RESEARCH ARTICLE SUMMARY

SUSTAINABILITY

Reducing emissions and air pollution from informal brick kilns: Evidence from Bangladesh

Nina Brooks*, Debashish Biswas, Sameer Maithel, Grant Miller, Aprajit Mahajan, M. Rofi Uddin, Shoeb Ahmed, Moogdho Mahzab, Mahbubur Rahman, Stephen P. Luby

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INTRODUCTION: In many low- and middle-income countries, it is commonly believed that weak state and regulatory capacities limit the ability to reduce pollution and mitigate climate impact. In Bangladesh and across South Asia, most brick manufacturing takes place in informal, traditional coal-fired kilns. These kilns are among the largest sources of greenhouse gas emissions and air pollution, leading to an enormous public health burden.

RATIONALE: In Bangladesh, efforts to improve the brick kiln industry over the past 30 years have had limited success. Our past work suggests that a correctly operated zigzag kiln (a traditional kiln type that accounts for 81% of the sector) can not only improve efficiency but also increase kiln profits. However, most zigzag kilns in Bangladesh are incorrectly operated, leaving these social and private benefits unrealized. Improving energy efficiency presents an alternative strategy to reduce emissions and pollution while also delivering productivity gains.

RESULTS: We developed a low-cost intervention to improve the energy efficiency of zigzag kilns and conducted a randomized controlled trial (RCT) of the intervention among 276 kilns in Bangladesh. Our study included a control arm and two intervention arms (a "technical" arm and a "technical+incentive information" arm). All kilns assigned to both intervention arms received information, training, and technical support to adopt operational improvements that improve fuel combustion and reduce heat loss in the kilns. These improvements specifically targeted how coal is fed during the firing process and how bricks are stacked inside the kiln, along with several other aspects of operation. Kilns assigned to the "technical+incentive information" arm also received explicit information regarding the business rationale for incentivizing workers to adhere to the new practices.

There was high demand for the intervention, with 65% of intervention kilns adopting the intervention's recommended firing and stacking practices. Notably, 20% of control kilns also adopted these practices, bolstering the interpretation that demand was high. There were no differences in adoption between the two intervention arms and no use of incentives or benefits in the "technical+incentive information" arm.

We studied the intention-to-treat (ITT) effect of random assignment to the intervention, as well as the impact of the intervention after adjusting for compliance using an instrumental variables (IV) framework. Among compliers, the intervention led to substantial reductions in the amount of energy used to fire bricks (23%) and corresponding reductions in carbon dioxide (20%) and particulate matter with a diameter of <2.5 μm (20%). These gains were achieved without any evidence of a rebound in energy demand. Kiln owners also benefited financially from the intervention; production of the highest quality category of bricks increased in intervention kilns and spending on fuel per brick declined.

The primary costs of the RCT were the training costs and technical support costs throughout the season. Using a social cost of carbon of 185 USD per metric ton to value the reductions in CO_2 emissions, we find the benefits of the intervention outweighed the costs by a factor of 65 to 1, and that these reductions were achieved at an average cost of 2.85 USD per ton.

CONCLUSIONS: Our study demonstrates that meaningful reductions in emissions by traditional kilns are achievable, even in the absence of stronger regulations, if they can be made financially attractive to private kiln owners. □

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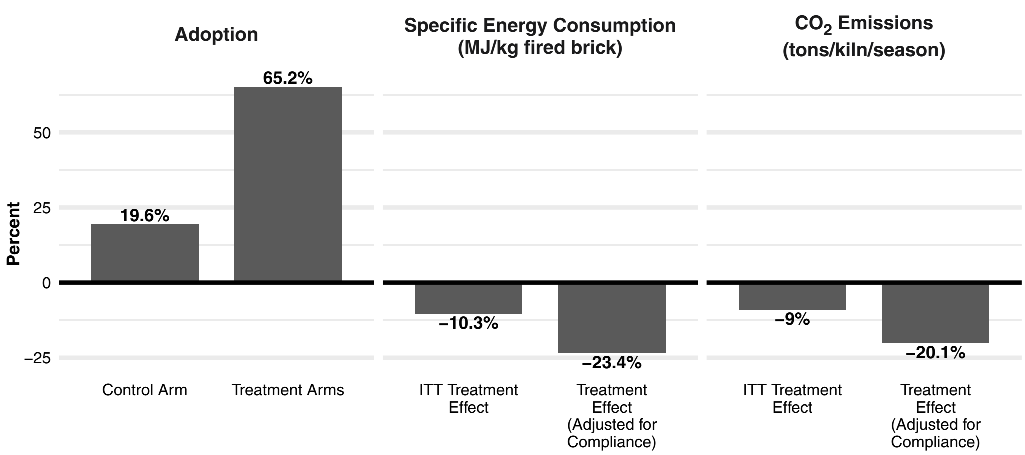

Adoption and impact of energy-efficient kiln operation practices. This figure shows the percent of study kilns that adopted the improved brick stacking and fuel feeding practices across control and intervention arms (left), and the corresponding effect of the intervention on energy consumption (middle) and CO_2 emissions (right). For energy consumption and CO_2 emissions, the ITT effect of random assignment to the intervention (left) and the effect of the intervention after adjusting for compliance (using an IV framework) (right) are estimated with regressions that control for randomization strata and are presented as the percent change relative to the control mean.

SUSTAINABILITY

Reducing emissions and air pollution from informal brick kilns: Evidence from Bangladesh

Nina Brooks[1]*, Debashish Biswas[2]†, Sameer Maithel[3], Grant Miller[4,5], Aprajit Mahajan[5,6,7,8], M. Rofi Uddin[2], Shoeb Ahmed[9], Moogdho Mahzab[10], Mahbubur Rahman[2], Stephen P. Luby[11]

We present results from a randomized controlled trial in Bangladesh that introduced operational practices to improve energy efficiency and reduce emissions in 276 "zigzag" brick kilns. Of all intervention kilns, 65% adopted the improved practices. Treatment assignment reduced energy use by 10.5% (P-value <0.001) and decreased CO_2 and $PM_{2.5}$ emissions by 171 and 0.45 metric tons, respectively, per kiln per year. Valuing the CO_2 reductions using a social cost of carbon of 185 USD per metric ton, we find that the social benefits outweigh costs by a factor of 65 to 1. The intervention, which required no new capital investment, also decreased fuel costs and increased brick quality. Our results demonstrate the potential for privately profitable, as well as publicly beneficial, improvements to address environmental problems in informal industries.

In many low- and middle-income countries (LMICs), limited state capacity restricts the potential of regulations to control pollution and mitigate climate impacts. Improving energy efficiency presents an alternative strategy to reduce emissions and pollution while also delivering productivity gains (*1*). The promise of energy efficiency is particularly important in LMICs, where energy demand is large and growing (*2*), air pollution is high (*3*), and energy efficiency is low (*1*). Most attention to energy efficiency in LMICs has focused on household technologies, such as efficient lights (*4*, *5*) and improved cookstoves (*6*–*11*), but both adoption of these technologies and energy savings have been low. Few studies have explored the potential of energy efficiency in industrial settings in LMICs (*12*–*14*).

In this paper, we study the potential benefits of improving energy efficiency in brick manufacturing in Bangladesh. In Bangladesh and across South Asia, most brick manufacturing takes place in informal, traditional coal-fired kilns (*15*–*17*). These kilns are among the largest sources of greenhouse gas emissions in South Asia (*15*, *18*, *19*), degrading local air quality (*19*–*23*), harming human health (*15*, *18*, *24*–*26*), and reducing agricultural productivity (*27*, *28*).

The Bangladeshi brick sector is an ideal setting in which to test the potential of energy efficiency improvements because, as in many informal industries, regulating pollution is difficult (*29*, *30*). In Bangladesh, regulatory efforts to improve the brick kiln industry over the past 30 years have been largely ineffective (*31*–*35*). Existing regulations specify where brick kilns can be established (kilns are banned near schools, city centers, health facilities, national forests, and other areas of interest), prohibit certain fuels (e.g., firewood), mandate kiln technologies (since 2010 all kilns must be "environmentally friendly", which includes hybrid Hoffman kilns, tunnel kilns, and zigzag kilns), set standards for particulate matter emissions, and require that kilns obtain official environmental clearance (*31*–*34*). There has been limited enforcement—for example, over 75% of brick kilns are illegally located within 1 km of a school (*35*) and only 40% of officially registered kilns have environmental clearance (*36*). Regulations are also often inadequate or inappropriate for the context. For example, past research has documented adverse health impacts beyond the distance cutoffs used for establishing regulations (*24*) and the government lacks the equipment, expertise, and methodology for measuring stack emissions of particulate matter (*33*). And, similar to other regulations, enforcement has also been undermined by corruption (*37*).

The other dominant approach to reducing the harm created by brick manufacturing has been to promote technologically advanced, capital-intensive kilns, which supposedly produce less pollution. These modern kilns are up to 25 times more expensive to construct and operate (*15*, *16*, *33*) and therefore adoption is particularly onerous for informal firms with limited access to formal credit and technical expertise (*38*). International development agencies such as the World Bank, Asian Development Bank, and United Nations Development Program, together with the Government of Bangladesh, have invested more than 150 million USD in demonstration projects since 2009 (*34*). Perhaps unsurprisingly, the diffusion of such modern kilns has been minimal despite substantial promotion efforts, and they currently represent <2% of all kilns in Bangladesh (*36*). Proponents were overly optimistic about their efficiency potential, and real-world energy performance was often not substantively better than that of traditional kilns (particularly for zigzag kilns) (*31*, *39*–*44*).

This background informed our strategy for designing an intervention to improve the environmental performance of Bangladeshi zigzag kilns, which are a type of traditional kiln in the informal sector functioning as the dominant technology in Bangladesh, representing 81% of registered brick kilns (*36*). Specifically, we designed an energy efficiency intervention that was incentive-compatible for existing zigzag kiln owners and that did not rely on state action. Several relatively modest modifications to the operational practices of zigzag kilns met these criteria. These practices reduce heat loss and improve combustion efficiency by altering how fuel is fed and how bricks are stacked (Fig. 1), as well as several other practices, and require no new capital investment; through these efficiency gains, the improved practices can reduce black carbon, CO_2, and $PM_{2.5}$ while also increasing kiln profitability by reducing fuel costs and increasing brick quality (*45*–*48*). However, most zigzag kilns in Bangladesh are incorrectly operated, leaving these social and private benefits unrealized (*15*, *31*, *33*, *34*, *42*).

Our pilot work suggested that kiln owners were unaware of proper operating practices and their profitability (*34*). Upon being informed of these practices, they were reluctant to introduce them, noting their lack of technical expertise to implement the improvements and their concern about the ability of their workers to adhere to the new practices. Collectively, these barriers appeared to prevent the proper operation of the kilns.

We therefore designed an intervention that provided zigzag kiln owners, managers, and workers with technical training and support to improve energy efficiency. We implemented the study as a randomized controlled trial (RCT) during the 2022 to 2023 brick firing season with a control group and two intervention groups. We assigned kilns to each of the three experimental arms using stratified randomization with strata defined by the district of operation and baseline class 1 brick production.

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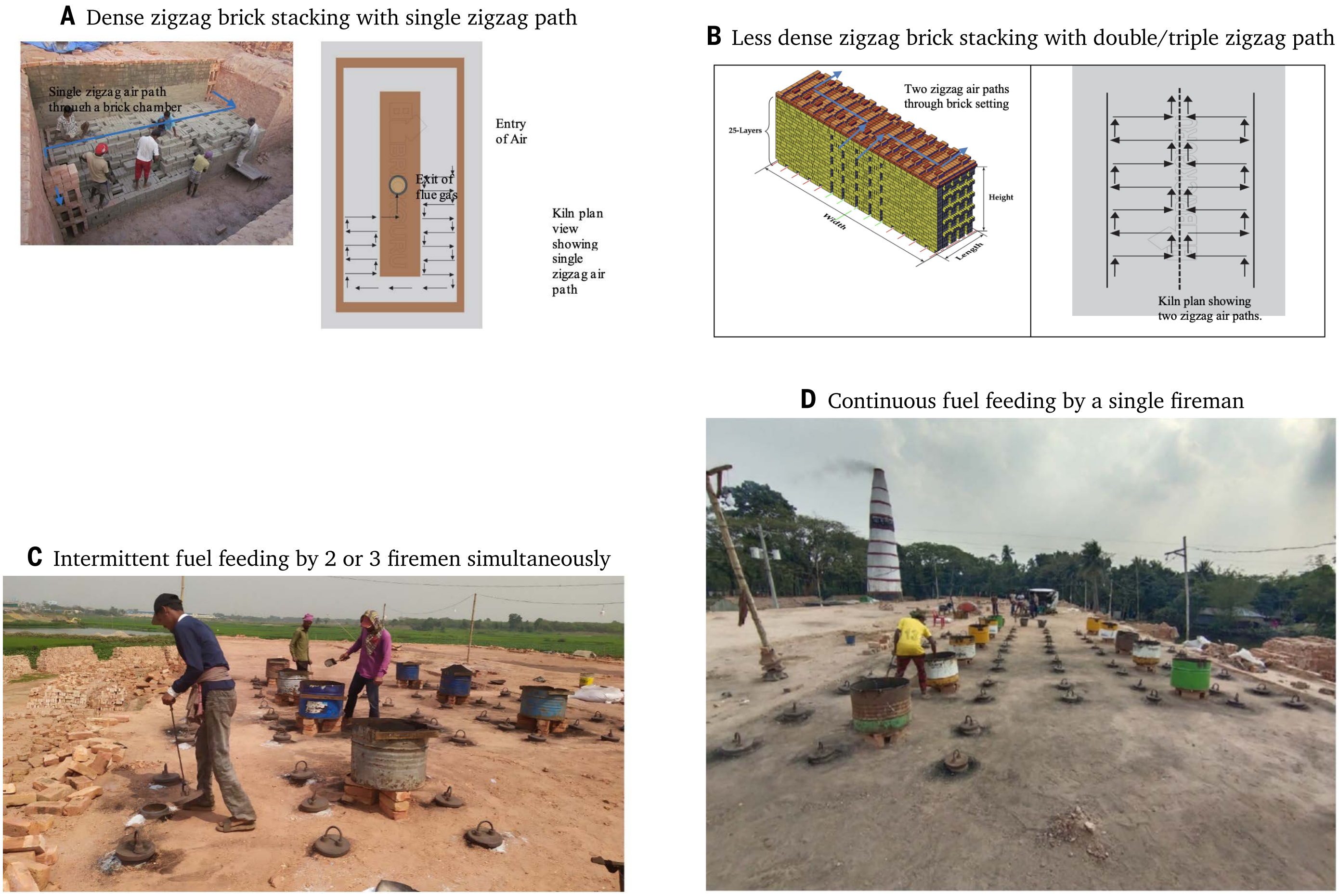

Fig. 1. Key intervention practices. This figure depicts the standard brick setting and fuel feeding practices and the changes proposed in the intervention. (**A**) The standard zigzag kiln brick setting practice in which brick columns are packed densely with a single zigzag airpath. (**B**) The intervention recommended practice of less dense brick setting with two or three zigzag air paths. (**C**) The standard fuel feeding practice of several firemen feeding simultaneously during intermittent feeding intervals. (**D**) The improved practice of individual firemen feeding fuel continuously in shifts so that there is no pause in feeding overall. More details on the intervention can be found in the full materials and methods in the SM.

The first intervention arm provided training and technical support (the "technical arm"). Kilns assigned to the technical arm received information, training, and technical support to adopt a suite of operational improvements. We focused on five operational improvements: (i) single fireman continuous fuel feeding, (ii) improved brick stacking, (iii) a thicker ash layer on kiln top, (iv) closing the kiln gate with a cavity wall, and (v) complementary use of powdered biomass fuel (Fig. 1; see the full materials and methods in the SM for detailed explanations of each practice). These practices improve fuel combustion and reduce heat loss in the kilns, which should improve efficiency and reduce emissions, as well as improve brick quality and reduce fuel expenditures.

In the initial pilot work (*34*) the first two interventions, which have a direct impact on fuel combustion, demonstrated the highest gain in fuel efficiency, and in the empirical analysis we define a kiln as having adopted the intervention if it implemented both of these practices. The training highlighted the financial benefits of the operational improvements and included participation from owners who had adopted them during our pilot study, which allowed the intervention team to directly address owner uncertainty about economic returns. In addition to training kiln owners, we trained their managers and workers involved in key tasks (brick stacking and firing). After training, project engineers provided ongoing technical support to intervention kilns throughout the firing season and were available to help troubleshoot any difficulties that arose.

In addition to the information, training, and support outlined above, kilns assigned to the "technical+incentive information" arm (or simply "technical+ arm") also received explicit information on the business case for incentivizing workers to adhere to the new practices. These messages were reinforced with examples of strategies to motivate workers, including the use of both financial incentives (e.g., bonuses, higher wages, return bonuses) and worker amenities (e.g., better working conditions, such as meals, housing, and clothing). See the full materials and methods in the SM for further details on both interventions.

First, we assessed adoption of the technical intervention, defined as following both (i) single fireman continuous fuel feeding and (ii) improved brick stacking. Then, we estimated the impact of the intervention on outcomes related to energy efficiency: specific energy consumption (a measure of the energy used to fire 1 kg of bricks); specific fuel consumption (the quantity of fuel used to fire 100,000 bricks); CO_2 emissions (calculated by applying IPCC conversion factors to specific energy consumption) (*49*); $PM_{2.5}$ emissions [calculated by applying $PM_{2.5}$ emissions factors (*50*) to specific energy consumption], and outcomes that captured the economic benefits of improved efficiency. Additionally, we estimated the percentage of the highest quality bricks (a higher percentage of class 1 bricks is both an indicator of more efficient operation and kiln owner benefits), spending on fuel, and the value of bricks produced during the season.

We estimated intention-to-treat (ITT) specifications by regressing each outcome on binary indicators for assignment to each intervention arm, as well as an ITT specification that bundles assignment to either intervention arm into a single indicator. To quantify treatment effects among compliers (e.g., the subpopulation of kilns that would adopt if assigned to the treatment arm but would not adopt if assigned to the control arm), we implemented instrumental variable (IV) specifications using a two-stage least squares regression, instrumenting adoption with the treatment assignment. Lastly, we conducted a back-of-the-envelope analysis that compared the cost of the intervention to the value of the CO_2 reductions to compare with other contexts. See the full materials and methods in the SM for more detailed explanations.

Results

Adoption of improved zigzag kiln operation practices

During the study season, 66.3% of kilns in the technical arm (59 of 89 kilns) and 64.2% of kilns in the technical+ arm (61 of 95 kilns) adopted the intervention (Fig. 2). Estimating the treatment effect on adoption after accounting for the stratified design finds increases in adoption of 45 percentage points (pp) for the technical arm and 44 pp for the technical+ arm relative to the control arm, ($P < 0.001$) (table S1).

Among the control kilns, 19.6% (18 of 92 kilns) adopted the intervention as well. All kiln owners in the study, including owners of control kilns, were aware of the intervention (which was explained as part of the consent process, prior to study enrollment and randomization) and some were disappointed not to receive it during the study year (all kiln owners were promised they could receive training the next season if they were assigned to the control arm). Of the 18 control kiln adopters, 8 sought to learn more about the technical intervention from other intervention kilns and to implement the production improvements on their own. The other 10 sought training from the intervention team (by attending trainings in their subdistrict or making direct requests to the intervention team). Although these 10 kiln owners obtained some of the formal training or support, it was not equivalent to the implementation received by intervention arm kilns (for example, fewer workers would have received the training relative to treatment kilns and they did not receive any technical support).

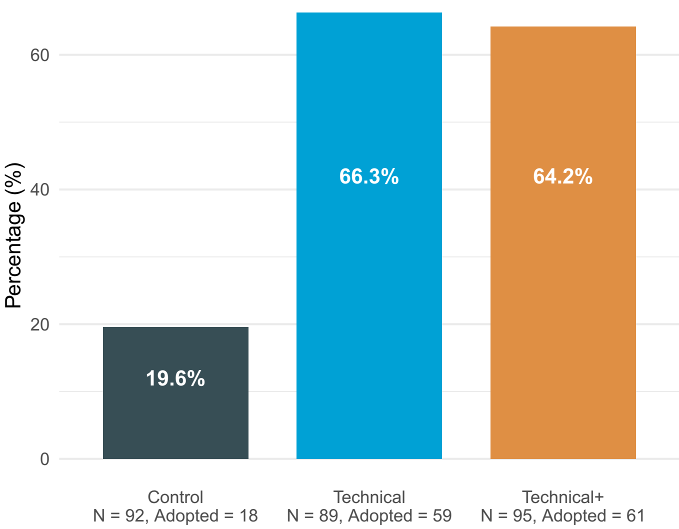

Fig. 2. Adoption by study arm. This figure presents the raw means of adopting double/triple zigzag brick stacking and single fireman continuous feeding by treatment arm.

At the endline, we also administered survey questions to control kiln owners who adopted the intervention, asking how they learned about the intervention. Among these 18 control kilns, the most common sources of information were the Bangladesh Brick Manufacturing Owners Association (or local chapter) (78%), another kiln owner (67%), or the intervention team (39%) (the responses were not mutually exclusive and owners could report learning about the intervention from multiple sources) (table S2). Overall, the control group adoption provided additional revealed preference evidence of the value of the intervention to kiln owners (we also note that it does not influence the suitability of the statistical frameworks that we use for inference). Moreover, it informs expectations about the likely reception of future intervention scale-up efforts.

We returned to the study kilns the following firing season (2023 to 2024) and found that adoption had increased by 7 to 11 pp in both treatment arms (up to 73.2% in the technical arm and 74.4% in the technical+ arm) (fig. S1). Perhaps most encouragingly, among the 18 control kilns that had adopted the intervention during the RCT, all continued to use the improved practices, and an additional 28 control kilns whose owners were trained after the completion of the RCT, also adopted in the subsequent season, bringing total adoption to 56.5% of control kilns (fig. S1). The sustained and increased adoption across two firing seasons provides strong evidence of kiln owners' high demand for and satisfaction with the technical intervention. In what follows, for sake of brevity we discuss the experimental results from the specifications that combine the two treatment arms (the arm-specific treatment effects and associated standard errors are also provided in tables S11 to S17).

Energy use and emissions

Treatment effects for specific energy consumption indicate that energy use was reduced by 0.11 MJ per kg of fired brick [95% confidence interval (CI): (0.07, 0.16), P-value < 0.001; Fig. 3A and table S11] in the treatment arms, equivalent to a 10.5% reduction relative to the control mean. The IV estimates suggest a 0.25 reduction in MJ/kg fired brick [95% CI: (0.15, 0.35), P-value < 0.001] or 23.5% relative to the control mean (table S11). These results are meaningful from an energy perspective; for instance, the IV estimate of the reduction in energy use (0.25) brings specific energy consumption in line with the lowest previously reported specific energy consumption values among brick kilns in South Asia for the most efficient coal-burning kilns (*33*). We also find assignment to the intervention reduced fuel use by 1.8 tons per 100,000 bricks [95% CI: (1, 2.6), P-value < 0.001], which represents an 11.5% decrease in fuel use relative to the control mean of 16.3 tons per 100,000 bricks (table S18).

Assignment to the intervention reduced CO_2 emissions by 171 tons per kiln over the season [9.0%, 95% CI: (53, 289), P-value < 0.001], and the IV estimates suggest even larger reductions among compliers of 382 tons [20.1%, 95% CI: (105,660), P-value < 0.001] (Fig. 3A and table S12). The intervention also reduced $PM_{2.5}$ emissions by 0.45 tons per kiln over the season [9.0%, 95% CI: (0.139, 0.763), P-value < 0.001] and the IV estimates are more than double the ITT estimates at 1 ton [20.1%, 95% CI: (0.28, 1.7), P-value < 0.001] (Fig. 3A and table S12). Suspended particulate matter (SPM) was measured in a small sample of kilns (8 adopters and 4 nonadopters, refer to the section on data collection in the full materials and methods in the SM) and shows lower values of SPM among adopting kilns; however, we caution overinterpretation of these data due to the small sample (fig. S3).

Both the ITT and IV results show small and statistically insignificant reductions in the mean CO/CO_2 ratio (table S23), a measure of combustion efficiency (*51*) that was preregistered. Compared with our pilot, the measurements collected were noisy (and not all were physically plausible given the expected ranges of O_2, CO_2, and CO).

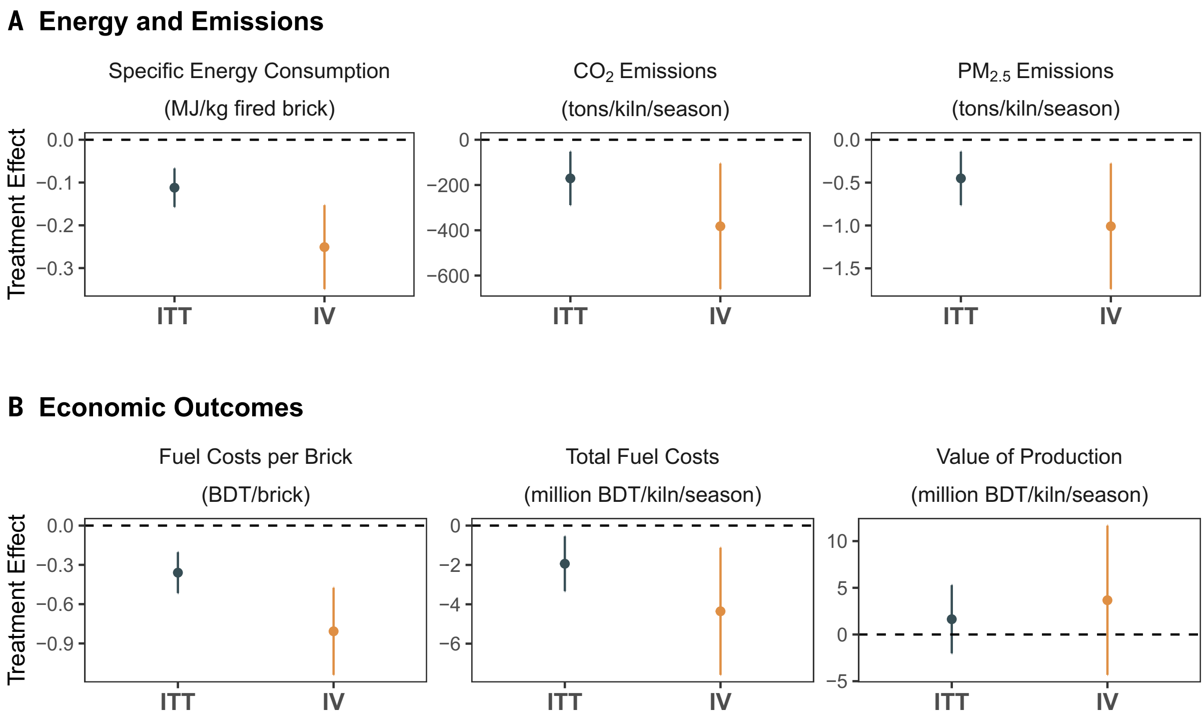

Fig. 3. Intervention impact on energy, emissions, and economic outcomes. (**A**) The intervention's impact on outcomes related to energy use and emissions. (**B**) The findings for economic outcomes for kiln owners. Both panels show regression results for ITT and IV specifications for a different outcome. The ITT specification, shown on the left in dark gray, bundles both treatment arms. The IV specification, shown on the right in orange, uses random assignment to either treatment arm as an instrument for adopting the technical intervention and can be interpreted as the effect of adopting the intervention on a given outcome. Both specifications include randomization strata–fixed effects and estimated heteroskedasticity-robust standard errors. In each panel, coefficients are denoted by dots and vertical bars represent 95% CI around the regression coefficient.

The increased sample size posed unanticipated additional difficulties with flue gas measurement because it necessitated more servicing and replacement filters, which ultimately increased measurement variability [we describe the measurement protocol in detail in the full materials and methods in the supplementary materials (SM)]. For example, the industrial flue gas analyzers we used were manufactured in Europe and designed to measure flue gas in modern industries, which have lower dust and moisture loads. Because of the excessive dust and moisture in the flue gases of the brick kilns, frequent replacement of the filters was necessary, and data was more variable. In the SM, we present results from sensitivity tests of the CO/CO_2 that include specifications that drop kilns with implausible values and explore alternative outcomes based on the CO/CO_2 (which were not prespecified; tables S40 to S54. These results provide suggestive evidence that the intervention significantly reduced the variance (tables S41, S45, S46, S49, S53, and S54) of the CO/CO_2 ratio, which is indicative of improved combustion efficiency. Ultimately, this analysis suggests that the mean values alone may not capture combustion efficiency in the CO/CO_2 measure and highlights the need for better approaches for measuring combustion performance and particulate matter emissions from kilns.

Kiln owner economic benefits

Fuel is a kiln owner's most expensive input. A key hypothesis was that the intervention's efficiency gains would reduce fuel use, and therefore spending, per unit of output. Assignment to the intervention reduced spending by 0.36 Bangladeshi taka (BDT) [USD 0.0031; 95% CI: (0.20, 0.52), P-value < 0.001] per brick on fuel; the IV estimate suggests a reduction of 0.81 BDT [USD 0.0069; 95% CI: (0.63, 0.98), P-value < 0.001] per brick (Fig. 3B and table S14). These magnitudes are large and imply 9.6 and 21.6% reductions in fuel costs/brick for the ITT and IV results, respectively, relative to the control mean. Applying the per brick estimates to each kiln's total brick production for the season finds that fuel costs were reduced by 1.94 million BDT [16,569 USD; 95% CI: (0.54, 3.3), P-value < 0.001] or by 4.35 million BDT among compliers [37,153 USD; 95% CI: (1.1,7.6), P-value < 0.001, Fig. 3B and table S15].

Brick kilns produce bricks of varying quality which are sold at correspondingly varying prices. The highest quality are class 1 bricks, which owners reported selling for 11 BDT per brick (0.09 USD) on average, and the lowest quality are sold as broken bricks (65 BDT per cubic foot or 0.55 USD). Assignment to the intervention increased the percentage of class 1 bricks produced by 6.3 pp [95% CI: (4.6, 8.0), P-value < 0.001], an 8.1% increase, while also reducing the percentage of inferior bricks (classes 2 and 3, see Fig. 4). The IV estimates suggest a 14.2 pp [95% CI: (11.0, 17.3), P-value < 0.001] increase or 18.2% (Fig. 3 and table S16) among compliers. We see similar, though smaller, effect sizes [ITT: 4.9 pp (95% CI: (3.0, 6.9)); IV: 11.1 pp (95% CI: (7.4, 14.8))] when using kiln owner self-reported average brick quality over the entire season, reported at the endline (fig. S3 and table S30). During qualitative interviews kiln owners that adopted the intervention reported being very satisfied with the proportion of class 1 bricks, consistent with these experimental results.

Because kiln owners can time brick sales with stock from multiple production seasons, we do not have direct measures of revenues from each kiln and the endogeneity of sales timing would make such measures hard to interpret, even if available. Instead, we estimate the total value of production from the current firing season by multiplying the median reported brick prices for each class of brick by the quantity of each class of brick (reported at the endline) and summing across the

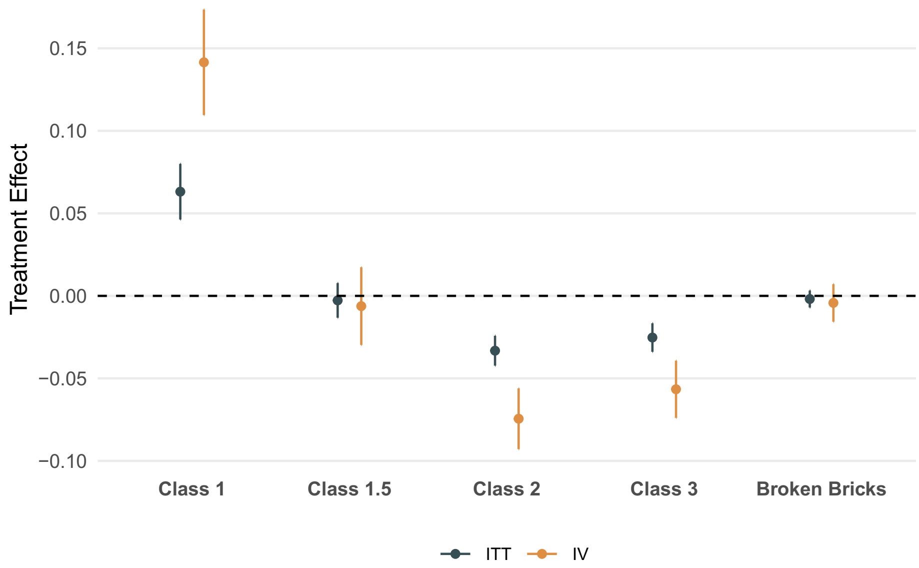

Fig. 4. Intervention impact on distribution of brick quality. This figure presents regression results for the ITT and IV specifications for each classification of brick quality as a percentage of total production. The ITT specification, shown on the left in dark gray, bundles both treatment arms. The IV specification, shown on the right in orange, uses random assignment to either treatment arm as an instrument for adopting the technical intervention. Both specifications include randomization strata fixed effects and estimated heteroskedasticity-robust standard errors. In each panel, coefficients are denoted by dots and vertical bars represent 95% CI around the regression coefficient.

various classes, using the kiln owner's self-reported data on the entire season's production.

We saw positive but noisy effects of the intervention on total value of production over the firing season (both ITT and IV specifications; Fig. 3B and table S17). Although the intervention resulted in a larger fraction of class 1 bricks (Fig. 4), there was no difference in total brick production over the season (Fig. 3B) and differences in prices are not large (e.g., the median reported price for class 1 and class 2 bricks was 11 and 9 BDT, respectively); consequently, we may be underpowered to detect significant differences in the value of production. We also calculated total value of brick production by applying the objective brick quality data measured during the kiln performance assessment to the annual production reported at endline, but because the effect sizes for the objective and self-reported brick quality were similar, the total value of production is also similar (see table S26). We prespecified a "normalized" version in which we divided the value of production by the total quantity of bricks (see the full materials and methods section on Outcome Measurement in the SM for more details). This normalized measure ends up being driven entirely by differences in brick quality and thus we report the effect on brick quality in Fig. 4 and the value of production per brick in the SM (table S27 with monitoring data and S28 using kiln owner self-reports at endline).

Kiln owner costs

Although the intervention did not require any capital investment from kiln owners, the technical intervention recommended using sawdust during brick firing and it is possible that other costs could have changed as a result of the intervention. We explored whether other input costs changed because of the intervention (tables S33 to S39) and found that spending on sawdust was lower due to the intervention while all other costs were unchanged. The reduction in sawdust costs is surprising as the intervention recommended using more, rather than less, sawdust. Reports from the intervention team suggest that because of sawdust supply constraints, owners that had adopted the improved firing and stacking practices and were happy with their operation opted not to incorporate sawdust. We note that these outcomes were not prespecified.

Rebound effects

By effectively reducing the price of energy, energy efficiency interventions can potentially increase total energy use if overall production increases (1, 12, 52). We find a small and statistically insignificant effect of the intervention on total annual brick production (table S24), which suggests there was not a rebound effect on brick production in our setting. We explore potential rebound effects through another channel—total number of firing circuits completed (brick production is completed in batches called "circuits," and a single circuit reflects the bricks fired in a single circle around the kiln)—in the SM and, consistent with the null effect on total annual production, we do not see any difference due to the intervention (table S25). We note that both these outcomes were not prespecified.

Work conditions

Because the operational changes promoted by the intervention substantively changed workers' tasks, the technical+ intervention encouraged kiln owners to use incentives of their choosing to motivate workers to enhance adoption of the improved technical practices. Although we provided examples of incentives, we did not emphasize a one-size-fits-all approach and left owners and their managers to determine the best approach for their kilns. Arm-specific ITT specifications suggest that the intervention had no effect on explicit incentives that kiln owners report providing to workers (Fig. 5).

Costs and benefits of CO_2 reductions

The primary cost for the RCT was the training expense and technical support throughout the season. These included venue costs, staff costs for engineers, materials (e.g., handouts, pens), travel and food costs for participants, "train the trainers" sessions in which the technical lead trained the project engineers, and staff time to provide ongoing technical support throughout the season (including travel to and from kiln sites from support visits). Training was provided at the district level (i.e., to all treatment kilns in the same district) and the total cost was approximately 89,374 USD or about 486 USD (89,374/184) per treatment kiln.

Assuming a social cost of carbon (SCC) of 185 USD per MT (53), our intention-to-treat results suggest a single year valuation of the reduced carbon emissions of 31,580 USD per kiln (Table 1A). This compares favorably with the cost of delivering the intervention (486 USD per kiln), implying a benefit-cost ratio (BCR) of 65 (31,580/486). To contextualize these benefits, a payment-for-ecosystem services scheme in Uganda that sequestered CO_2 attained a BCR of 2.4 (or 14.8 in the most optimistic scenario), an improved cookstove intervention in Rwanda achieved a BCR of 5.6 (54), and modeled scenarios of improved cookstove/clean fuel programs globally had estimated BCRs ranging from negative to 27 (55). Alternatively, we can compare the cost per ton of CO_2 reduced, 2.85 USD (486/171), to other mitigation strategies (56), for example reforestation (1.2 to 11.9 USD), the US Clean Power Plan (13.1 USD), fuel economy standards for vehicles (CAFE standards, 57.3 to 370 USD), or weatherization assistance programs (418 USD) (Table 1B).

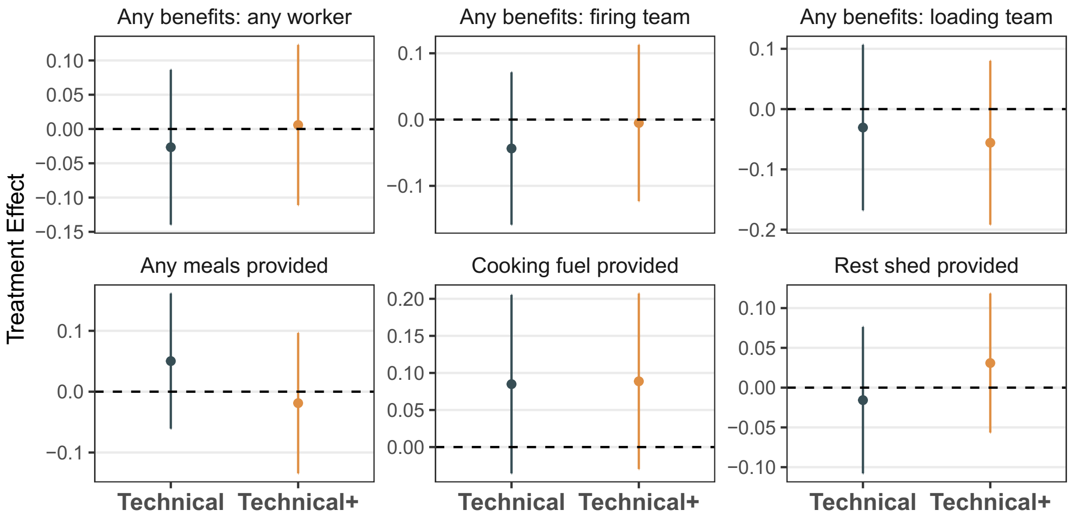

Fig. 5. Intervention impact on working conditions and benefits. This figure presents regression results for the ITT specifications for outcomes related to improved working conditions and provision of benefits to workers. In each panel, the coefficients for the technical arm are shown on the left in dark gray and the coefficients for the technical+ arm are shown on the right in orange. The specification includes randomization strata fixed effects and estimated heteroskedasticity-robust standard errors. In each panel, coefficients are denoted by dots and vertical bars represent 95% CI around the regression coefficient.

The ITT estimate of total season CO_2 emissions reduced makes the strong assumption that the specific energy consumption measured during monitoring was constant throughout the season. However, if we instead use the lower bound of the 95% CI around the ITT estimate (52.5 MT, table S11) to value the CO_2 emissions reduction and calculate the benefit-cost ratio, the intervention is still extremely beneficial from a societal perspective and achieves a BCR of 20 and a cost per ton of CO_2 reduced of 9.25 USD (Table 1A). Alternatively, the BCR and cost per ton of CO_2 reduced implied by the IV estimate for compliers are even larger: 146 and 1.27 USD, respectively.

Given that we have not accounted for the health cobenefits of reduced $PM_{2.5}$ emissions [the SCC accounts for the economic impact of climate change from human mortality related to heat, agricultural productivity, energy expenditures for heating and cooling buildings, and the coastal impacts of rising sea levels (*53*, *57*)], the BCR calculation for the base scenario presumably underestimates the total social benefits substantially. For example, a cost-benefit analysis of potential pollution control measures for informal brick kilns in Mexico found that when accounting for health cobenefits of reduced pollution, net benefits vastly exceeded costs (*58*). It is important to note that our BCR and cost per ton of CO_2 reduced are both based on a single firing season and single-year adherence to the new practices. We saw that adoption was not only sustained but actually increased in the subsequent season, which suggests these figures underestimate the cost effectiveness as multiple years of adoption are attainable with the single year delivery of the intervention. Lastly, these calculations, which are from the societal perspective, also do not include the private benefits to kiln owners from adopting (through cost savings on fuel and production of more high-quality bricks).

Conclusions

The urgent global need to reduce greenhouse gas emissions to mitigate climate change has put a spotlight on the potential for energy efficiency interventions to not only reduce emissions but also achieve health cobenefits from reduced air pollution. We designed an intervention to improve informal brick kiln operations in Bangladesh. The intervention aimed to reduce emissions and air pollution while also reducing fuel costs and increasing revenue for owners by introducing a set of operational practices to improve kiln efficiency.

In contrast to past efforts that promoted technologically advanced kilns in Bangladesh (*31*, *34*), demand for this intervention was very high, with 65% of treatment kilns adopting the key improved practices (and control group kilns requesting the intervention as well—a potentially promising sign for scaling efforts). Furthermore, the sustained and increased adoption in all study arms in the post intervention period provides even stronger evidence that kiln owners valued the intervention. This high demand also differs from the experience of promoting energy efficiency interventions to households in LMICs (e.g., improved cookstoves) (*11*, *59*), who often have low demand for them. A key difference between our intervention and many household energy efficiency interventions is that the intervention achieved short-term and substantive economic benefits for kiln owners in the form of cost savings on fuel and increased production of the highest quality bricks (which can be sold at higher prices and hence may be more profitable). As other energy efficiency programs such as weatherization in the USA have failed to live up to promises of both efficiency gains and private economic benefits, a lesson from our intervention is that tangible private economic benefits support uptake.

Evidence on the realized energy savings from energy efficiency interventions is mixed (*1*). The efficiency improvements that we promoted achieved large reductions in energy use, which we captured with high quality and detailed assessments collected from each kiln during 30-hour kiln performance monitoring assessments. Importantly, these reductions were achieved without evidence of contemporaneous rebound effects, a common concern in the energy efficiency literature (*35*–*42*). Although it is difficult to compare the energy performance of different types of kilns, the magnitude of the reductions in energy use we found for compliers are on par with what technologically advanced kilns can in principle realize—yet were achieved without any capital investment or large-scale institutional financing (*2*, *25*).

The intervention yielded considerable social benefits as well, reducing both CO_2 and $PM_{2.5}$. To approximate the potential impact if this intervention were scaled up nationally in Bangladesh, we conducted a back-of-the-envelope calculation. Optimistically, if all 6352 zigzag kilns (*36*) in Bangladesh adopted these efficiency improvements, the reductions among compliers (382 MT) imply that CO_2 would be reduced by 2.4 million MT over a single brick firing season

Table 1. Costs and Benefits of CO_2 Reductions. (**A**) Results of a back-of-the-envelope benefit-cost analysis of the CO_2 reductions from the intervention for three different scenarios. The benefits are calculated by multiplying a given estimate of tons of CO_2 reduction per kiln by the SCC (185 USD per ton) (*53*). The BCR is calculated by dividing the benefits per kiln by the per kiln cost of delivering the intervention (485.73 USD). We also report the cost per ton of CO_2, which is calculated as the per kiln cost divided by the per kiln CO_2 reduction for each scenario. We present results for three scenarios: (i) a base scenario that uses the intention-to-treat estimate of CO_2 reductions; (ii) a conservative scenario that uses the lower bound of the 95% CI from the ITT estimate of CO_2 reductions; and (iii) an optimistic scenario that uses the instrumental variables estimate of CO_2 reductions among compliers. (**B**) Inflation adjusted costs per ton of CO_2 for a subset of existing mitigation strategies reported in Gillingham and Stock (*56*) for comparison. All dollar amounts are reported in 2022 USD amounts.

(A) Costs and benefits of the kiln efficiency intervention

Scenario	Estimate	Benefit per kiln (USD)	BCR	Cost per ton CO_2 (USD)
Base: ITT effect	170.7	31,579.5	65	2.85
Conservative: ITT lower bound	52.5	9,712.5	20	9.25
Optimistic: IV effect	382.3	70,725.5	146	1.27

(B) Costs of other CO_2 mitigation strategies

Policy	(2.022 USD per ton CO_2) - lower bound	(2022 USD per ton CO_2) - upper bound
Reforestation	1.19	11.94
Wind energy subsidies	2.39	310.49
Clean power plan	13.14	
Gasoline tax	21.50	56.13
Methane flaring regulation	23.88	
Reducing federal coal leasing	39.41	81.21
CAFE standards	57.32	370.20
Renewable fuel subsidies	119.42	
Solar photovoltaics subsidies	167.19	2507.83
Energy efficiency programs (China)	298.55	358.26
Cash for clunkers	322.44	501.57
Weatherization assistance program	417.97	764.29

(6352 kilns × 382 tons = 2,426,464 tons)—a 2% reduction in Bangladesh's annual CO_2 emissions (although a more conservative scenario that uses the 171 tons per kiln per season ITT estimate suggests a reduction of approximately 1% of total CO_2 emissions) (*60*). To contextualize these CO_2 reductions, we used the EPA's CO_2 equivalence calculator which estimates that this is equivalent to the amount of CO_2 emitted from the energy used to power 316,434 homes in the United States for 1 year or the CO_2 sequestered by planting over 40 million tree seedlings and allowing them to grow for 10 years (*61*).

We observed no significant differences in adoption or efficiency between the two treatment arms, despite both the information provided to owners in the technical+ arm regarding the profit rationale for offering incentives and the repeated nudges throughout the season. Importantly, however, we also found no evidence that the intervention worsened conditions for this vulnerable and often exploited workforce. Other studies, in which researchers directly provided monetary incentives to workers to adopt an improved operational practice, found large and statistically significant effects of the bonus payments (*62*). Qualitative interviews we conducted with kiln owners revealed that owners remained concerned about workers' interest in and ability to adopt the new practices, which suggests that more research is needed to identify incentive-compatible strategies for improving work conditions. These outcomes, as well as indicators of labor trafficking and child labor, are explored in detail in a companion paper (*63*).

Our findings add to the literature on innovative approaches for reducing emissions and pollution in LMICs and more specifically demonstrate conditions under which an energy efficiency intervention can successfully achieve efficiency gains, without rebound effects, as well as private economic benefits (*1*, *12*–*14*, *29*, *30*, *64*–*69*). We also contribute to a growing body of literature on the productivity and management capacity of firms in LMICs, particularly among informal firms (*14*, *70*–*74*). Past research has found that better-managed firms in the UK were less energy intensive (*73*), but few firm-level interventions in LMICs have been effective (*70*). Our study demonstrates that focused training and technical support provided to both management and labor can effectively reduce energy use and emissions, representing an important opportunity for improving energy efficiency of informal enterprises.

Our approach is promising for scaling both within Bangladesh and possibly across South Asia, where brick production is similar, though some modifications to account for local variation in kiln design and practices may be necessary. Future work could identify whether and how learning from other kiln owners—and, in particular, learning from influential peers such as owners' association leadership—is an effective strategy to scale the intervention. Our study also provides lessons for implementing energy efficiency interventions in other polluting industries, particularly in contexts with weak regulatory enforcement—environments in which aligning private incentives with public policy goals may be necessary (sugar mills, rice mills, and metal foundries in South Asia share many of these characteristics and may be particularly promising). Overall, our results demonstrate that substantial reductions in emissions and air pollution by informal sector kilns are achievable and can be attractive to kiln owners as well.

Materials and methods summary

Experimental design

During the 2022 to 2023 brick firing season (informal kilns operate seasonally in much of South Asia; in Bangladesh the brick firing season is during the dry months of November to May, coinciding with the off-season for agriculture), we conducted an RCT with three experimental arms: (i) a technical arm, (ii) a technical+incentive information arm ("technical+" arm), and (iii) a control arm. We assigned kilns to each of the three experimental arms using stratified randomization with strata defined by the district of operation and baseline class 1 brick production.

Kilns assigned to the technical arm received information, training, and technical support to adopt a suite of operational improvements. We focused on five operational improvements: (i) single fireman continuous fuel feeding, (ii) improved brick stacking, (iii) thicker ash layers on kiln tops, (iv) closing the kiln gate with a cavity wall, and (v) complementary use of powdered biomass fuel. These practices improve fuel combustion and reduce heat loss in the kilns, which should improve efficiency and reduce emissions, as well as improve brick quality and reduce fuel expenditures. In the initial pilot work (*34*), the first two interventions demonstrated the highest gain in fuel efficiency, and in the empirical analysis we define a kiln as having adopted the intervention if it implemented at least these two practices. The training highlighted the financial benefits of the operational improvements and included participation from owners who had adopted them during our pilot study, which allowed the intervention team to directly address owner uncertainty about economic returns.

In addition to the information, training and support outlined above, kilns assigned to the technical+ arm also received explicit information about the importance of incentivizing workers to adhere to the new practices. These messages were reinforced with examples of strategies to motivate workers, including the use of both financial incentives (e.g., bonuses, higher wages, return bonuses) and worker amenities (e.g., better working conditions, such as meals, housing, and clothing). See the full materials and methods in the SM for further details on the interventions.

Sampling

Our initial sample randomized 357 zigzag kilns operating across six districts in Khulna Division in Bangladesh (Jahsore, Khulna, Jhenaidah, Chuadanga, Kushtia, and Narail). Baseline data collection revealed that 294 kilns met the criteria to receive the technical intervention (owners planned to operate during the upcoming season and would be using coal) and a further 18 kilns later dropped out of the sample because they were shut down by the government (n = 9), closed down early (n = 6), or refused to participate (n = 3). Due to high coal prices in 2022 to 2023, some kiln owners in our sample chose not to operate their kiln or reverted to (illegal) exclusive use of firewood. In table S9, we show that eligibility is uncorrelated with treatment assignment. Further, due to Ramadan (March 22, 2023 to April 21, 2023) falling toward the end of the firing season in 2023, some kiln owners stopped operating earlier than usual. Also, during the 2022 to 2023 firing season some kilns were demolished by the government before outcome data could be collected. As a result, kiln performance monitoring to collect outcomes data was completed in 276 kilns, which forms the final sample for the analysis. The analytic sample of 276 kilns (as well as the initial sample of 357 kilns and the subsequent sample of 294 eligible kilns) is balanced on a set of baseline kiln and kiln owner characteristics (tables S3 to S8). Ineligibility for the intervention and attrition are uncorrelated with treatment (table S9). More kilns in the technical arm were not operated during the 2022 to 2023 firing season (row 2 of table S9), but overall eligibility for the intervention was not significantly different by treatment arm. Moreover, kiln owners were not informed of their treatment assignment prior to making decisions about whether to operate, therefore we assume this difference is not due to knowledge of treatment assignment.

Data collection

Field workers collected baseline data on kiln owner demographics, the location of the kiln, and retrospective information on the previous brick firing season. Adoption of the technical intervention was assessed through an adoption checklist fielded in January to February 2023 and again between March and May 2023, during the kiln performance assessment.

Outcome data were collected during a kiln performance monitoring which was conducted by teams of engineers and took approximately 30 hours per kiln. The assessment included counting and classifying the quality of fired bricks, weighing the quantity of coal consumed during a 24-hour period, weighing a sample of fired bricks, collecting coal samples for measurement of calorific value, and measuring emissions in the flue gas. The full Materials and Methods in the SM describes the monitoring protocol in detail. After firing was completed for the season, we fielded an endline survey, which collected self-reported information from owners.

Measurement

Our outcomes are adoption of the technical intervention; specific energy consumption (a measure of the energy used to fire 1 kg of bricks); the percentage of bricks fired of the highest quality (a higher percentage of class 1 bricks is both an indicator of more efficient combustion and kiln owner benefits); CO_2 emissions (calculated by applying Intergovernmental Panel on Climate Change (IPCC) conversion factors to specific energy consumption) (*49*); $PM_{2.5}$ emissions [calculated by applying $PM_{2.5}$ emissions factors (*50*) to specific energy consumption]; kiln owners' spending on fuel; the economic value of brick production (e.g., quantity of each type of brick produced multiplied by their price); measures of working conditions and the use of incentives and amenities for workers; specific fuel consumption (the quantity of coal used to fire 100,000 bricks); and the ratio of CO/CO_2 (which captures the completeness of combustion) (*51*). These outcomes are based on detailed and objective data collected during the kiln performance monitoring (for more details, see materials and methods in the SM).

Because CO_2 and $PM_{2.5}$ emissions are estimated using the specific energy consumption measured during the kiln performance monitoring, the total season calculations assume the kilns operated with this constant energy use over the entire season. Because energy use varies over a firing season, this may be an unrealistic assumption and we test the sensitivity of the cost-benefit calculation to less efficient levels of energy use. We note that $PM_{2.5}$ emissions were not preregistered as an outcome, but are calculated using specific energy consumption, which was preregistered. In cases in which outcomes can be constructed using both the kiln performance assessment data and endline data, we report endline equivalents in the SM.

Estimation

We estimate ITT specifications by regressing each outcome on binary indicators for assignment to each intervention arm, as well as an ITT specification that bundles assignment to either intervention arm into a single indicator. Specifically, our primary specification is of the form $\gamma_i = \beta_0 + \beta_1 T_i + \beta_2 I_i + \delta_s + \epsilon_i$, where T_i is a binary indicator equal to 1 if kiln i is in the technical treatment arm and I_i is a binary indicator equal to 1 if kiln i is in the technical+ arm; δ_s are strata fixed effects. In addition, we also estimate ITT regressions of the form $\gamma_i = \tau_0 + \tau S_i + \delta_s + \nu_i$, where S_i is a binary indicator equal to 1 if kiln i was in either treatment arm and zero otherwise. To quantify treatment effects among compliers, we also implement IV specifications of the form $\gamma_i = \gamma_0 + \gamma_1 A_i + \delta_s + u_i$, where A_i is a binary indicator equal to 1 if kiln i adopts the two key operational practices—improved brick stacking and single fireman continuous fuel feeding. We estimate this model using a two-stage least squares regression, instrumenting the adoption (A_i) with the treatment status.

In settings with one-sided noncompliance (specifically, when the population comprises only "compliers" and "never-takers" in the language of Imbens and Angrist) (*75*), the Treatment-on-the-Treated (ToT) parameter is equal to the average treatment effect among compliers [sometimes referred to as the local average treatment effect (LATE)]. In the presence of always- takers—particularly relevant in our case as 20% of control kilns adopted the intervention and can reasonably be thought of as always-takers—this equivalence no longer holds and the ToT parameter is not identified, whereas the LATE continues to be identified and is consistently estimable using IV. For this reason, we refer to our estimand as the IV effect (or equivalently the LATE or the average treatment effect among compliers).

To provide context for interpreting the magnitudes of the regression coefficients, we also present the results as a percentage change relative to the control mean for both the ITT and IV specifications. For the IV, the control mean does not account for the noncompliance (e.g., adoption by control kilns) and may represent an underestimate in terms of the percentage change. However, when we use the Imbens and Rubin (*76*) method to recover $E(Y_0|C)$ the results are similar.

Our analysis was preregistered with the American Economic Association and International Standard Randomized Controlled Trial Number. Any specifications that deviate from this plan are indicated in the main text (for more details see the full Materials and Methods in the SM).

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SUPPLEMENTARY MATERIALS

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Materials and Methods; Figs. S1 to S15; Tables S1 to S60; References (*78*–*85*); MDAR Reproducibility Checklist

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