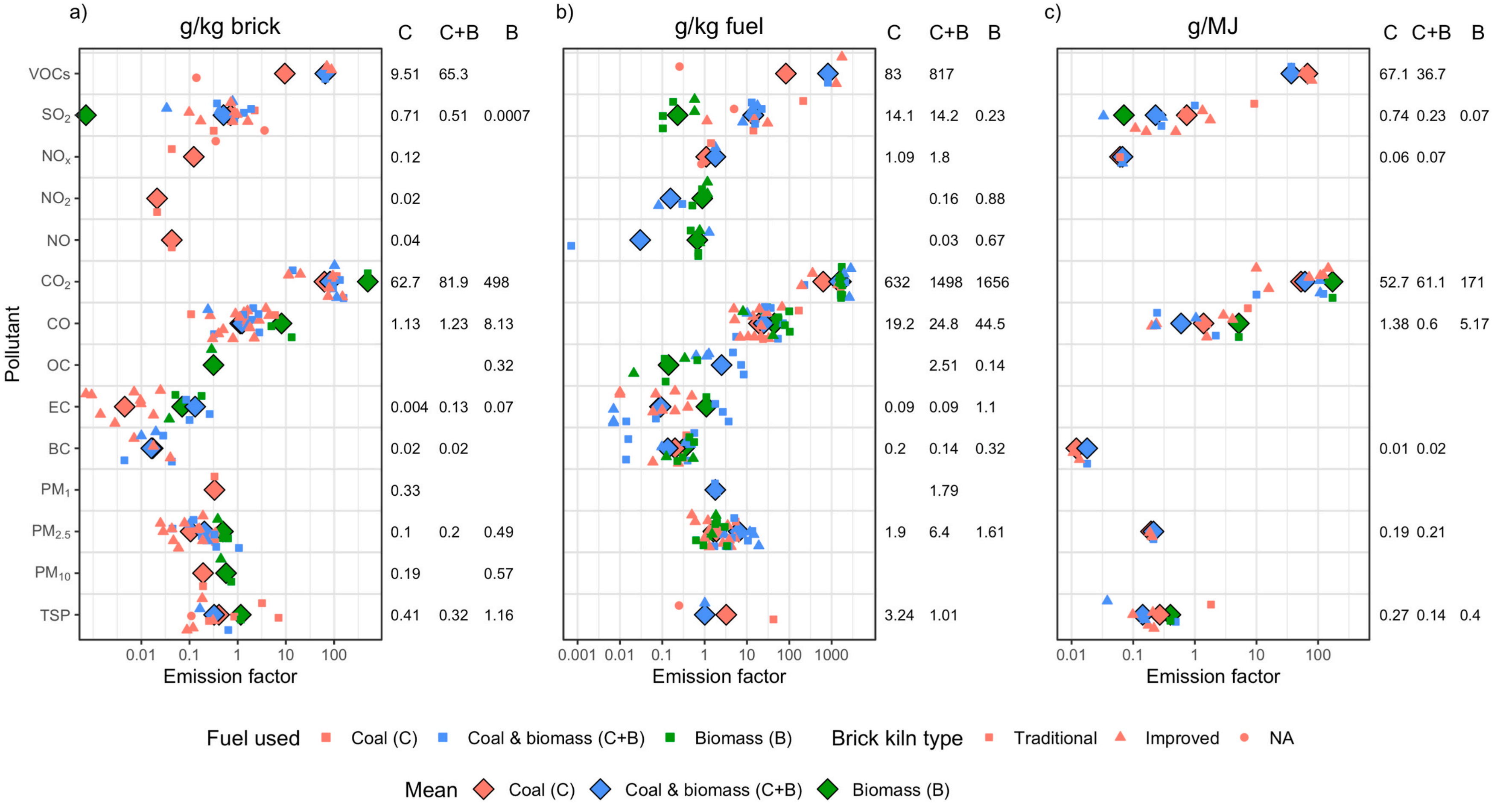

Fig. 4. Geometric mean emission factors and means by fuel type in (a) g/kg brick, (b) g/kg fuel, and (c) g/MJ. We plot geometric mean emission factors for multiple pollutants, categorized by brick kiln design and fuel used. Symbols in red, blue and green represent kilns that used coal only, coal and biomass, and biomass, respectively. Traditional brick kilns are shown as squares, improved kilns are shown as triangles, and those whose type was not specified are shown as circles. Means for kilns that used coal, coal and biomass, and biomass are shown in the red, blue and green diamonds, respectively. Values displayed on the right of each plot represent the mean geometric mean emission factors for coal (C), coal and biomass (C + B), and biomass (B).

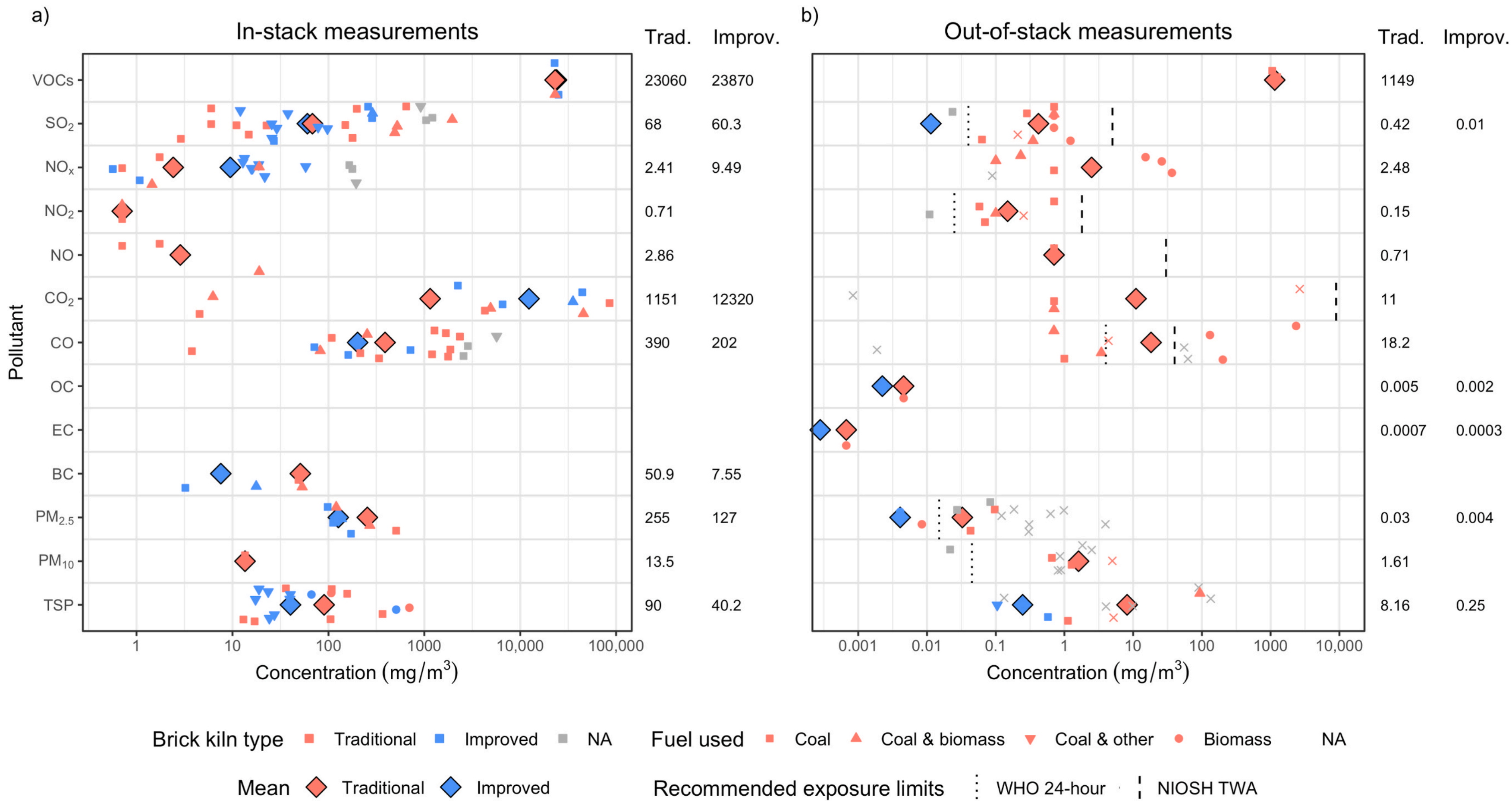

Fig. 5. Geometric mean pollutant concentrations and means by brick kiln design from (a) in-stack measurements, and (b) brick kiln site measurements. We plot geometric mean concentrations for multiple pollutants, categorized by brick kiln design and fuel used. Symbols in red and blue represent kiln types categorized as traditional and improved, respectively. Symbols in grey represent kilns whose type was not specified. Brick kilns that used coal only are shown as squares, those that used coal and biomass are shown as upward-pointing triangles, those that used coal and solid waste are shown as downward-pointing triangles, and those that used biomass only are shown as circles. Means for traditional and improved kiln designs are shown in the red and blue diamonds, respectively. Values displayed on the right of each plot represent the mean geometric mean pollutant concentrations for traditional vs improved kiln designs.

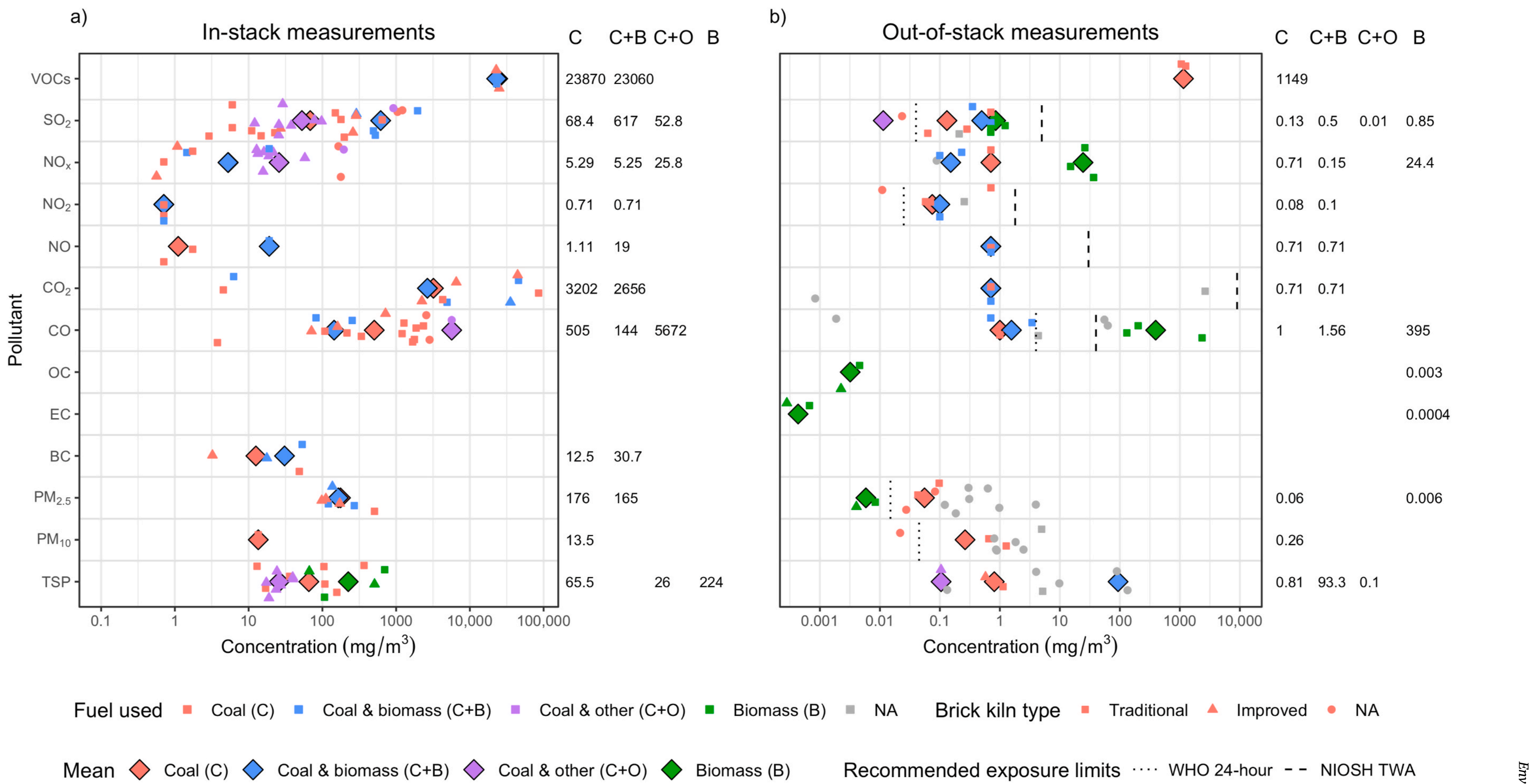

Fig. 6. Geometric mean pollutant concentrations and means by fuel type from (a) in-stack measurements, and (b) brick kiln site measurements. We plot geometric mean concentrations for multiple pollutants, categorized by brick kiln design and fuel used. Symbols in red, blue, purple, and green represent kilns that used coal only, coal and biomass, coal and other (non-biomass) fuel, and biomass, respectively. Symbols in grey represent kilns whose fuel type was not specified. Traditional brick kilns are shown as squares, improved kilns are shown as triangles, and those whose type was not specified are shown as circles. Means for kilns that used coal, coal and biomass, coal and other, and biomass are shown in the red, blue, purple, and green diamonds, respectively. Values displayed on the right of each plot represent the mean geometric mean pollutant concentrations for coal (C), coal and biomass (C + B), coal and other (C + O), and biomass (B).

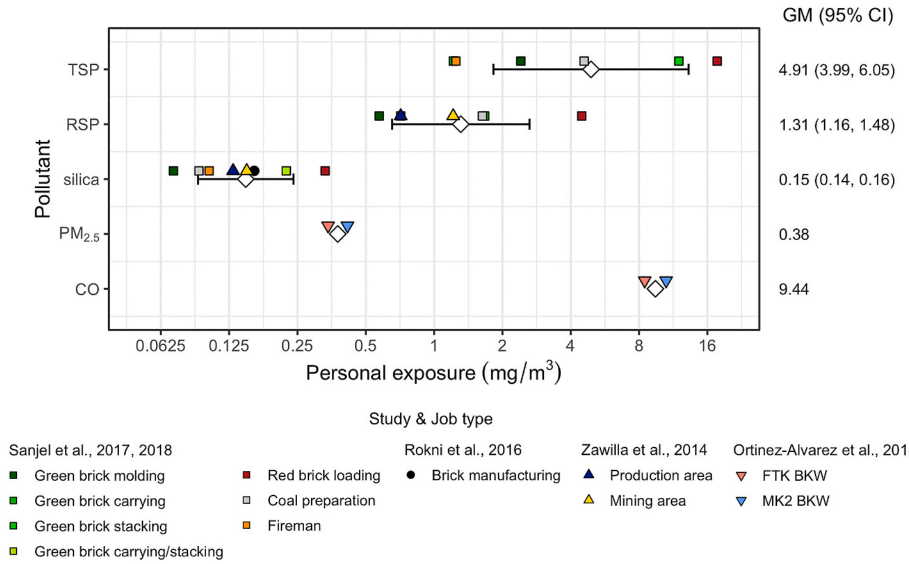

Fig. 7. Geometric means and 95% confidence intervals of personal exposures by brick kiln job type. Diamonds and error bars represent the pooled geometric means and 95% confidence intervals, respectively, for each pollutant. Values displayed on the right represent pooled geometric means and 95% confidence intervals for each pollutant.

those reported by Sanjel et al. (2017), with mean values ranging between 0.4 mg/m^3 and 10 mg/m^3. Personal samples collected in a brick factory in Southern Cairo, Egypt, showed exposures were higher in the mining area than in the production area for both RSP and silica (Zawilla et al., 2014).

Another study conducted in Durango, Mexico measured personal exposures to $PM_{2.5}$ and CO among workers in one fixed traditional kiln (n = 2) and one MK2 Marquez kiln (n = 2) (Ortinez-Alvarez et al., 2018). The assessments were conducted on the worker responsible for feeding the kilns and the assistant to the main operator. Despite the more energy-efficient design of the MK2 and lower emission concentrations, average personal exposures to $PM_{2.5}$ and CO were higher in the MK2 vs the FTK (Fig. 5). This was attributed to the presence of a flat shade roof and observational portholes, as well as mismanagement of the operational processes in the MK2, resulting in an accumulation of pollutants.

3.7. *Exposure biomarkers in brick kiln workers and residents near brick kilns*

We identified 13 (17%) studies that measured exposure biomarkers among brick kiln workers, children at kiln sites, and children living in communities near kilns (Table S3). Brick kiln workers and children near kilns had higher urinary concentrations of PAH exposure biomarkers (1-hydroxypyrene, α-naphthol, β-naphthol) (Flores-Ramírez et al., 2018; Martínez-Salinas et al., 2010; Pérez-Maldonado et al., 2019; Kamal et al., 2014b), and benzene exposure biomarkers (trans,trans-muconic acid) (Flores-Ramírez et al., 2018) compared to controls or even individuals living near heavy traffic, waste landfill or metallurgical industry (Table S10). Heavy metal concentrations in blood among brick kiln workers and nonworkers living near kilns were also higher compared to controls (David et al., 2021, 2022; Sughis et al., 2014; Ahmad et al., 2020; Jahan et al., 2016), but not compared to those in other urban marginalized communities (Flores-Ramírez et al., 2018).

3.8. *Health outcomes*

Forty-six studies evaluated health outcomes (Table S11). The most evaluated conditions were respiratory health, biomarkers, and musculoskeletal disorders. Overall study quality across health outcomes was low (Table S12). The Kappa value for agreement with consensus between two reviewers was 0.86.

3.8.1. *Respiratory health*

We summarized characteristics of studies reporting respiratory health data in the Online Supplement and Table S13. Forced expiratory volumes (FEVs) were lower in brick kiln workers than in controls (Fig. 8). Tobacco smoking may be an important effect modifier: brick kiln workers who were smokers had lower FEVs when compared to non-smoking brick kiln workers, non-brick kiln worker smokers, or non-smoking non-brick kiln workers (Table 1); however, this interaction was not formally evaluated by any of the studies and missing information on sample size in subgroups for most studies did not allow us to conduct a meta-analysis. Reported mean percent predicted values of FEV were lower in brick kiln workers than in controls (Table 2) but there were too few studies to conduct a meta-analysis.

The prevalence of respiratory symptoms was higher in brick kiln workers than in controls and was higher in participants living near kilns than in those living farther away from the kilns (Table 3). Both chronic diseases, like asthma, COPD and chronic bronchitis, and respiratory infections were also more common in brick kiln workers when compared to controls (Table 3). One study found higher odds of tonsillitis and throat inflammation in children living near brick kilns compared to those living father away from bricks kilns (Joshi and Dudani, 2008). Another study found a higher incidence of pneumonia and upper respiratory infections when brick kilns was the source category of fine particulate matter (Sherris et al., 2021). A study in India reported that 9.4% of adult and child brick kiln workers had chest symptoms consisting of productive cough for two weeks or longer with or without chest pain, intermittent fever or hemoptysis.

Ten studies evaluated the association between respiratory outcomes and number of years worked (Table S13): one study reported a positive correlation between the score obtained from a screening questionnaire for COPD and number of years worked (numerical value for correlation not given) (Berumen-Rodriguez et al., 2021); one study found a higher prevalence of small opacities on chest X-ray (≥0/1) and either number of years worked or estimated cumulative exposure to respirable quartz (Love et al., 1999); four studies did not find any relationship between respiratory symptoms or lung function and number of years worked (Biswas et al., 2018; Kaushik et al., 2012; Shrestha et al., 2021; Raza et al., 2014); four studies found either a higher prevalence of respiratory symptoms or lower lung function with more years of work exposure (Shaikh et al., 2012; Kazi and Bote, 2019; Sheta and El Laithy, 2015; Tandon et al., 2017). Ten studies evaluated the association between

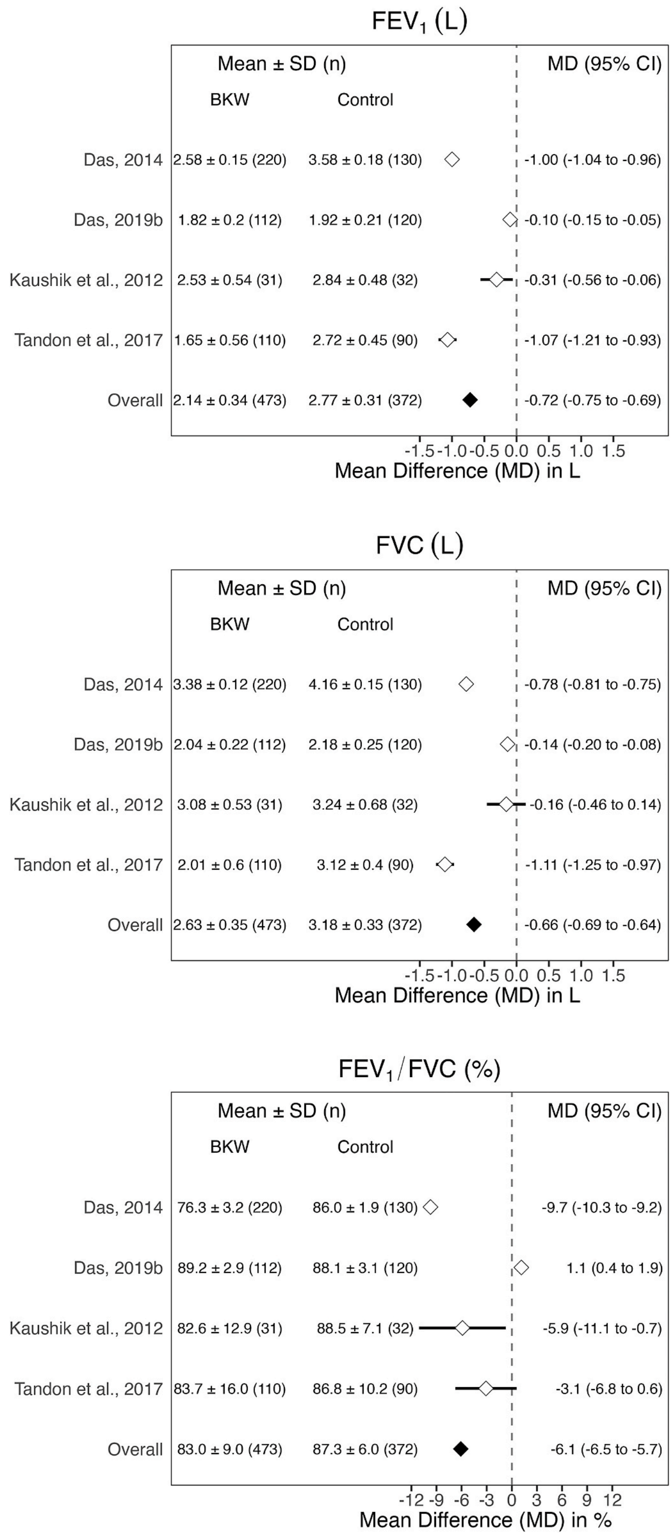

Fig. 8. Mean values of lung function for brick kiln workers and controls, and mean difference between brick kiln workers and controls.

respiratory outcomes and brick kiln worker occupation: three found more respiratory symptoms (including conditions like chronic bronchitis and asthma) in bakers when compared to other brick kiln worker types (Shaikh et al., 2012; González et al., 2021; Sheta and El Laithy, 2015), four did not find an association between lung function or respiratory symptoms and brick kiln worker type (Shrestha et al., 2021; Sanjel et al., 2017; Raza et al., 2014; Raza and Ali, 2021), one found that among workers in the modulation, loading, burning and unloading sites, obstructive and restrictive impairments were highest in workers at the loading and burning sites, respectively (Raza and Ali, 2021), one found that respiratory symptoms were lower in molders compared to carriers, stackers or firemen (Biswas et al., 2018), and one found more respiratory symptoms in bigaaris (translates to carriers) when compared to other brick kiln types (Kazi and Bote, 2019).

Table 1
Mean values of lung function for brick kiln workers and controls stratified by smoking status, and mean difference between brick kiln workers and controls stratified by smoking status.

	Mean ± SD (n)			
	Brick kiln workers		Reference (or control) group	
	Smokers	Non-smokers	Smokers	Non-smokers
FEV_1 (in L)				
Goel et al., 2015	2.15 ± 0.50 (N/A)	N/A	2.75 ± 0.73 (N/A)	3.53 ± 0.24 (N/A)
Raza and Ali, 2021	1.98 ± 0.53 (25)	2.16 ± 0.62 (35)	N/A	N/A
Tandon et al., 2017	N/A	1.65 ± 0.56 (110)	N/A	N/A
FVC (in L)				
Goel et al., 2015	2.56 ± 0.66 (N/A)	N/A	3.17 ± 0.69 (N/A)	3.86 ± 0.25 (N/A)
Raza and Ali, 2021	2.27 ± 0.67 (25)	2.53 ± 0.74 (35)	N/A	N/A
Tandon et al., 2017	N/A	2.01 ± 0.60 (110)	N/A	N/A
FEV_1/FVC (in %)				
Goel et al., 2015	82.8 ± 8.5 (N/A)	N/A	85.9 ± 7.5 (N/A)	91.4 ± 3.6 (N/A)
Srivastava et al., 2002	74.2 ± 8.8 (47)	70.4 ± 6.2 (23)	79.4 ± 6.8 (52)	78.6 ± 5.1 (54)
Tandon et al., 2017	N/A	83.69 ± 16.02 (110)	N/A	N/A

Table 2
Mean percent predicted values of lung function for brick kiln workers and controls, and mean difference between brick kiln workers and controls.

	Mean ± SD (n)		Mean difference (95% CI)
	Brick kiln worker	Reference (or control) group	
FEV_1 percent predicted			
Sheta and El Laithy, 2015	74.1 ± 7.8 (173)	81.8 ± 10.1 (170)	−7.7 (−9.6 to −5.8)
Srivastava et al., 2002 (non-smokers)	N/A	N/A	N/A
Srivastava et al., 2002 (smokers)	N/A	N/A	N/A
Tandon et al., 2017	86.5 ± 12.0 (110)	93.0 ± 8.5 (90)	−6.5 (−9.4 to −3.6)
FVC percent predicted			
Sheta and El Laithy, 2015	75.9 ± 6.7 (173)	80.3 ± 6.1 (170)	−4.4 (−5.8 to −3.0)
Srivastava et al., 2002 (non-smokers)	81.2 ± 4.6 (52)	83.6 ± 3.8 (54)	−2.4 (−4.0 to −0.8)
Srivastava et al., 2002 (smokers)	79.2 ± 8.8 (47)	81.1 ± 4.8 (23)	−1.9 (−5.1 to 1.3)
Tandon et al., 2017	88.9 ± 9.3 (110)	94.4 ± 8.9 (90)	−5.5 (−8.0 to −3.0)
FEV_1/FVC percent predicted			
Sheta and El Laithy, 2015	N/A	N/A	N/A
Srivastava et al., 2002 (non-smokers)	79.4 ± 6.8 (52)	78.6 ± 5.1 (54)	0.8 (−1.5 to 3.1)
Srivastava et al., 2002 (smokers)	74.2 ± 8.8 (47)	70.4 ± 6.2 (23)	3.8 (0.2–7.4)
Tandon et al., 2017	80.7 ± 4.8 (110)	85.2 ± 5.0 (90)	−4.5 (−5.9 to −3.1)

3.8.2. *Gastrointestinal disease*

We identified three studies reporting data on gastrointestinal problems among brick kiln workers (Kazi and Bote, 2019; Srivastava et al., 2002; Zawilla et al., 2014), but only one related to kiln exposures (Zawilla et al., 2014). Zawilla et al. (2014) examined liver function among 87 silica-exposed brick kiln workers and 45 non-exposed controls in Egypt. Mean liver function test concentrations (except albumin and bilirubin), MMP-9, and immunoglobulins (G and E) were all significantly higher in brick kiln workers compared to controls; more than half of brick kiln workers had abnormal AST and GGT and almost 20% had abnormal ALT and ALP levels, but no comparative data was reported for controls. The other studies, conducted among different brick kiln worker groups in India, reported proportions between 4% and 13.2% with gastrointestinal disorders but it was unclear if these were attributed to brick kilns or poor sanitary facilities and polluted drinking water (Kazi and Bote, 2019; Srivastava et al., 2002).

3.8.3. *Reproductive health risks*

Three studies reported data on reproductive health in brick kiln workers (David et al., 2020, 2022; Jahan et al., 2016). One study conducted in Pakistan compared health risks in 232 female brick kiln workers to 113 controls and found a lower age at menarche for brick kiln workers when compared to controls (11.1 ± 0.16 years vs. 14.1 ± 0.19 years, respectively) (David et al., 2020). Female brick kiln workers had a higher average number of pregnancies, abortions and stillbirths when compared to controls; however, controls were younger and fewer were married than brick kiln workers. Another study in Pakistan examined testosterone and luteinizing hormone (LH) levels in 110 male brick kiln workers with at least 10 years of work experience, 30 non-brick kiln workers aged 19–45 years living in nearby communities to the kilns, and 57 adult males aged 21–40 years (distance from kilns not reported) (Jahan et al., 2016). The authors found that testosterone in brick kiln workers was lower when compared to controls or non-brick kiln workers who lived near the kilns. Testosterone levels were also lower in brick bakers compared to other brick kiln worker occupations. LH was lower in brick makers and brick carriers compared to controls or nonworkers who lived near the kilns. Brick bakers appear to have higher LH than controls and nonworkers who lived near the kilns, although the text and table report this finding inconsistently. The last study, also from Pakistan, compared 346 adult brick kiln workers to 200 non-brick kiln worker controls of a similar age range (David et al., 2022). The authors found higher FSH and LH and lower testosterone in brick kiln workers compared to controls.

3.8.4. *Musculoskeletal disorders*

Nine studies reported data on musculoskeletal pain (Hamid et al., 2023; Biswas et al., 2018; Das, 2014, 2019a, 2019b; Kazi and Bote, 2019; Shrestha et al., 2021; Srivastava et al., 2002; Vaidya et al., 2015); however, none of these studies linked musculoskeletal pain directly to brick kiln pollution exposure. Four studies compared brick kiln workers to controls and found that the prevalence of musculoskeletal problems was consistently higher in brick kiln workers than in controls (Das, 2014, 2019b; Srivastava et al., 2002; Vaidya et al., 2015).

Table 3
Prevalence of respiratory symptoms or chronic respiratory disease and mean difference between brick kilns workers (or participants living near kilns) and controls (or participants living far from kilns).

Symptom or disease	Exposed population	Brick kiln worker or lives near brick kilns, % (n[a]/total)	Reference group (non-brick kiln worker, other control or lives far), % (n[a]/total)	Mean difference (95% CI)
Cough[c]				
Biswas et al., 2018	Adult brick kiln workers	39.1% ([86]/220)		
Hamid et al., 2023 (dry cough)	Adult and child brick kiln workers	72.9% ([321]/440)		
Khan et al., 2019 (non-crushing period)	Adult and child residents near kilns	75% (75/100)	32% (32/100)	43% (30.1%–55.5%)
Khan et al., 2019 (crushing period)	Adult and child residents near kilns	78% (78/100)	36% (36/100)	52% (29.6%–54.5%)
Rahman et al., 2013	Adult brick kiln workers	57% ([232]/407)	6% ([24]/407)	51% (45.7%–56.3%)
Raza and Ali, 2021	Adult brick kiln workers	50% (30/60)		
Raza and Ali, 2022	Adult brick kiln workers	76.9% (389/506)		
Sanjel et al., 2017	Adult and child brick kiln workers	55.2% (221/400)	28.8% (115/400)	26.8% (19.8%–33.0%)
Tandon et al., 2017	Adult brick kiln workers	67.3% (74/110)	24.4% (22/90)	42.9% (30.4%–55.4%)
Vaidya et al., 2015[b]	Adult brick kiln workers	18% ([7]/40)	20% ([13]/63)	2% (−17%.5–13.5%)
Overall		56.8% (54.9%–58.7%)		32.3% (28.6%–35.9%)
Chronic cough				
Biswas et al., 2018	Adult brick kiln workers	6.8% ([15]/220)		
González et al., 2021	Adult brick kiln workers	26.8% (22/82)		
Gupta et al., 2019	Adult brick kiln workers	23.6% (163/692)		
Raza and Ali, 2021	Adult brick kiln workers	11.7% (7/60)		
Raza and Ali, 2022	Adult brick kiln workers	66.4% (336/506)		
Sanjel et al., 2017	Adult and child brick kiln workers	14.3% (35/244)	6.8% (11/162)	7.5% (1.6%–13.4%)
Shaikh et al., 2012(non-smokers)	Adult brick kiln workers	11.3% ([22]/194)		
Shaikh et al., 2012(smokers)	Adult brick kiln workers	37% ([54]/146)		
Sheta and El Laithy, 2015	Adult brick kiln workers	34.7% (60/173)	10% (17/170)	24.7% (16.3%–33.1%)
Overall		25.8% (24.3%–27.4%)		20.6% (16.0%–25.2%)
Phlegm/sputum				
Biswas et al., 2018	Adult brick kiln workers	37.7% ([83]/220)		
Gupta et al., 2019	Adult brick kiln workers	22.8% (158/692)		
Rahman et al., 2013	Adult brick kiln workers	33% ([134]/407)	3% ([12]/407)	30% (25.1%–34.9%)
Raza and Ali, 2021	Adult brick kiln workers	21.7% (13/60)		
Raza and Ali, 2022	Adult brick kiln workers	61.5% (311/506)		
Sanjel et al., 2017	Adult and child brick kiln workers	42.2% (169/400)	11.2% (45/400)	31% (25.3%–36.7%)
Overall		36.5% (34.6%–38.4%)		30.5% (26.8%–34.2%)
Chronic phlegm				
Biswas et al., 2018	Adult brick kiln workers	19.1% ([42]/220)		
Raza and Ali, 2021	Adult brick kiln workers	11.7% (7/60)		
Raza and Ali, 2022	Adult brick kiln workers	62.5% (316/506)		
Sanjel et al., 2017	Adult and child brick kiln workers	16.6% (28/169)	5.8% (5/86)	10.8% (3.3%–18.3%)
Shaikh et al., 2012 (non-smokers)	Adult brick kiln workers	9.8% ([19]/194)		
Shaikh et al., 2012 (smokers)	Adult brick kiln workers	36.3% ([53]/146)		
Sheta and El Laithy, 2015	Adult brick kiln workers	19.7% (34/173)	6.5% (11/170)	13.2% (6.2%–20.2%)
Tandon et al., 2017	Adult brick kiln workers	70% (77/110)	34.4% (31/90)	35.6% (23.6%–47.6%)
Overall		30.7% (28.7%–32.7%)		19.9% (15.1%–24.6%)
Wheezing				
Biswas et al., 2018	Adult brick kiln workers	37.7% ([83]/220)		
González et al., 2021	Adult brick kiln workers	30.5% (25/82)		
Love et al., 1999	Adult brick kiln workers	20.6% (381/1851)		
Raza and Ali, 2021	Adult brick kiln workers	20% (12/60)		
Raza and Ali, 2022	Adult brick kiln workers	56.9% (288/506)		
Sanjel et al., 2017	Adult and child brick kiln workers	11.3% (45/400)	2% (8/400)	9.3% (5.9%–12.7%)
Shaikh et al., 2012 (non-smokers)	Adult brick kiln workers	13.4% ([26]/194)		
Shaikh et al., 2012 (smokers)	Adult brick kiln workers	27.4% ([40]/146)		
Sheta and El Laithy, 2015	Adult brick kiln workers	20.2% (35/173)	8.8% (15/170)	11.4% (4.1%–18.7%)
Overall		26.4% (25.1%–27.7%)		10.4% (7.3%–3.4%)
Asthma[c,d]				
Biswas et al., 2018	Adult brick kiln workers	35.0% ([77]/220)		
David et al., 2022	Adult brick kiln workers	8% (28/346)	0% (0/200)	8% (5.1%–10.9%)
Khan et al., 2019 (non-crushing period)	Adult and child residents near kilns	33% (33/100)	18% (18/100)	15% (3.1%–26.9%)
Khan et al., 2019 (crushing period)	Adult and child residents near kilns	38% (37/100)	16% (16/100)	22% (10.1%–33.9%)
Raza and Ali, 2021 (self-reported)	Adult brick kiln workers	3.3% (2/60)		

(continued on next page)

Table 3 (*continued*)

Symptom or disease	Exposed population	Brick kiln worker or lives near brick kilns, % (n[a]/total)	Reference group (non-brick kiln worker, other control or lives far), % (n[a]/total)	Mean difference (95% CI)
Raza and Ali, 2021 (physician-diagnosed)	Adult brick kiln workers	0% (0/60)		
Raza and Ali, 2022 (self-reported)	Adult brick kiln workers	14.6% (74/506)		
Raza and Ali, 2022 (physician-diagnosed)	Adult brick kiln workers	9.5% (48/506)		
Sanjel et al., 2017	Adult and child brick kiln workers	6.3% ([25]/400)	1.8% ([7]/400)	4.6% (1.8%–7.2%)
Shaikh et al., 2012	Adult brick kiln workers	8.2% ([28]/340)		
Sheta and El Laithy, 2015	Adult brick kiln workers	15.6% (27/173)	7.1% (12/170)	8.5% (0.2%–15.1%)
Overall		15.5% (14.2%–16.7%)		9.0% (7.1%–10.9%)
Chronic bronchitis				
Biswas et al., 2018	Adult brick kiln workers	17.7% ([39]/220)		
Gupta et al., 2019	Adult brick kiln workers	20.5% (142/692)		
Love et al., 1999	Adult brick kiln workers	14.2% (263/1851)		
Sanjel et al., 2017	Adult and child brick kiln workers	19.0% ([76]/400)	10.8% ([43]/400)	8.2% (3.3%–13.1%)
Shaikh et al., 2012	Adult brick kiln workers	17.1% ([58]/340)		
Sheta and El Laithy, 2015	Adult brick kiln workers	19.7% (34/173)	6.5% (11/170)	13.2% (6.2%–20.2%)
Srivastava et al., 2002	Adult brick kiln workers	4.7% ([6]/131)		
Overall		16.1% (15.0%–17.3%)		10.7% (6.7%–14.7%)
COPD[e]				
Berumen-Rodriguez et al., 2021	Adult brick kiln workers	46% ([19]/41)		
Berumen-Rodríguez et al., 2023	Adult brick kiln workers	38% ([8]/21)		
Khan et al., 2019(non-crushing period)	Adult and child residents near kilns	37% (37/100)	14% (14/100)	23% (11.3%–34.7%)
Khan et al., 2019 (crushing period)	Adult and child residents near kilns	38% (38/100)	16% (16/100)	22% (10.1%–33.9%)
Rahman et al., 2013	Adult brick kiln workers	18.9% ([77]/407)	2.6% ([11]/407)	16.3% (12.2%–20.4%)
Acute respiratory infections				
Ali et al., 2013	Children near kilns	24.5% (NA/NA)	12.8% (NA/NA)	11.7%
Khan et al., 2019 (non-crushing period)	Adults and children near kilns	50% (50/100)	26% (26/100)	24% (11.0%–37.0%)
Khan et al., 2019 (crushing period)	Adults and children near kilns	53% (53/100)	28% (28/100)	25% (11.8%–38.2%)
Respiratory problems (overall)				
Biswas et al., 2018	Adult brick kiln workers	63.6% ([140]/220)		
Das, 2019b	Child brick kiln workers	52.5% ([59]/112)	3.5% ([4]/120)	48.7% (39.2%–58.8%)
González et al., 2021	Adult brick kiln workers	20.7% (17/82)		
Kazi and Bote, 2019	Adult brick kiln workers	27.4% (115/420)		
Sheta and El Laithy, 2015	Adult brick kiln workers	39.9% (69/173)	11.7% (20/170)	28.2% (19.5%–37%)
Shrestha et al., 2021	Adult brick kiln workers	53.8% ([242]/450)		
Srivastava et al., 2002	Adult brick kiln workers	12.1% (31/257)	4.6% (6/131)	7.5% (2.1%–12.9%)
Subhanullah et al., 2022	Adult and child brick kiln workers	62% ([31]/50)		
Overall		41.5% (39.5%–43.5%)		28.2% (24.1%–32.4%)
Dyspnea[e]				
González et al., 2021 (at rest)	Adult brick kiln workers	14.6% (12/82)		
González et al., 2021 (with exercise)	Adult brick kiln workers	20.7% (17/82)		
Gupta et al., 2019 (Grades 2+)	Adult brick kiln workers	9.2% (64/692)		
Love et al., 1999 (breathlessness)	Adult brick kiln workers	4.4% (81/1851)		
Rahman et al., 2013 (dyspnea)	Adult brick kiln workers	14% ([57]/407)	1% ([4]/407)	13% (9.5%–16.5%)
Raza and Ali, 2021 (Grade 1 and 2 dyspnea)	Adult brick kiln workers	38.3% (23/60)		
Raza and Ali, 2022 (Grade 1 and 2 dyspnea)	Adult brick kiln workers	75.7% (383/506)		
Sanjel et al., 2016 (breathlessness)	Adult and child brick kiln workers	31.5% (126/400)	8.2% (33/400)	23.3% (18.0%–28.6%)
Shaikh et al., 2012 (Grade 3, non-smokers)	Adult brick kiln workers	7.75% ([15]/194)		
Shaikh et al., 2012 (Grade 3, smokers)	Adult brick kiln workers	7.5% ([11]/146)		
Sheta and El Laithy, 2015 (dyspnea)	Adult brick kiln workers	21.4% (37/173)	5.3% (9/170)	16.1% (9.1%–23.1%)
Tandon et al., 2017 (shortness of breath)	Adult brick kiln workers	60% (66/110)	32.2% (29/90)	27.8% (14.5%–41.1%)
Vaidya et al., 2015 (breathlessness)	Adult brick kiln workers	20% (N/A)	10% (N/A)	10%

[a] [n] = number calculated based on percentage and total as n was not reported.
[b] Reference group is made up of construction workers.
[c] Overall estimates do not include data from Khan et al., 2019 crushing period.
[d] Overall estimates do not include Raza and Ali, 2021 or Raza and Ali, 2022 physician-diagnosis of asthma.
[e] We do not calculate an overall score for dyspnea or COPD because authors used different definitions or approaches across studies.

3.8.5. Cardiovascular disease

We did not identify any papers reporting prevalence of cardiovascular disease among brick kiln workers or any associations of cardiovascular outcomes with kiln pollutants. One study reported a prevalence of hypertension at 25.5% among Mexican brick kiln workers (Berumen-Rodriguez et al., 2021), and two studies reported heart rate and blood pressure before and after completion of work in the brick kiln as an assessment of physiological stress (Das, 2014, 2019b). Comparing 220 male brick field workers from 12 brick fields in West Bengal, India and 130 controls engaged in office work, Das found no difference in resting heart rate between groups (Das, 2014). Resting blood pressure was lower among brick kiln workers although results presented in the table and text were inconsistent. Just after work, both heart rate and blood pressure were higher in brick kiln workers than controls. In a later study among 112 child brick kiln workers aged 9–16 years and 120 controls engaged in household jobs, the author found no difference in heart rate or blood pressure at rest between the two groups, but significantly higher values among brick kiln workers than controls after completion of work (Das, 2019b). A total of 46% of kiln workers reported cardiovascular problems compared to 4% of controls.

3.8.6. Cancer

We identified four papers reporting cancer risk due to exposure to kiln emissions, namely PAHs, metals, and radionucleotides (Abedin et al., 2020; Kamal et al., 2014a; Pokhrel et al., 2018; Shaikh et al., 2020). However, all four of these studies were excluded from the health outcomes review as the risk assessment was based on models rather than collected health outcome data. In addition, one of the studies modeled the risk based on PAH concentrations in an agricultural and brick production area rather than at a kiln site (Pokhrel et al., 2018).

3.8.7. Biomarkers

Eleven studies evaluated biomarkers in brick kiln workers against unexposed controls (Table S11). We summarized the findings for each study in the Online Supplement. Overall, there was evidence of higher reactive oxygen species, lower concentrations of superoxide dismutase and catalyse, and more DNA damage in brick kiln workers when compared to controls (Table S14). There was also evidence of more inflammation as evidenced by a higher C-reactive protein and cortisol in brick kiln workers when compared to controls, and elevated cytokine levels in exhaled breath condensate of brick kiln workers. Two studies identified down-regulated expression of genes associated with DNA and protein repair in brick kiln workers when compared to controls.

3.8.8. Linear growth

Three studies examined the role of brick kiln pollution on child linear growth (e.g., stunting) (Nasir et al., 2021; Roshania et al., 2022; Sinaga et al., 2022). Nasir et al. (2021) examined 383 children aged 5–12 years from Pakistan, measured their height and calculated Z-scores using the 2007 World Health Organization (WHO) international reference. Mean height-for-age Z-score was −0.50 (prevalence of stunting not reported). The authors used propensity score matching on a probit regression using four different techniques to match on household and child characteristics for children living within 3 km of a brick kiln (exposed) when compared to children living farther away (controls). Using nearest neighbor and radius matching, exposed children had a Z-score that was −0.68 and −0.6 lower than controls, respectively ($p < 0.01$). Z-scores were −0.43 and −0.42 lower with kernel and stratification matching, albeit not statistically significant. Roshania et al. (2022) conducted a large cross-sectional study with a cluster design and measured height and in weight in 2564 migrant children (aged 0–11 months and 12–23 months) from 1156 brick kilns in India. Z-scores were calculated using the 2006 WHO Multi Growth Reference studies. Overall prevalence of stunting was 51.6% (mean Z-score not reported). Among children whose first episode of migration to a kiln occurred before age 6 months, the odds of stunting were 1.6 (95% CI 1.17–2.19) and 2.1 (1.30–3.41) times higher in those with two and three migration episodes, respectively, when compared to one. Sinaga et al. (2022) evaluated 192 children from Indonesia aged 0–24 months who lived in villages with ($n = 101$) and without ($n = 91$) clay brick kilns. The overall prevalence of stunting was 19%. The authors did not find a difference in the prevalence of stunting between children who lived in villages with clay brick kilns and those who lived in villages without clay brick kilns (19.8% vs. 18.6%; $p = 0.45$).

3.8.9. Other health outcomes

Other health outcomes reported in the literature included skin complaints (Das, 2019b; Erdim et al., 2020; Kazi and Bote, 2019; Shrestha et al., 2021; Srivastava et al., 2002; Subhanullah et al., 2022; Sanjel et al., 2016; Vaidya et al., 2015), ocular problems (Hamid et al., 2023; Das, 2019b; Kazi and Bote, 2019; Shrestha et al., 2021; Srivastava et al., 2002; Subhanullah et al., 2022; Sanjel et al., 2016; Vaidya et al., 2015), injuries (Kazi and Bote, 2019; Sanjel et al., 2016), and nasal and otologic complications (Erdim et al., 2020). The proportion of brick kiln workers with skin complaints ranged between 5% (Vaidya et al., 2015) and 19% (Kazi and Bote, 2019), with the major problems being callosities, eczema, dermatitis and itchy hands and feet (Kazi and Bote, 2019; Srivastava et al., 2002). Results on eye problems varied widely, with ∼4% of brick kiln workers reporting eye complaints in 2 studies (Kazi and Bote, 2019; Srivastava et al., 2002), and 48% reporting problems in vision in another (Vaidya et al., 2015). Interestingly, a comparative study between brick kiln workers and grocery workers as controls, found that the proportion experiencing eye problems was significantly lower among brick kiln workers (14.8%) than controls (22.5%) (Sanjel et al., 2016). On the other hand, the occurrence of injuries was significantly higher among brick kiln workers (55.0%) than controls (44.2%). Among the 420 brick kiln workers interviewed by Kazi and Bote (2019) however, only 7% reported injuries. Lastly, an otorhinolaryngologic evaluation of 103 brick kiln workers in Erbaa, Turkey, showed that 1.9% had structural otologic complications, whereas general otologic complications, including dust in the external ear canal or tympanic membrane, were observed in 25.2% of workers (Erdim et al., 2020). Structural and general nasal complications were observed in 26.2% and 68.0% of brick kiln workers, respectively, and were significantly higher among workers who did not wear a mask and those who had worked for more than 10 years when compared to those who did not wear masks or worked fewer than 10 years, respectively. The authors did not find differences in otologic or rhinologic complications by brick kiln worker occupation.

3.9. Interventions

We identified four studies that compared different brick kiln technologies and provided recommendations for reducing emissions (Nepal et al., 2019; Nasim and Sharif, 2020; Haque et al., 2018; Ortinez-Alvarez et al., 2018). A study which compared emission concentrations from a FTK and an improved MK2 Marquez kiln in Durango, Mexico, showed that average emissions of $PM_{2.5}$, OC and EC from the FTK were a factor of two higher than the MK2, despite initial mismanagement by the MK2 operator which led to higher concentrations in the MK2 during the first sampling cycle (Ortinez-Alvarez et al., 2018). The authors highlighted the need for supervision by authorities, training, and good practice on implementation and operation to maximize the environmental benefits of improved technologies.

Among 18 brick kilns in Greater Dhaka, Bangladesh, consisting of FCBTKs, ZZKs and HKs, Haque et al. (2018) found average fuel-based emission factors of BC, $PM_{2.5}$ and CO were highest in FCBTKs, whereas CO_2 and SO_2 emissions were highest in ZZKs and HKs, respectively. They noted, however, that SO_2 concentrations not only depend on kiln technology but also on the sulfur content in the fuel used. Fuel consumption per fired brick was highest for FCBTKs. Similar results were observed in a comparative study conducted across 4 FCBTKs and 3 ZZKs in Kathmandu Valley, Nepal (Nepal et al., 2019). Compared with

ZZKs, FCBTKs had higher $PM_{2.5}$ and BC, comparable SO_2, and lower CO_2 emissions based on fuel-based emission factors. Emissions per kilogram of fired brick were lower in ZZKs than FCBTKs for all pollutants, and brick production capacity was higher in ZZKs. Their results suggested that a conversion from FCBTKs to ZZKs could result in emission reductions in $PM_{2.5}$ by ~20% and BC by ~30% per kilogram of fuel used, and ~40% for $PM_{2.5}$ and ~55% for BC per kilogram of fired brick. Another study conducted in Punjab, Pakistan, found fuel-based emission factors were substantially higher in FCKs than ZZKs for all pollutants measured (SO_2, CO, CO_2, PM), except for NO_x (Nasim and Sharif, 2020). In this case, emission reductions per kilogram of fuel used in ZZKs compared to FCBTKs were 98% for PM, 96% for SO_2, 83% for CO, and 64% for CO_2. While the emission factors and emission reduction estimates varied significantly across these studies, the results suggest that converting from FCBTKs to ZZKs or HKs, along with the use of high-grade coal with lower sulfur content, could be an effective solution for reducing emissions from brick kilns. Indeed, we found lower mean emission factors and in-stack concentrations of SO_2, CO, TSP and EC for ZZKs compared to FCBTKs; and, while mean emission factors were similar, in-stack concentrations of $PM_{2.5}$, BC and NOx were also lower for ZZKs (Figs. S2 and S3). The higher combustion efficiency of ZZKs also translates into higher private net benefits for ZZK owners, providing an incentive to shift from FCBTKs to ZZKs (Nasim and Sharif, 2020).

An additional two studies offered similar recommendations to reduce emissions, namely optimizing airflow in existing kilns to improve combustion efficiency such as zig-zag firing, switching to cleaner brick-making technologies, and utilizing clay and coal with lower sulfur, carbon and metal contents (Akinshipe and Kornelius, 2018; Kim et al., 2015). Additional recommendations on air quality management measures for clamp kilns based on findings from various firing campaigns in a model kiln included ensuring an even distribution of clay and fuel across the firing batch, ensuring a steady rise and fall in temperature, and ensuring adequate sun drying of bricks prior to firing to help reduce energy consumption (Akinshipe and Kornelius, 2018).

We did not find any studies on interventions to reduce exposures among brick kiln workers, and only five studies that measured personal exposures and provided some recommendations on dust control and personal protection (Sanjel et al., 2017, 2018; Rokni et al., 2016; Love et al., 1999; Zawilla et al., 2014). These recommendations included the use of water to reduce dust when possible, a decrease in the long hours on the job leading to greater risk of overexposure, the use of respiratory protection with priority given to brick haulers and stackers, changing into clean clothes after work, and regular health surveillance. The authors also advocated for enforcement of stricter regulations on brick kilns.

4. Discussion

We conducted a comprehensive systematic review and meta-analysis of brick kiln pollution exposures and health. While published data presents on brick kiln emissions extensively, our review identified important knowledge gaps in personal exposures and evaluation of health outcomes among brick kiln workers and residents living near kilns. First, despite silica being one of the most important exposures to workers, we identified only four studies that measured personal exposures to silica and one that measured silica concentrations in kilns, two that provided data on silicosis and one that evaluated for profusions on chest X-rays out of 104 studies. Second, while most studies correctly focused on respiratory conditions, they largely ignored other important organ systems well known to be affected by pollution such as the cardiovascular and nervous systems. Indeed, hypertension and cardiovascular disease are the leading risk factor and cause of illness and death, respectively, worldwide (Mills et al., 2020; Li et al., 2021), and long-term exposure to silica is linked to higher risk of cardiovascular disease mortality (Liu et al., 2014). Third, even among the studies that evaluated respiratory health, standardized questionnaires were not used consistently to report on respiratory symptoms, and guidelines and reference equations for spirometry were not reported in most studies. Most studies did not provide clear definitions of how respiratory symptoms were asked. Dyspnea, while generally higher in brick kiln workers than in controls, was not consistently reported across studies. No studies reported Z-scores for lung function and only two studies out of 14 described the reference equations used to calculate percent predicted values. Without adjustment for parameters that affect lung function such as age, sex, height, and risk factors including tobacco smoking, exposure to biomass smoke and other sources of air pollution, it is difficult to interpret whether differences in lung function between study groups are meaningful. Moreover, many studies had small sample size or did not specify whether sampling was done at random or by convenience, which may affect inferences. Multiple studies reporting pollution data did not specify the number of measurements collected or the sampling duration. Lastly, most studies were predominantly conducted in South Asia. While recognized as an important problem in South Asia, brick kilns are ubiquitous in LMICs worldwide.

To our surprise, we found that only five studies (5%) measured silica concentrations or personal exposures (Beard et al., 2022; Sanjel et al., 2018; Rokni et al., 2016; Love et al., 1999; Zawilla et al., 2014), and only four reported personal exposures to other pollutants like $PM_{2.5}$, RSP and CO (Ortinez-Alvarez et al., 2018; Sanjel et al., 2017; Love et al., 1999; Zawilla et al., 2014). While the three studies reporting on silica exposures in LMICs were limited in sample size and scope with no more than 48 participants (Sanjel et al., 2018; Rokni et al., 2016; Zawilla et al., 2014), they nonetheless highlight the problem of silica exposure among brick kiln workers in countries where regulations may be less closely monitored. Silica exposures were severalfold higher than the American Conference of Governmental Industrial Hygienists threshold limit value (ACGIH TLV; 25 $\mu g/m^3$), NIOSH recommended exposure limit (NIOSH REL; 50 $\mu g/m^3$) and Occupational Safety and Health Administration permissible exposure limit (OSHA PEL; 50 $\mu g/m^3$) (Occupational Safety and Health Adminstration, 2016), and were similar or higher than other occupations where silica dust exposure is also prevalent like mining and pottery (Chen et al., 2001; Dosemeci et al., 1995). Exposure to silica dust is associated with lung cancer, silicosis, kidney disease, chronic obstructive pulmonary disease and cardiovascular disease (Merget et al., 2002). Our review identified that better epidemiological data linking silica exposures in brick kilns with health outcomes is needed. Indeed, better studies estimating the association between cumulative exposure and health outcomes will help to drive policy for exposure mitigation in this neglected group of workers.

While brick kiln emissions contribute to the surrounding air quality, and therefore also impact nearby residents, most of the studies we identified focused on occupational health, likely due to the logistical and cost challenges of quantifying the contribution of brick kiln emissions to the personal exposures of individuals near kilns and determining attributable health effects. Only five studies reported health outcomes in individuals living near kilns (Ali et al., 2013; Sherris et al., 2021; Sinaga et al., 2022; Khan et al., 2019; Joshi and Dudani, 2008), four measured exposure biomarkers among residents near kilns (Flores-Ramírez et al., 2018; Martínez-Salinas et al., 2010; Pérez-Maldonado et al., 2019; Jahan et al., 2016), and one study measured exposure biomarkers in children living at kiln sites (David et al., 2021). Studies reported a higher prevalence of respiratory problems, including acute respiratory infections, COPD and asthma, and hypertension among individuals living near kilns compared to controls, and an association between $PM_{2.5}$ with higher mass percent of particles from brick kilns and child pneumonia (Ali et al., 2013; Sherris et al., 2021; Khan et al., 2019; Joshi and Dudani, 2008). Compared to controls, individuals living near kilns had higher urinary concentrations of PAH exposure biomarkers and fluoride. Heavy metal concentrations in blood were elevated in residents near kilns but lower than in brick kiln workers and GSH and testosterone levels were lower compared to controls but higher than in brick kiln workers, (Jahan et al., 2016) indicating an exposure-response relationship. Children living within 3 km of kilns were also found to have reduced cognitive ability compared to children living farther away (Nasir et al., 2021), but studies did not find a significant association between brick kiln pollution exposure and stunting (Nasir et al., 2021; Sinaga et al., 2022). Given that millions of people live near kilns, these data, albeit limited, suggests that transitioning to cleaner brick kiln technologies and fuels would have a substantial positive impact in the surrounding communities.

Our review also identified that no study has collected longitudinal data to evaluate associations between long-term exposures and health outcomes or conducted a randomized controlled trial (RCT) to evaluate exposure mitigation strategies on health outcomes. Cross-sectional studies, while less expensive and faster to conduct than longitudinal studies, do not allow for evaluation of causal or temporal relationships and may be prone to biases such as recall bias and the healthy worker effect (McMichael, 1976). Common conditions including hypertension, chronic obstructive pulmonary disease, and chronic kidney disease would benefit from longitudinal studies to understand the relationship between cumulative exposures to silica and other brick kiln pollutants on health outcomes. RCTs to determine the health impacts of individual-level interventions like the use of personal protective equipment or clustered interventions such as the use of water spraying at kilns to mitigate personal exposures to silica and other pollutants would help to inform exposure mitigation strategies. Moreover, RCTs can be used to study multiple primary outcomes including the impact of mitigation of brick kiln pollution exposures on musculoskeletal health where evidence is lacking. However, one difficulty with longitudinal studies or RCTs is that brick kiln workers tend to be migrants and temporary workers, which may complicate long-term follow-up due to high rate of loss to follow-up.

Other important observations identified in our review include the association between a higher number of seasons worked and health outcomes particularly for respiratory health; however, findings were not consistent across studies and were almost equally divided between higher prevalence and no effect. We also identified interaction effects between exposure to brick kiln pollution and tobacco smoking, with worse lung function when compared to neither exposure or one exposure. The interaction between brick kiln pollution and tobacco smoking is important because of the well-recognized higher risk of mortality in individuals who are occupationally exposed to silica and who are also smokers (Wang et al., 2020). Our review also revealed a large variability in dust and silica exposures across job types within kilns (Sanjel et al., 2017, 2018). However, few studies examined the association between job type and health outcomes, and none showed a clear link between worse respiratory health and job type. More comprehensive, standardized research is needed to better understand the effect of job type on exposures and health outcomes and help inform exposure mitigation strategies.

5. Conclusions

Our review identified worse health outcomes, particularly respiratory health, in brick kiln workers when compared to controls but study quality supporting the evidence was low and methods were not reported consistently or accurately. On average, traditional kilns emitted higher levels of PM, EC, OC and CO compared to improved brick kilns. However, results were mixed for other pollutants. We also did not identify a clear difference in pollutant emissions by fuel type, which highlights the large variability in emissions due to factors such as environmental conditions and stage in the firing cycle, as well as differences in sampling. Estimated contributions of brick kiln emissions to ambient air pollution varied widely across studies and settings but indicate that brick kilns are an important source of air pollution. Few studies have quantified personal exposure to silica among brick kiln workers, but the few that have suggest that exposures are high and may be similar or higher than in other occupations where silica dust is also a prevalent exposure. We identified knowledge gaps that can serve as research opportunities to better understand the relationship between brick kiln pollution and health among workers, family members living on site and nearby residents, and to evaluate the effectiveness of exposure mitigation strategies.

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CRediT authorship contribution statement

Laura Nicolaou: Writing – review & editing, Writing – original draft, Visualization, Supervision, Software, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Fiona Sylvies:** Writing – review & editing, Methodology, Data curation. **Isabel Veloso:** Writing – review & editing, Data curation. **Katherine Lord:** Writing – review & editing, Formal analysis, Data curation. **Ram K. Chandyo:** Writing – review & editing. **Arun K. Sharma:** Writing – review & editing. **Laxman P. Shrestha:** Writing – review & editing. **David L. Parker:** Writing – review & editing. **Steven M. Thygerson:** Writing – review & editing. **Peter F. DeCarlo:** Writing – review & editing. **Gurumurthy Ramachandran:** Writing – review & editing, Resources. **William Checkley:** Writing – review & editing, Writing – original draft, Supervision, Resources, Project administration, Methodology, Formal analysis, Conceptualization.

Declaration of competing interest

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.

Data availability

Data included in the Supplemental Material.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envres.2024.119220.

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