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Reducing Emissions and Air Pollution from the Informal Sector: Evidence from Bangladesh
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ABSTRACT

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. 65% of intervention kilns 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 metric tons and 0.45 metric tons, respectively, per kiln per year. Valuing the CO_2 reductions using a social cost of carbon of $185/MT, 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.

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A randomized controlled trials registry entry is available at
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Introduction

In many low- and middle-income countries (LMIC), limited state capacity limits 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 LMIC, where energy demand is large and growing (*2*), air pollution is high (*3*), and energy efficiency is low (*1*). However, most attention to energy efficiency in LMIC has focused on household adoption of energy efficient technologies, such as efficient lights (*4*, *5*) or improved cookstoves (*6*–*11*), where typically both adoption and energy savings have been low. Few studies have explored the potential of energy efficiency in industrial settings in LMIC (*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 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, like 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 largely been 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 health beyond the distance cutoffs used for siting regulations (*24*) and the government lacks 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 harms of brick manufacturing has been to promote technologically advanced capital-intensive kilns, which are supposedly less polluting. These modern kilns are up to 25 times more expensive to construct and operate (*15*, *16*, *33*)—and therefore particularly onerous for informal firms with limited access to formal credit and technical expertise to adopt (*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 over $150 million in demonstration projects since 2009 (*34*). Perhaps unsurprisingly, the diffusion of such modern kilns has been minimal despite the substantial promotion efforts and they currently represent fewer than 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 that of zigzag kilns) (*31*, *39*–*44*).

This background informed our strategy for designing an intervention to improve the environmental performance of Bangladeshi zigzag kilns, a type of traditional kiln in the informal sector, which is the dominant technology in Bangladesh and represents 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 informal 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) 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 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 2022–2023 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.

The first intervention 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: (a) single fireman continuous fuel feeding, (b) improved brick stacking, (c) a thicker ash layer on kiln top, (d) closing the kiln gate with a cavity wall, and (e) complementary use of powdered biomass fuel (Fig. 1; see Materials and Methods 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 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 adopted 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.

[Fig. 1 HERE]

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, clothing). See the Materials and Methods for further details on both interventions.

First, we assessed adoption of the technical intervention, defined as following both (a) single fireman continuous fuel feeding and (b) 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: and the percentage of bricks fired of the highest quality (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 sub-population 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 to other contexts. See the Materials and Methods 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 44pp for the technical+ arm relative to the control arm, ($p<0.001$) (Table S1).

[Fig. 2 HERE]

19.6% of control kilns (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, eight 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 sub-district 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 ongoing technical support).

At 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 provides 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 study kilns the following firing season (2023-2024) and found that adoption had increased by 7 to 11 percentage points 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, who 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 - S17).

Energy use and emissions
Treatment effects for specific energy consumption indicate that energy use was reduced by 0.11 MJ/kg fired brick (95% 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 0.25 reduction in energy use 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/l00,000 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/l00,000 bricks (Table S18).

[Fig. 3 HERE]

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 non-adopters, refer to the section on Data Collection in the Materials and Methods) and shows lower values of SPM among adopting kilns; however, we caution over-interpretation 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 pre-registered. 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). 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 Materials and Methods). For example, the industrial flue gas analyzers we used were manufactured in Europe and designed to measure flue gas in modern industries, in which flue gas has lower dust and moisture loads. Because of the excessive dust and moisture in the brick kilns' flue gases, frequent replacement of the filters was necessary, and data was more variable. In the Supplementary Materials, 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 – S54. These results provide suggestive evidence that the intervention significantly reduced the variance (Tables S41, S45, S46, S49, S53, 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 kiln owners' 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 Bangladeshi Taka (BDT) 0.36 (USD 0.0031; 95% CI: [0.20,0.52], p-value<0.001) per brick on fuel; the IV estimate suggests a reduction of BDT 0.81 (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 BDT 1.94 million (USD 16,569; 95% CI: [0.54,3.3], p-value<0.001) or by BDT 4.35 million among compliers (USD 37,153; 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 BDT 11/brick (USD 0.09) on average, and the lowest quality are sold as broken bricks (BDT 65 per cubic foot or USD 0.55). Assignment to the intervention increased the percentage of Class 1 bricks produced by 6.3 percentage points (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 percentage point (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: 4.9pp (95% CI: [3.0, 6.9]); IV: 11.1pp (95% CI: [7.4, 14.8]) when using kiln owner self-reported average brick quality over the entire season, reported at endline (Fig. S3, 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.

[Fig. 4 HERE]

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 endline) and summing across the 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). While 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 so stark (e.g., the median reported price for Class 1 bricks was BDT 11 for Class 2 bricks was BDT 9); 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 as 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 Materials and Methods section on Outcome Measurement in the Supplementary Materials for more details). This normalized measure ends up being driven entirely by differences in brick quality, thus, we report the effect on brick quality in Fig. 4 and the value of production per brick in the Supplementary Materials (Table S27 with monitoring data and S28 using kiln owner self-reports at endline).

Kiln owner costs

While the intervention did not require any capital investment from kiln owners, the technical intervention recommended using sawdust during brick firing and it is possible other costs could have changed as a result of the intervention. We explored whether other input costs changed due to the intervention (Tables S33-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, since the intervention recommended using more sawdust. Reports from the intervention team suggest that due to 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 Supplementary Materials 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).

[Fig. 5 HERE]

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 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 USD $89,374 or about USD $486 (89,374/184) per treatment kiln.

[Table 1 HERE]

Assuming a social cost of carbon (SCC) of $185/MT (*53*), our intention-to-treat results suggest a single year valuation of the reduced carbon emissions of USD 31,580 per kiln (Table 1, Panel A). This compares favorably with the cost of delivering the intervention (USD $486 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 (486/171), to other mitigation strategies (*56*), for example reforestation ($1.2 - $11.9), the U.S. Clean Power Plan ($13.1), fuel economy standards for vehicles (CAFE standards, $57.3 - $370), or weatherization assistance programs ($418) (Table 1, Panel B).

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% confidence interval 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 (Table 1, Panel A). 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, respectively.

Given we have not accounted for the health co-benefits of reduced $PM_{2.5}$ emissions (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 co-benefits 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 (via cost savings on fuel and production of more high-quality bricks).

Conclusion

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 co-benefits 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 willingness to pay 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 programs in the United States, 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*, *36*, *37*–*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 significant 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 6,352 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 (6352 kilns x 382 tons = 2,426,464 tons)—a 2% reduction in Bangladesh's annual CO_2 emissions (while a more conservative scenario that uses the 171 ton/kiln/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 this is equivalent to the amount of CO_2 emitted from the energy used to power 316,434 homes in the U.S. 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 conducted with kiln owners revealed that owners remained concerned about workers' interest in and ability to adopt the new practices, which suggests 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 LMIC and in particular, 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 literature on the productivity and management capacity of firms in low- and middle-income countries (LMIC), particularly among informal firms (*14*, *70–74*). Past research has found that better-managed firms in the United Kingdom 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 and 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

Experimental Design

During the 2022–2023 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-May, coinciding with the off-season for agriculture), we conducted an RCT with three experimental arms: (1) a technical arm, (2) a technical+incentive information arm ("technical+" arm), and (3) 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: (a) single fireman continuous fuel feeding, (b) improved brick stacking, (c) thicker ash layers on kiln tops, (d) closing the kiln gate with a cavity wall, and (e) 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 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 adopted 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, clothing). See Materials and Methods in the Supplementary Materials for further details on the interventions.

Sampling

Our initial sample randomized 357 zigzag kilns operating across 6 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 2022-2023 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 - 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-

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-S8). Ineligibility for the intervention and attrition are uncorrelated with treatment (Table S9). More kilns in the technical arm were not operated during the 2022-2023 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
Fieldworkers 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-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. Appendix D 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 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 Supplementary Materials).

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 pre-registered as an outcome, but are calculated using specific energy consumption, which was pre-registered. In cases in which outcomes can be constructed using both the kiln performance assessment data and endline data, we report endline equivalents in the Supplementary Materials.

Estimation

We estimate 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. Specifically, our primary specification is of the form $y_i = \beta_0 + \beta_1 T_i + \beta_2 I_i + \delta_s + \epsilon_i$ 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 $y_i = \tau_0 + \tau S_i + \delta_s + \nu_i$ 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 instrumental variable (IV) specifications of the form $y_i = \gamma_0 + \gamma_1 A_i + \delta_s + u_i$ 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 non-compliance (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 or LATE). In the presence of always takers—in our case, this is particularly relevant because 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 while 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 non-compliance (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 AEA and ISRCTN. Any specifications that deviate from this plan are indicated in the main text (for more details see Appendix A).

References

1. M. Fowlie, R. Meeks, The Economics of Energy Efficiency in Developing Countries. *Review of Environmental Economics and Policy* **15**, 238–260 (2021).

2. IEA, Accelerating Energy Efficiency in Small and Medium-sized Enterprises. (2015).

3. J. Rentschler, N. Leonova, Global air pollution exposure and poverty. *Nat Commun* **14**, 4432 (2023).

4. E. Carranza, R. Meeks, Energy Efficiency and Electricity Reliability. *The Review of Economics and Statistics* **103**, 461–475 (2021).

5. A. Iimi, R. Elahi, R. Kitchlu, P. Costolanski, Energy-Saving Effects of Progressive Pricing and Free CFL Bulb Distribution Program: Evidence from Ethiopia. *The World Bank Economic Review* **33**, 461–478 (2019).

6. S. K. Pattanayak, M. Jeuland, J. J. Lewis, F. Usmani, N. Brooks, V. Bhojvaid, A. Kar, L. Lipinski, L. Morrison, O. Patange, N. Ramanathan, I. H. Rehman, R. Thadani, M. Vora, V. Ramanathan, Experimental evidence on promotion of electric and improved biomass cookstoves. *Proc Natl Acad Sci USA* **116**, 13282–13287 (2019).

7. N. Brooks, V. Bhojvaid, M. A. Jeuland, J. J. Lewis, O. Patange, S. K. Pattanayak, How Much do Alternative Cookstoves Reduce Biomass Fuel Use? Evidence from North India. *Resource and Energy Economics* **43**, 153–171 (2015).

8. T. Beltramo, G. Blalock, D. I. Levine, A. M. Simons, Does Peer Use Influence Adoption of Efficient Cookstoves? Evidence From a Randomized Controlled Trial in Uganda. *Journal of Health Communication* **20**, 55–66 (2015).

9. G. Miller, A. M. Mobarak, "Intra-household Externalities and Low Demand for a New Technology: Experimental Evidence" (NBER Working Paper No. 18964, NBER, 2013).

10. M. A. Jeuland, V. Bhojvaid, A. Kar, J. J. Lewis, O. Patange, S. K. Pattanayak, N. Ramanathan, I. H. Rehman, J. S. Tan Soo, V. Ramanathan, Preferences for improved cook stoves: Evidence from rural villages in north India. *Energy Economics* **52**, 287–298 (2015).

11. R. Hanna, E. Duflo, M. Greenstone, Up in smoke: The influence of household behavior on the long-run impact of improved cooking stoves. *American Economic Journal: Economic Policy* **8**, 80–114 (2016).

12. N. Ryan, "Energy Productivity and Energy Demand: Experimental Evidence from Indian Manufacturing Plants" (NBER Working Paper 24619, 2018).

13. E. Somanathan, R. Somanathan, A. Sudarshan, M. Tewari, The Impact of Temperature on Productivity and Labor Supply: Evidence from Indian Manufacturing. *Journal of Political Economy*, 713733 (2021).

14. A. Adhvaryu, N. Kala, A. Nyshadham, "The light and the heat: Productivity co-benefits of energy-saving technology" (Working Paper 24314, 2018).

15. A. Eil, J. Li, P. Baral, E. Saikawa, "Dirty Stacks, High Stakes: An Overview of Brick Sector in South Asia" (World Bank, 2020); https://doi.org/10.1596/33727.

16. The World Bank, "Introducing Energy-efficient Clean Technologies in the Brick Sector of Bangladesh" (IBRD/World Bank, Washington, DC, 2011).

17. Department of Environment, "National Strategy for Sustainable Brick Production in Bangladesh" (Dhaka, Bangladesh, 2017).

18. GBD MAPS Working Group, "Burden of Disease Attributable to Major Air Pollution Sources in India" (Special Report 21, Health Effects Institute, Boston, MA, 2018).

19. C. Weyant, V. Athalye, S. Ragavan, U. Rajarathnam, D. Lalchandani, S. Maithel, E. Baum, T. C. Bond, Emissions from South Asian Brick Production. *Environmental Science & Technology* **48**, 6477–6483 (2014).

20. BUET, "Small Study on Air Quality of Impacts of the North Dhaka Brick Cluster by Modeling of Emissions and Suggestions for Mitigation Measures including Financing Models" (Bangladesh University of Engineering and Technology, 2007).

21. A. Jamatia, S. Chakraborti, Air Quality Assessment of Jirania Brick Industries Cluster: A Case Study. **6**, 3 (2015).

22. S. Ahmed, I. Hossain, Applicability of Air pollution Modeling in a Cluster of Brickfields in Bangladesh. *Chem. Eng. Res. Bull.* **12**, 28–34 (2008).

23. Md. M. Rana, "Sources of Air Pollution in Bangladesh: Brick Kiln & Vehicle Emission Scenario" (Department of Environment, Bangladesh, 2019).

24. N. Brooks, D. Biswas, R. Hossin, A. Yu, S. Saha, S. Saha, S. K. Saha, S. P. Luby, Health consequences of small-scale industrial pollution: Evidence from the brick sector in Bangladesh. *World Development* **170**, 106318 (2023).

25. A. R. Sherris, B. A. Begum, M. Baiocchi, D. Goswami, P. K. Hopke, W. A. Brooks, S. P. Luby, Associations between ambient fine particulate matter and child respiratory infection: The role of particulate matter source composition in Dhaka, Bangladesh. *Environmental Pollution* **290**, 118073 (2021).

26. T. R. Tusher, Z. Ashraf, S. Akter, Health effects of brick kiln operations: A study on largest brick kiln cluster in Bangladesh. *SE Asia J. Pub. Health* **8**, 32–36 (2019).

27. M. H. R. Khan, M. K. Rahman, A. Ajm, Y. Oki, T. Adachi, Evaluation of degradation of agricultural soils associated with brick burning in selected soil profiles in the eastern region of Bangladesh. *Japanese Journal of Tropical Agriculture* **50**, 183–189 (2006).

28. D. Biswas, E. S. Gurley, S. Rutherford, S. P. Luby, The drivers and impacts of selling topsoil for brick making in Bangladesh. *Environmental Management* **62**, 792–802 (2018).

29. A. Blackman, Informal Sector Pollution Control: What Policy Options Do We Have? *World Development* **28**, 2067–2082 (2000).

30. A. Blackman, "Making Small Beautiful: Lessons from Mexican leather tanneries and brick kilns" in *The Informal Sector and the Environment* (Routledge, 1st Edition., 2022).

31. M. Khaliquzzaman, A. S. Harinath, S. A. Ferdousi, S. M. M. H. Khan, Thirty Years' Quest for Emission Reduction and Energy Efficiency Improvement of Brick Kilns in Bangladesh. *International Journal of Environmental Monitoring and Analysis* **8**, 11–22 (2020).

32. N. Haque, Technology mandate for greening brick industry in Bangladesh: a policy evaluation. *Clean Techn Environ Policy* **19**, 319–326 (2016).

33. S. P. Luby, D. Biswas, E. S. Gurley, I. Hossain, Why highly polluting methods are used to manufacture bricks in Bangladesh. *Energy for Sustainable Development* **28**, 68–74 (2015).

34. N. Brooks, D. Biswas, S. Maithel, S. Kumar, M. R. Uddin, S. Ahmed, M. Mahzab, G. Miller, M. Rahman, S. P. Luby, Building blocks of change: The energy, health, and climate co-benefits of more efficient brickmaking in Bangladesh. *Energy Research & Social Science* **117**, 103738 (2024).

35. J. Lee, N. R. Brooks, F. Tajwar, M. Burke, S. Ermon, D. B. Lobell, D. Biswas, S. P. Luby, Scalable deep learning to identify brick kilns and aid regulatory capacity. *Proceedings of the National Academy of Sciences* **118**, e2018863118 (2021).

36. Department of Environment, "Registered Brick Kilns" (DOE Report, Government of Bangladesh, Dhaka, Bangladesh, 2023).

37. Transparency International Bangladesh, "Corruption in Service Sectors: National Household Survey 2022 - Extended Executive Summary" (Transparency International Bangladesh, 2022).

38. A. D. Foster, M. R. Rosenzweig, Microeconomics of Technology Adoption. *Annual Review of Economics* **2**, 395–424 (2010).

39. The World Bank, "Bangladesh - Brick Kiln Efficiency Project (P105226)" (Final Implementation Status Report, 2016).

40. UNDP/GEF, "UNDP/GEF Project: Improving Kiln Efficiency in Brick Making Industry (IKEBMI) (GEF PIMS 1901)" (Terminal Evaluation Report, 2016).

41. The World Bank, "Clean Air and Sustainable Environment Project" (Implementation Completion and Results Report, 2019).

42. Md. N. Alam, S. Barman, "Bangladesh Brick Sector Roadmap 2019-2030" (UNEP Collaborating Centre for Climate & Sustainable Energy Finance & The Climate and Clean Air Coalition to Reduce Short-Lived Climate Pollutants, 2019).

43. UNDP/GEF, "Improving Kiln Efficiency in the Brick Making Industry" (Project Document, 2010); https://info.undp.org/docs/pdc/Documents/BGD/00060015_BGD_Brick_Award-00060015.pdf.

44. Frankfurt School of Finance and Management, "Tunnel kiln technology overview and project assessment guideline" (2019); https://www.ccacoalition.org/resources/tunnel-kiln-technology-overview-and-project-assessment-guideline.

45. S. Maithel, D. Lalchandani, G. Malhotra, P. Bhanware, R. Uma, S. Ragavan, V. Athalye, K. Bindiya, S. Reddy, T. Bond, C. Weyant, "Brick kilns performance assessment" (Greentech Knowledge Solutions, 2012).

46. S. Kumar, A. Ravi, S. Maithel, "Report on Training on Cleaner Fired Clay Brick Production Practices, Sri Ganganagar, India" (Greentech Knowledge Solutions, Delhi, India, 2016).

47. S. Kumar, S. Rana, S. Maithel, "Learnings from Bihar's Experience of Implementing Cleaner Brick Kiln Directive: A Case Study" (Greentech Knowledge Solutions, Delhi, India, 2018).

48. D. Lalchandani, S. Maithel, "Towards Cleaner Brick Kilns in India: An Approach Based on Zig Zag Firing Technology" (Greentech Knowledge Solutions, 2013).

49. UNFCC, "Small-scale Methodology: Fuel Switch, process improvement and energy-efficiency in brick manufacture" (2015).

50. M. I. Haque, K. Nahar, M. H. Kabir, A. Salam, Particulate black carbon and gaseous emission from brick kilns in Greater Dhaka region, Bangladesh. *Air Qual Atmos Health* **11**, 925–935 (2018).

51. R. Ahmad, Y. Zhou, C. Liang, G. Li, N. Zhao, A. Abbas, F. Yu, L. Li, J. Gong, D. Wang, Y. Yang, Z. Tang, M. Sultan, C. Sun, R. Dong, Comparative evaluation of thermal and emission performances for improved commercial coal-fired stoves in China. *RSC Adv.* **12**, 20886–20896 (2022).

52. K. Gillingham, D. Rapson, G. Wagner, The Rebound Effect and Energy Efficiency Policy. *Review of Environmental Economics and Policy* **10**, 68–88 (2016).

53. K. Rennert, F. Errickson, B. C. Prest, L. Rennels, R. G. Newell, W. Pizer, C. Kingdon, J. Wingenroth, R. Cooke, B. Parthum, D. Smith, K. Cromar, D. Diaz, F. C. Moore, U. K. Müller, R. J. Plevin, A. E. Raftery, H. Ševčíková, H. Sheets, J. H. Stock, T. Tan, M. Watson, T. E. Wong, D. Anthoff, Comprehensive evidence implies a higher social cost of CO2. *Nature* **610**, 687–692 (2022).

54. C. Barstow, R. Bluffstone, K. Silon, K. Linden, E. Thomas, A cost-benefit analysis of livelihood, environmental and health benefits of a large scale water filter and cookstove distribution in Rwanda. *Development Engineering* **4**, 100043 (2019).

55. G. Hutton, E. Rehfuess, F. Tediosi, Evaluation of the costs and benefits of interventions to reduce indoor air pollution. *Energy for Sustainable Development* **11**, 34–43 (2007).

56. K. Gillingham, J. H. Stock, The Cost of Reducing Greenhouse Gas Emissions. *Journal of Economic Perspectives* **32**, 53–72 (2018).

57. K. Rennert, C. Kingdon, “Social Cost of Carbon 101” (Resources for the Future, Washington, DC, 2022); https://www.rff.org/publications/explainers/social-cost-carbon-101/.

58. A. Blackman, J.-S. Shih, D. Evans, M. Batz, S. Newbold, J. Cook, The benefits and costs of informal sector pollution control: Mexican brick kilns. *Environment and Development Economics* **11**, 603 (2006).

59. A. M. Mobarak, P. Dwivedi, R. Bailis, L. Hildemann, G. Miller, Low demand for nontraditional cookstove technologies. *Proceedings of the National Academy of Sciences of the United States of America* **109**, 10815–20 (2012).

60. Global Carbon Budget – with major processing by Our World in Data, Annual CO_2 emissions – GCB [dataset], version Global Carbon Project, “Global Carbon Budget [original data] (2024); https://ourworldindata.org/co2-and-greenhouse-gas-emissions.

61. US EPA, Greenhouse Gas Equivalencies Calculator (2023). https://www.epa.gov/energy/greenhouse-gas-equivalencies-calculator.

62. D. Atkin, A. Chaudhry, S. Chaudry, A. K. Khandelwal, E. Verhoogen, Organizational Barriers to Technology Adoption: Evidence from Soccer-Ball Producers in Pakistan. *The Quarterly Journal of Economics* **132**, 1101–1164 (2017).

63. G. Miller, D. Biswas, A. Mahajan, K. Babiarz, N. Brooks, J. Brunner, S. Ashraf, J. Shane, S. Maithel, S. Ahmed, M. Mazab, M. R. Uddin, M. Rahman, S. P. Luby, “A Business Case for Human Rights at Work? Experimental Evidence on Labor Trafficking and Child Labor at Brick Kilns in Bangladesh” (Working Paper 32829, National Bureau of Economic Research, Cambridge, MA, 2024).

64. A. Blackman, W. Harrington, The use of economic incentives in developing countries: Lessons from international experience with industrial air pollution. *The Journal of Environment & Development* **9**, 5–44 (2000).

65. S. Jayachandran, J. De Laat, E. F. Lambin, C. Y. Stanton, R. Audy, N. E. Thomas, Cash for carbon: A randomized trial of payments for ecosystem services to reduce deforestation. *Science* **357**, 267–273 (2017).

66. A. Blackman, Alternative Pollution Control Policies in Developing Countries. *Review of Environmental Economics and Policy* **4**, 234–253 (2010).

67. A. Blackman, G. J. Bannister, Pollution Control in the Informal Sector: The Ciudad Juárez Brickmakers’ Project. *Naturl Resources Journal* **37**, 829–856 (1997).

68. E. Somanathan, R. Bluffstone, Biogas: Clean Energy Access with Low-Cost Mitigation of Climate Change. *Environ Resource Econ* **62**, 265–277 (2015).

69. D. Naeher, R. Narayanan, V. Ziulu, Impacts of energy efficiency projects in developing countries: Evidence from a spatial difference-in-differences analysis in Malawi. *Energy for Sustainable Development* **73**, 365–375 (2023).

70. D. Atkin, D. Donaldson, I. Rasul, E. Verhoogen, C. Woodruff, “Firms, trade, and productivity” (International Growth Centre, London, United Kingdom, 2021).

71. N. Bloom, A. Mahajan, D. McKenzie, J. Roberts, Why do firms in developing countries have low productivity? *American Economic Review* **100**, 619–623 (2010).

72. N. Bloom, R. Lemos, R. Sadun, D. Scur, J. Van Reenen, The New Empirics of Management. *Journal of the European Economic Association* **12**, 835–876 (2014).

73. N. Bloom, C. Genakos, R. Martin, R. Sadun, Modern Management: Good for the Environment or Just Hot Air? *The Economic Journal* **120**, 551–572 (2010).

74. N. Bloom, B. Eifert, A. Mahajan, D. McKenzie, J. Roberts, Does Management Matter? Evidence from India. *The Quarterly Journal of Economics* **128**, 1–51 (2013).

75. G. W. Imbens, J. D. Angrist, Identification and Estimation of Local Average Treatment Effects. *Econometrica* **62**, 467–475 (1994).

76. G. W. Imbens, D. B. Rubin, Estimating Outcome Distributions for Compliers in Instrumental Variables Models. *The Review of Economic Studies* **64**, 555–574 (1997).

77. N. Brooks, D. Biswas, S. Maithel, G. Miller, A. Mahajan, M. R. Uddin, S. Ahmed, M. Mazab, M. Rahman, S. P. Luby, Replication Data for: Reducing Emissions and Air Pollution from Informal Brick Kilns: Evidence from Bangladesh, Harvard Dataverse (2024). doi:10.7910/DVN/MV9FEH

78. S. B. Bajracharya, A. Mishra, A. Hussain, K. Gurung, L. Mathema, B. Banmali Pradhan, Do working and living conditions influence brick-kiln productivity? Evidence from Nepal. *International Journal of Occupational Safety and Ergonomics* **28**, 1452–1460 (2022).

79. P. Saha, S. Mazumder, Impact of Working Environment on Less Productivity in RMG Industries: a Study on Bangladesh RMG Sector. (2015).

80. K. L. Morgan, D. B. Rubin, Rerandomization to improve covariate balance in experiments. *Ann. Statist.* **40** (2012).

81. M. Bruhn, D. McKenzie, In Pursuit of Balance: Randomization in Practice in Development Field Experiments. *American Economic Journal: Applied Economics* **1**, 200–232 (2009).

82. X. Li, P. Ding, D. B. Rubin, Asymptotic theory of rerandomization in treatment–control experiments. *Proc. Natl. Acad. Sci. U.S.A.* **115**, 9157–9162 (2018).

83. M. J. Uddin, P. S. Hooda, A. S. M. Mohiuddin, M. E. Haque, M. Smith, M. Waller, J. K. Biswas, Soil organic carbon dynamics in the agricultural soils of Bangladesh following more than 20 years of land use intensification. *Journal of Environmental Management* **305**, 114427 (2022).

84. International Labour Organization, “Small-scale brickmaking” (ILO, Geneva, Switzerland, 1984).

85. J. Angrist, J.-S. Pischke, *Mostly Harmless Econometrics: An Empiricist’s Companion* (Princeton University Press, 2009).

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Visualization: NB
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Supplementary Materials

Materials and Methods
Supplementary Figures (Figs. S1 to S15)
Supplementary Tables (Tables S1 to S60)
References (78-85)

Figures and Tables

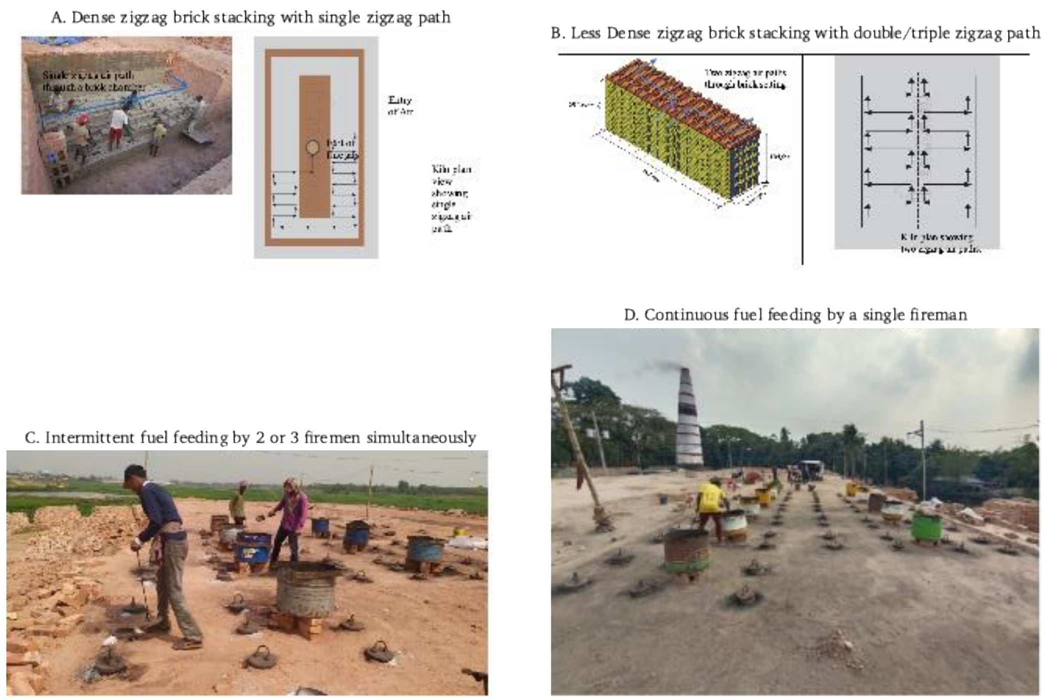

Fig. 1. Key Intervention Practices. This figure depicts the standard brick setting and fuel feeding practices and the changes proposed in the intervention. Panel A shows the standard zigzag kiln brick setting practice in which brick columns are packed densely and there is a single zigzag airpath. Panel B shows the intervention recommended practice of less dense brick setting with two or three zigzag air paths. Panel C shows the standard fuel feeding practice of several firemen feeding simultaneously during intermittent feeding intervals. Panel D presents 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 Materials and Methods.

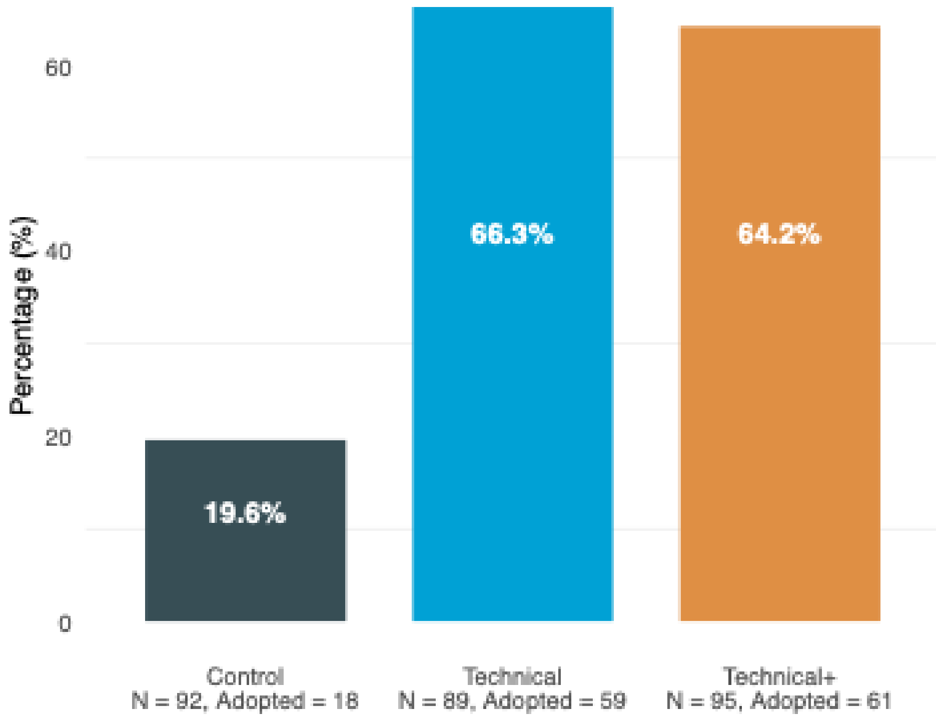

Fig. 2. Adoption by study arm. This figure presents the raw means of adopting double/triple zigzag brick stacking and single fireman continuous feeding by treatment arm.

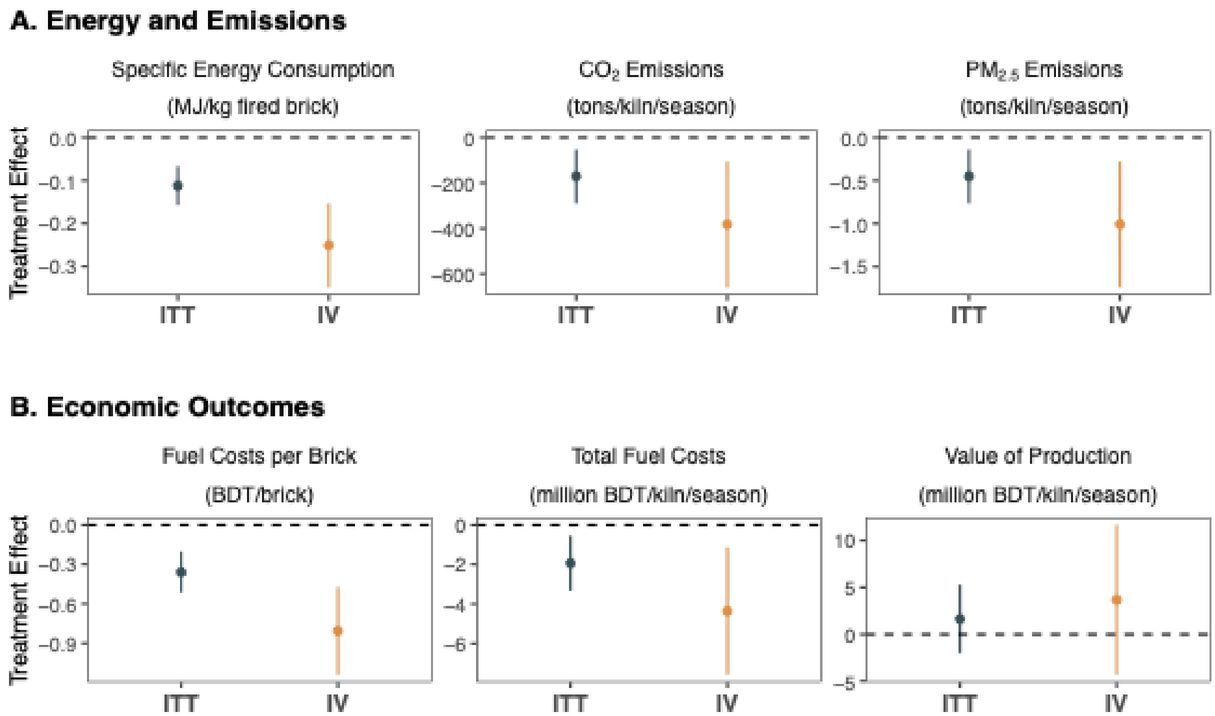

Fig. 3. Intervention impact on energy, emissions, and economic outcomes. Panel A presents the intervention's impact on outcomes related to energy use and emissions. Panel B reports the findings for economic outcomes for kiln owners. Both panels show regression results for the intention-to-treat (ITT) and instrumental variable (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% confidence intervals around the regression coefficient.

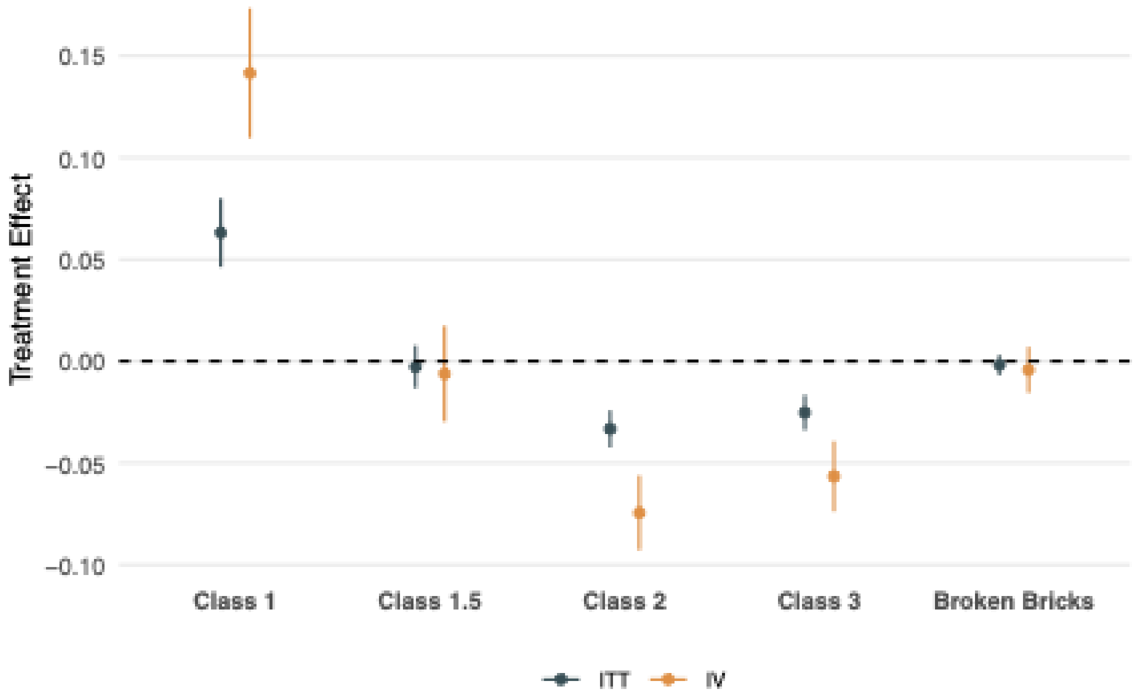

Fig. 4. Intervention impact on distribution of brick quality. This figure presents regression results for the intention-to-treat (ITT) and instrumental variables (IV) specifications for each classification of brick quality as a percentage of total production. The ITT specification, shown on the left 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% confidence intervals around the regression coefficient.

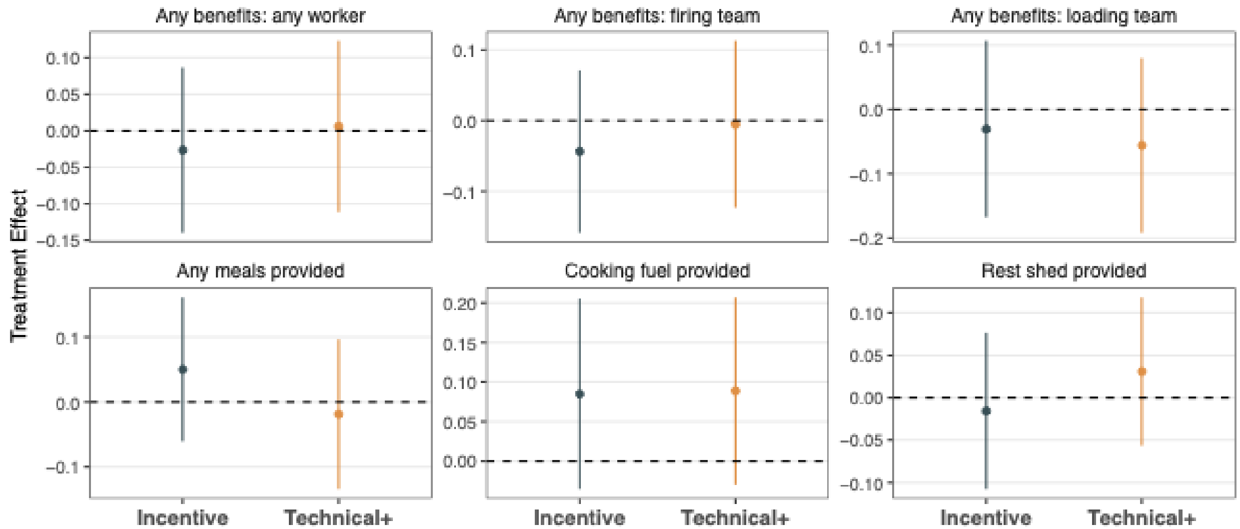

Fig. 5. Intervention impact on working conditions and benefits. This figure presents regression results for the intention-to-treat (ITT) specifications for outcomes related to improved working conditions and provision of benefits to workers. In each panel, the coefficients for the technical arm are shown 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% confidence intervals around the regression coefficient.

Table 1. Costs and Benefits of CO_2 Reductions. Panel A presents 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 social cost of carbon ($185/ton, (*53*)). The benefit-cost ratio (BCR) is calculated by dividing the benefits per kiln by the per kiln cost of delivering the intervention ($485.73). 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: 1) a base scenario that uses the intention-to-treat estimate of CO_2 reductions, 2) a conservative scenario that uses the lower bound of the 95% confidence interval from the intention-to-treat estimate of CO_2 reductions, and 3) an optimistic scenario that uses the instrumental variables estimate of CO_2 reductions among compliers. Panel B reports 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.

Panel A: Costs and benefits of the kiln efficiency intervention

	Estimate	**Benefit per kiln**	**BCR**	**Cost per tCO2**
Scenario				
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

Panel B: Costs of other CO_2 mitigation strategies

Policy	**($2022/ton CO_2) - Lower Bound**	**($2022/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	
Dedicated battery electric vehicle subsidy	417.97	764.29

Supplementary Materials for

Reducing emissions and air pollution from informal brick kilns: evidence from a randomized controlled trial in Bangladesh

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This PDF file includes:

Materials and Methods

Experimental design

The experimental design was based our theory of change, which emphasizes working with existing zigzag kiln owners and directly considering their profit motives. We hypothesized this strategy would provide an opportunity to quickly improve the dominant production model, achieve immediate reductions in air pollution and greenhouse gas emissions, and simultaneously increase kiln profits. This was informed by our pilot study *(34)*, critical analysis of past efforts and their effectiveness *(15, 24, 32-35, 39-44)*, studies of brick kilns in Mexico *(29-30, 58, 66-67)*, and research within economics on management interventions *(62, 70-74)*, energy efficiency *(1, 4, 12-14, 52, 68-69)*, and technology adoption *(6-11, 38, 59)*.

The RCT contained three experimental arms: (1) technical, (2) technical+, and (3) control. Kilns assigned to the technical arm received information, intensive training, and technical support to adopt a suite of operational improvements that included improved firing practices, improved brick setting, and increased insulation (see Section below). These operational improvements have the potential to both reduce emissions and energy use, as well as increase kiln profitability, if done correctly, via reduced fuel expenditures and increased revenue from producing more high quality bricks.[1]

The training highlighted the financial benefits of these improvements and included live participation from owners who had adopted them during our pilot study in order to directly address owners' uncertainty regarding economic returns. The training was delivered in the form of initial orientation sessions for owners and their managers, then separate sessions for firing and loading sardar (labor supervisors). These initial sessions were followed by on-site training of sardar and workers in brick loading and firing. Throughout the brick firing season, our team provided technical support to help owners and their workers implement the new practices.

Kilns assigned to the technical+ arm received everything delivered to the technical arm in terms of technical training and support, plus additional information and encouragement that targeted owners to address workers' misaligned incentives. Suggestions included a mix of financial (e.g., bonuses, higher wages, return bonuses) and nonfinancial incentives (e.g., better working conditions, such as meals, housing, and clothing). These examples were directly informed by the experience of other kiln owners successfully operating ZZKs, our own pilot study in Jashore district, and the economics literature *(13-14, 62)*-— including evidence from brick kilns in Nepal *(78)* and garment factories in Bangladesh *(79)*. The implementation included a preliminary group meeting with all owners assigned to the technical+ arm, in which our team explained the profit-based case for incentivizing workers to adopt the new practices, the importance of workers' properly adhering to the new technical practices and giving them enough time, training, and positive reinforcement to adopt the new practices, and descriptions of several ways to incentivize workers to adhere to the new practices (see the Incentive Arm Script section below for the script). A handout that described the importance of motivating workers to adopt the new technical practices was left with owners at this initial meeting. Our team conducted two follow-up "nudge" visits to all kilns in the technical+ arm. At the first follow-up nudge visit, they gave owners a poster that presented a few simplified key messages about the importance of incentives as a reminder.

The control arm received no information or training from our team but participated in all data

[1]Brick quality is an indicator of both improved efficiency and kiln owner benefits. When bricks are fired in a traditional kiln, the highest quality or properly baked bricks are classified as Class-1 bricks and sold for a higher price than inferior classes. See Section for more details.

collection efforts.

This project was reviewed and approved by Institutional Review Boards (IRBs) at Stanford University (#67263) and ICDDR,B (PR-22052).

Technical Intervention Details

Less dense brick stacking with multiple (two or three) zigzag air paths

The existing practice was dense brick setting with single zigzag air path (Fig. S5). Typical packing density[2] and packing fraction[3] was in the range of 1,050-1,150 kg/m3 and 60%-65%, respectively.

The technical intervention introduced brick stacking that was less dense and formed two or three zigzag air paths. The typical packing density and packing fraction of the setting was in the range of 900-1,000 kg/m3 and 50%-55%, respectively. A less dense brick setting with two zigzag air paths is shown in Fig. S6. A kiln with less dense brick setting results in better distribution of air in the brick setting, which leads to uniform distribution of heat and temperature and a higher percentage of Class-1 bricks. Better air distribution improves the combustion of coal, and thus reduces the generation of black carbon and small particulates. Also, less dense brick setting results in less pressure loss, and hence requires less energy to drive the fan to create kiln draft.

Single fireman continuous fuel feeding

The fuel is fed through the feed holes provided at the roof of the kiln by firemen. As per the existing fuel feeding practice, fuel is fed by two or three firemen simultaneously (Fig. S7) at intermittent intervals—i.e., the firemen feed coal simultaneously for an interval of 10-15 minutes, followed by a non-feeding interval of 15-20 minutes. Intermittent feeding by two or three firemen simultaneously results in the accumulation of fuel in the kiln, which does not receive sufficient air for combustion. This results in incomplete combustion, unburnt fuel, and black smoke (excessive particulate matter emissions).

In the improved practice (technical intervention), a single fireman (Fig. S8) feeds fuel continuously for 30 minutes. After 30 minutes he pauses, and his place is taken by his partner fireman. The fuel is fed sequentially in all chambers in the firing zone. This cycle is repeated continuously in the firing zone. In this way, fuel is fed in small quantities continuously, which causes the coal to receive adequate air for combustion. As a result, it burns completely and results in less wasted fuel and less black smoke. It also enables more uniform heat distribution across the kiln cross-section.

Thicker ash layer on the kiln top

The layer of ash on the top of the brick setting serves as the kiln's temporary roof and provides insulation against heat loss. As per the existing practice, the layer of ash has a thickness of approximately 6 in (Fig. S9). In the improved practice (technical intervention), kilns are encouraged to increase the layer of ash to 9 in or more. Improved insulation due to the thicker ash layer reduces heat loss as well as the in-leakage of cold air into the kiln, helps reduce fuel consumption, and ensures that the top layers of the brick setting will attain a high temperature for baking and thus increase the percentage of Class-1 bricks.

Closing kiln entry gates with an ash-filled cavity wall

Entry gates are openings in the outer wall of the brick kiln that give workers access to the kiln in order

[2]Packing density (kg/m3) is the weight of green bricks stacked per m3 of kiln chamber volume.

[3]Packing fraction of brick setting (in %) can be defined as the volume of bricks stacked in a chamber to the volume of the chamber.

to stack green bricks and remove fired bricks. Once green bricks are stacked, a temporary wall of bricks is made to close the entry gates and seal the kiln. As per the existing practice, the temporary wall to close entry gates is a one-brick (approximately 10 in) thick single wall. As per the improved practice, the wall thickness is increased to 30 in. The wall now consists of two walls: an inner wall of 15-in thickness and an outer wall of 10-in thickness. The two walls are separated by a cavity (5-in thickness) filled with ash. The increased thickness of wicket gate walls and the presence of ash reduces heat loss and air leakage, and thus reduces the amount of coal required to maintain the kiln's temperature. Bricks set close to the entry gate attain a high temperature for baking, which in turn increases the percentage of Class-1 bricks.

Use of powdered biomass fuel in the newly inducted chamber in the fuel feeding zone
In a zigzag kiln, the fire moves around the kiln's firing chamber (a single cycle around the kiln is referred to as completing a circuit). As the fire moves, a new chamber enters the fuel feeding zone every 8-12 hours. The temperature of a newly inducted chamber is initially lower (<500°C). In the existing practice, coal is fed into the newly inducted chamber. Since the newly inducted chamber has a low temperature, the coal fed is not able to burn completely; this gives rise to black smoke (particulate matter) and CO emissions. In the improved practice, kilns are encouraged to feed saw dust and other powdery biomass fuels with high volatile matter content and low ignition temperatures into the newly inducted chamber (Fig. S10). These fuels are able to burn completely at a low temperature. Once the newly inducted chamber has attained a temperature higher than 700°C, coal begins to be fed.

Sample Selection and Randomization

We obtained lists of all zigzag kilns operating in Khulna Division from the division and district Brick Manufacturing Owners Associations. The initial sampling frame included 410 zigzag kilns operating in 7 of the 10 districts of Khulna Division. Based on initial conversations with the leadership of each district level Brick Manufacturing Owners Association to gauge their interest in supporting the study and the number of available kilns, we ultimately selected 6 districts for inclusion: Jahsore, Khulna, Jhenaidah, Chuadanga, Kushtia, and Narail. We aimed to enroll 300 kilns in the trial, based on our power calculations and logistical considerations. Figure S11 presents a map of the study districts and kiln locations in Khulna Division.

Field research assistants completed consent procedures and collected baseline data from an initial sample of 328 zigzag kilns from these 6 districts. During the baseline data collection, we learned that many of the initial 410 kilns chose not to operate their kiln that season due to the high price of coal or switching to exclusively using firewood, which rendered them ineligible for the technical intervention (as these were the inclusion criteria). Based on this information, our team consented, enrolled, and collected baseline data from an additional 29 kilns in Jashore District to enroll them in the trial. Thus, we enrolled 357 kilns, which were then randomized into technical (n = 119), incentive (n = 121), and control (n = 117) arms, stratified by district and the prior season's production of class-1 bricks (above or below the median). We ran randomized kilns 1,000 times to create 1,000 different potential allocations and selected the allocation that maximized the sum of p-values across all balance tests *(80-82)*.[4] The overall sample of 357 kilns was balanced on a set of baseline kiln and kiln owner

[4]Balance tests were done using the following variables: owner experience, owner education, existence of additional owners, knowledge of pilot intervention in Jashore, interaction with pilot kilns in Jashore, year they changed to ZZK, location, adjacency to water, count of bricks fired in previous year, percent Class 1 bricks in the preceding year, production cost estimates per thousand bricks, number of workers in each kiln job, and average weight of fired bricks.

characteristics, as was the initial sample of 328 kilns and the additional 29 kilns from Jashore.

Figure S12 presents a flowchart of the intervention kilns from baseline data collection to the final analytic sample and Fig S13 is a timeline of all study activities.

Data collection

We developed four quantitative data collection tools: (1) a baseline/endline questionnaire, (2) an adoption checklist, (3) a kiln performance monitoring tool, and (4) a worker survey. The baseline questionnaire collected information on kiln owner demographics, the GPS location of the kiln, retrospective information on the previous brick firing season (production, costs, revenue), and baseline information about kiln construction and operation.

Initial adoption visits were conducted between January and February 2023, after intervention kilns had been trained. The adoption checklist assessed take-up of the technical intervention components and collected some information on fuel use. We conducted extensive kiln performance monitoring between March and May 2023, after kilns had completed several rounds of brick firing and the firing process had reached an equilibrium in terms of energy use (typically, more coal is used in early rounds of firing, when the ground is cold and wet and green bricks contain more moisture). The performance assessment took approximately 30 hours per kiln and included classifying fired bricks, measuring the quantity of fuel consumed during 24-hours, counting the chambers in which fuel feeding occurred during monitoring, collecting coal samples for measurement of calorific value, and measuring emissions in the flue gas. The kiln performance monitoring tool included the same adoption checklist to assess take-up of the technical intervention components at a second point in time. These visits were not announced in advance to kiln owners. The data collected during the kiln performance monitoring was extremely detailed (see Kiln Performance Monitoring Protocol and includes objective measures of brick quality, brick quantities, and fuel use. However, we note that the measures were collected at a single point in time and thus are not representative of seasonal averages.

Fieldworkers were unable to complete the performance monitoring assessment in all kilns because kilns had to be operational during these visits and many kilns closed operation early due to the timing of Ramadan. Also, several kilns had been demolished or shut down by the government before the monitoring could be completed; see the subsection that presents the kiln performance monitoring protocol. Our team ultimately completed kiln performance monitoring of 276 kilns, which is the primary analytic sample (Fig. S12). Tables S4-S10 demonstrate that our sample remains balanced after each of these instances of dropout, and attrition due to these reasons is not correlated with the treatment. Data from the kiln performance assessments are used to construct the primary outcomes for this study.

In a subsample of 12 kilns in 4 different districts, a trained team from the Bangladesh University of Engineering and Technology measured suspended particulate matter (SPM) in the chimneys using an isokinetic sampler. Four kilns from each arm were considered in the subsample. Since the stacks lacked any sampling hole and were too thick, these measurements were performed by constructing a temporary chimney that diverted gas from the main chimney and facilitated the necessary particulate matter, moisture content, and velocity measurements. Measurements were performed for a sufficient time to capture the effect of coal feeding and idle time. A simple comparison of SPM by adoption status is presented in Fig. S2, as the small sample precludes any rigorous statistical analysis.

A separate trained team conducted a survey of 1,746 workers across 293 of the study kilns (this sample size did not differ from the final analytic sample size, Fig. S12, because kilns did not have to be operational at the time of the survey and was conducted at a different time). The goal of this survey was to understand the working conditions at these kilns, as well as worker characteristics and any benefits/incentives workers received. Using questions about working conditions, wages, contracts, and safety considerations, we also calculated the prevalence of labor trafficking according to standardized indicators and the existence of child labor. For each kiln, six individuals were interviewed: five workers spread across four job types (brick molders, brick loaders, brick unloaders, and firemen) and one sardar (work supervisor). Because some job types left early for Ramadan, we allowed for multiple workers of the same job type to be surveyed in order to obtain six individuals per kiln.

The baseline questionnaire was revised and used for endline data collection, which was collected from 328 (out of the original 357) kilns between June and July 2023. The endline survey sample is larger than the kiln performance monitoring sample because this survey did not require that kilns be operational during data collection.

Our primary outcomes are mostly derived from the kiln performance monitoring data. However, certain elements, such as brick prices and fuel spending, were collected only at endline from owners. In cases in which outcomes could be constructed using data reported at endline instead of the kiln performance monitoring data—such as specific fuel consumption, brick production by class, value of production, and fuel spending—we present results using the endline data in Tables S30, S20 and S28. The kiln owner measures reported at endline also differ in their reference period, as owners were asked to recall answers based on the entire season. In contrast, the kiln performance monitoring was collected at a single point in time during the firing season. However, we generally prefer the more objective measures from the kiln performance monitoring data, which are also not subject to recall bias.

Outcome Measurement Details

In this section we provide detailed explanations of the outcomes assessed in the main manuscript. See Table S3 for summary statistics of each outcome by treatment arm.

Adoption of the technical intervention

Adoption is defined as taking up both of the recommended brick stacking and firing practices (described in Technical Intervention Details above) based on objective observations from the evaluation team during the adoption checklist visit and the performance monitoring visit. A kiln must be following both of these recommended practices to be considered an "adopter."

Specific Energy Consumption (SEC)

SEC is defined as the thermal energy used in megajoules (MJ) for firing 1 kg of brick (MJ/kg of fired brick); lower SEC is associated with higher energy efficiency. The SEC was calculated based on data collected during kiln performance monitoring over a period of 24 ± 2 hours and is calculated according to the following equation:

$$SEC = \frac{H_{in}}{M_{fbr}} \tag{1}$$

where M_{fbr} is the mass of fired bricks produced during the monitoring period and H_{in} is the total thermal energy input to the kiln during the monitoring period, which is calculated as the energy input from external fuel fed into the kiln plus the energy input from internal fuel added to the bricks during soil preparation plus the energy input from organic matter present in the brick soil.

None of the study kilns were used internal fuel during the soil preparation process. The quantity of organic matter in agricultural soil in Bangladesh is small and has declined in recent years *(83)*. Thus, the energy input from organic matter was not considered. Only thermal energy input from the external fuel fed into the kiln during the period of monitoring was considered in our calculations. Therefore, H_{in} is calculated according to the following equation:

$$H_{in} = \sum_{i=1}^{n} M_{fe,i} \times CV_{fe,i} \tag{2}$$

where $M_{fe,i}$ is the mass of external fuel (i) fed into the kiln during the monitoring period and $CV_{fe,i}$ is the gross calorific value of fuel i in MJ/kg.

Samples of around 1.5 kg fuel of all the fuels being used were collected from the monitored kilns. Of the collected fuel samples, 45 coal samples (Indonesian coal = 35; Indian coal = 3; South African coal = 7) and 21 biomass samples (sawdust = 14; rice husk = 7) were tested for their gross calorific value (GCV) using the ASTM D 5865 standard in a laboratory. The mean GCV value for each type of fuel was used to calculate SEC (Equation 1). Results are shown in Table S11.

CO_2 Emissions

CO_2 emissions from brick firing were estimated following UNFCC approved methodology *(37.* Specifically, CO_2 emissions were calculated as tons of CO_2 entire season brick production according to the following equation:

$$CO2e = SEC \times M_{fbr} \times CEF \times CC \times Production \tag{3}$$

where SEC is the specific energy consumption of the kiln (Equation 1), M_{fbr} is the mass of 100,000 fired bricks, CEF is the IPCC default carbon emission factor for the other bituminous coal (25.8 tC/TJ), CC is the carbon to CO2 conversion factor, which is 44/12 or 3.67, and $Production$ is the total number of bricks produced over the entire season (measured in 100,000s), reported by owners at endline. Results are shown in Table S12. We also constructed an alternative measure of CO_2 emissions derived from the carbon fraction in the fuel mix. This measure was calculated as tons of CO_2 emissions produced by each kiln over the entire season brick production according to the following equation:

$$CO2e = \alpha \times SFC \times MW \times CEF \times CC \times Production \tag{4}$$

where, α is the mole of CO_2 produced per gram of fuel mix calculated applying the carbon balance method (using data on carbon present in the fuel mix and ratio of CO_2 to CO obtained from the flue gas analysis); SFC is the specific fuel consumption (tons of fuel mix used per 100,000 bricks), explained further below; MW is the molecular weight of CO_2, which is taken as 44 g/mol; and Production is the total number of bricks produced over the entire season, (measured in 100,000s), reported by owners at endline.

The results with both measures are very consistent and presented in Figure S4.

$PM_{2.5}$ Emissions

$PM_{2.5}$ emissions from brick firing were estimated using the energy-based emission factor for $PM_{2.5}$ emissions. The emission factor for zigzag kilns in Bangladesh *(50)* was used in these calculations.

$$PM_{2.5} = SEC \times M_{fbr} \times EF_{PM2.5} \times Production \tag{5}$$

where SEC is the specific energy consumption of the kiln (Equation 1), M_{fbr} is the mass of 100,000 fired bricks, $EF_{PM2\cdot5}$ is the $PM_{2\cdot5}$ energy-based emission factor for coal-based zigzag kilns in Bangladesh (0.25±0.18 g of $PM_{2\cdot5}$/MJ of energy input *(50)*), and $Production$ is the total number of bricks produced over the entire season, (measured in 100,000s), reported by owners at endline. Results are shown in Table S13.

Fuel Spending

Fuel is a kiln owner's most expensive input. By reducing the quantity of fuel used to fire a fixed quantity of bricks (e.g., the specific fuel consumption described below), the technical intervention should reduce the amount of money owners spend on fuel per unit of output. We calculated two measures of fuel spending per quantity of bricks produced. The first is based on the more objective measures of fuel consumption and quantity of bricks that were fired using that coal collected during kiln performance monitoring. Specifically, we calculated the fuel spending per brick using the following equation:

$$FS = \frac{\sum_{i=1}^{n} Q_i \times P_i}{N} \tag{6}$$

where Q_i is the quantity of fuel i consumed during the monitoring (or reported in the endline) and P_i is the price/ton reported for fuel i. N is the total number of bricks fired during monitoring. These results are shown in Table S14. Then, to estimate the total savings on fuel, we applied this per brick measure to the to quantity of bricks produced during this season, which was reported by kiln owners at endline (Table S15. Tables S21 and S22 report the comparable results using only spending on coal.

Brick Quality

Brick quality is an indicator of both improved efficiency and kiln owner benefits. When bricks are fired in a traditional kiln, the highest quality or properly baked bricks are classified as Class 1 bricks and sold for a higher price than inferior classes. Fired bricks get their strength from ceramic reactions that take place at a high temperature. The temperature depends on the type of soil; for Bangladesh, this is around 1,000°C. In the kiln, bricks must be raised to this finishing temperature and the temperature should be maintained for a few "soaking" hours to ensure that the entire brick has attained uniformity *(84)*. Class 1 bricks are obtained only when both the finishing temperature and soaking-time conditions are met. If the temperature is lower or sufficient soaking time is not provided, then under-fired (Class 2 and Class 3) bricks are produced. If the temperature or soaking time is exceeded, over-fired bricks are produced (which end up being crushed and sold in cubic feet of broken bricks). The intervention improves the uniformity in kiln temperature in the cross-section, and thus should result in a larger percentage of bricks that achieve the correct finishing temperature and soaking time. In other words, the fraction of bricks that are the highest quality—Class 1—should increase.

During the kiln performance monitoring, the evaluation team organized fired bricks that were unloaded from the kiln that day into classes (Class 1, Class 1.5, Class 2, Class 3, broken bricks) and recorded how many bricks in each class were unloaded. This was used to calculate the percentage of total bricks unloaded during the monitoring period that fell into each category. Results for the % of Class 1 bricks are shown in Table S16 and the entire distribution is shown in the main manuscript in Fig. 3. Also, during the endline survey owners reported the percentage of their total annual production this firing season that fell into each quality class. This measure was used in the supplementary analysis (Table S30 and Fig S3).

Value of Production

Since kiln owners can time brick sales 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 calculate the expected value of production by multiplying the median reported brick prices for each class of brick by the production of each class of brick, then normalizing by the total quantity of bricks produced according to the following equation:

$$VoP = \frac{\sum_{i=1}^{5} Q_i \times P_i}{N} \tag{7}$$

where Q_i is the quantity of brick class i for $i \in \{$Class 1, Class 1.5, Class 2, Class 3, and broken bricks$\}$ measured during the monitoring (or reported in the endline) and P_i is the median price reported for brick class i. N is the total number of bricks unloaded, counted, and classified during monitoring (or in some specifications, N is the total production reported by owners in the endline). This "normalized" measure ends up being driven entirely by differences in brick quality. Thus, we report the effect on brick quality in Fig. 3 and the value of production per brick in Table S27 with monitoring data and Table S28 using kiln owner self reports at endline. We also calculate the total value of production for the entire season using the kiln owner reported data on brick quality and production at endline, which is equivalent to $VoP = \sum_{i=1}^{5} Q_i \times P_i$. These results are reported in Table **??**. We can also calculate this by applying the objective brick quality data measured during the kiln performance assessment to the annual production reported at endline, but as the effect sizes for the objective and self-reported brick quality are similar, the total value of production is also similar (Table S29)

CO/CO_2 ratio

Particulate matter emitted with the flue gases from brick kiln chimneys causes air pollution. There are two main sources of primary particles in flue gas in a brick kiln:

1. Particles from incomplete combustion. This includes soot, tar particles, and char particles.
2. Particles originating from inorganic material in the fuel, primarily ash in the fuel.

In the case of complete combustion, the carbon (C) present in the fuel gets converted into carbon dioxide (CO_2). If the combustion is not complete, some of the carbon gets converted into carbon monoxide (CO). The carbon monoxide to carbon dioxide (CO/CO_2) ratio is a good measure of the completeness of combustion *(51)*. The CO/CO_2 ratio is strongly influenced by the kiln's operation and particularly by the fuel feeding status.

During kiln performance monitoring, measurements of CO and CO_2 were carried out using a flue gas analyzer for a period of around 2 hours per kiln. The analysis was conducted at the point at which flue gases exit the trench and enter the flue duct on their way to the chimney. The fuel feeding status (feeding/non-feeding) was also recorded for the duration of the flue gas analysis. The flue gas analyzer provided data at 5-second intervals, which was first averaged over 1-minute intervals. The ratio of CO/CO_2 was calculated for each time step, and these were averaged over the duration of flue gas monitoring to yield an average CO/CO_2 for the kiln. In addition to the average, the maximum CO/CO_2, standard deviation, and interquartile range were calculated (note that only the average was prespecified). Supplementary analyses explored the sensitivity of results to dropping abnormal values, as well as estimate specifications on the maximum and variance. See Tables S40-S57.

Specific Fuel Consumption (SFC)
SFC is defined as the amount of fuel used in tons for firing 100,000 bricks (tons of coal/100,000 bricks); a lower SFC is indicative of more efficient use of coal. This is the metric used by most brick kiln owners to estimate the efficiency of a kiln. SFC was calculated based on data collected during kiln performance monitoring over a period of 24 ± 2 hours and is calculated according to the following equation:

$$SFC = \frac{\sum_{i=1}^{n} M_{fe,i}}{N_{fbr}} \times 100000 \tag{8}$$

where $M_{fe,i}$ is the mass of external coal (i) fed into the kiln during the period of monitoring and N_{fbr} is the number of bricks fired during the period of monitoring. Additionally, specific coal consumption is calculated as the equivalent measure, based only on coal used (rather than all fuels used). Since coal is used in the largest quantities, specific fuel consumption and specific coal consumption are similar (Table S19).

Annual Production
The total quantity of bricks (in 100,000s) produced during this firing season (2022-2023) was collected from owners during the endline survey. This measure, which was not prespecified, was used to assess potential rebound effects and results are shown in Table S24.

Circuits Completed
In a zigzag kiln, the fire moves around the kiln's firing chamber (a single cycle around the kiln is referred to as completing a circuit). The total number of firing circuits completed was collected from owners during the endline survey. On average, kilns in our sample completed 5 firing circuits during the 2022-2023 season. This measure, which was not prespecified, was used to assess potential rebound effects and results are shown in Table S25.

Worker Incentives and Work Conditions
To analyze the impact of the worker incentive arm and the specific messaging delivered, we examined outcomes related to the provision of any benefits, provision of any benefits to the firing or loading teams, and the presence of several aspects of better working conditions: whether the kiln provides meals, cooking fuel, or a shed for resting. These are shown in Fig. 5 (in the main paper).

Statistical Methods

To estimate the treatment effects of the intervention, we regressed outcomes on indicator variables for treatment status.

$$Y_i = \beta_0 + \beta_1 T_i + \beta_2 I_i + \gamma_s + \epsilon_i \tag{9}$$

where Y_i is an outcome of interest for kiln i, T_i is a binary indicator for assignment to the technical only arm, and I_i is a binary indicator for assignment to the incentive arm. The coefficients on each treatment indicator, β_1 and β_2, respectively, capture the "intention-to-treat" (ITT) effect of assignment to the treatment arms on each of the outcomes relative to the control arm and δ_s is an indicator for the strata. We will also estimate a version of Equation 9 in which we bundle treatment into a single treatment indicator that captures the ITT effect of assignment to either treatment arm (Equation 10).

Heteroskedasticity-robust standard errors are calculated for all specifications.

$$Y_i = \delta_0 + \delta_1 G_i + \gamma_s + \epsilon_i \tag{10}$$

Because we did not expect all 200 kilns assigned to the treatment arms will adopt the technical intervention (where adoption is defined as taking up both of the recommended brick stacking and firing practices), we also estimated instrumental variable (IV) specifications. This allows us to quantify the impact of the technical intervention among the kilns that *actually* took up the recommended practices. Because non-adoption and noncompliance are not random but likely the result of systematic differences between kiln owners that are likely correlated with the outcomes, our second approach is to use the random assignment as an instrument for adoption in an instrumental variables analysis that measures the local average treatment effect (LATE) among the kilns that took up the intervention (e.g., the compliers) *(75,85)*.

In the absence of defiers (so that only compilers, never-takers and always-takers are present in the language of Imbens and Angrist *(75)*, the ToT parameter is equal to a weighted average of the treatment effect among compliers and the treatment effect among always-takers. If we rule out always-takers, then the ToT parameter is equal to the average treatment effect (ATE) among compliers and is consistently estimable using IV. In the presence of always takers (which is likely the case in our setting since 20% of control kilns adopted the intervention) the ToT is no longer identified, although the ATE among compliers continues to be identified (and is consistently estimable using IV). For this reason we refer to our estimand at the IV effect (or equivalently the LATE).

To estimate the IV, we used the following two-stage least squares (2SLS) approach:

$$A_i = \theta_0 + \theta_1 G_i + \gamma_s + \epsilon_i \tag{11}$$

$$Y_i = \gamma_0 + \gamma_1 A_i + \gamma_s + u_i \tag{12}$$

Equation 11 is the first stage in which adoption (A_i) of the two most critical intervention components (double or triple zigzag brick setting and single fireman continuous coal feeding) is predicted with the randomly assigned treatment (using a bundled treatment indicator, G_i). Then, in the second stage, Equation 12, we regress an outcome on the instrumented adoption and γ_1 captures the IV effect of adopting the intervention on the outcome. Heteroskedasticity-robust standard errors are calculated for all specifications.

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 non-compliance (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 method (*76*) to recover $\mathbb{E}(Y_0|\text{C})$, the results are similar.

We explored heterogeneity in the primary outcomes across dimensions such as kiln owner years of experience in the brick industry, kiln owner education, whether the kiln owner is involved in other businesses, and kiln location. Our preregistered analysis plan specified that we would examine heterogeneity in the primary outcomes by baseline kiln characteristics, including owner's experience, owner's education, location on highland, and whether the kiln is a joint proprietorship. For brevity, we present these results in Table S32 and find no significant differences in the treatment effects by these characteristics at the standard 5% level. Although our pre-analysis plan includes a correction for multiple hypothesis testing for the heterogeneous models, we do not make this correction given that the uncorrected interaction terms are statistically insignificant.

Our trial and analysis was preregistered with AEA (#AEARCTR-0010127) and the ISRCTN (#ISRCTN15354089). Any specifications that deviate from this plan are stated.

Incentive Arm Script

Kilns that were randomized into the technical+incentive arm received a detailed information session along with the hands-on training provided with the technical intervention. In these information sessions, our team described how our pilot work increased brick quality while decreasing fuel use, and that achieving these benefits depends on the ability to align worker incentives with the new production method, providing evidence that pilot firms that increased worker pay experienced greater benefits. The complete script is as follows:

[Begin Script]

I'm here to talk to you about how you can get more profit in this year's brick production. We are glad you are working with us to implement the new practices, but their success depends on every worker on your kiln. Our team is here to help with technical training and assistance to make sure your workers have the proper skills to implement everything correctly. **If everyone on your kiln works together and follows the instructions, you will use less coal and increase your production of Class-1 bricks. As a result, these new practices will increase your profit and your kiln will be more successful.**

How do we know this?

Our team worked with similar brick kilns in Jashore, and a 14% increase in the percentage of Class-1 bricks and a 20% reduction in coal spending per brick in kilns that successfully followed the recommended practices of single fireman continuous coal feeding and double zigzag brick setting owners saw, compared to kilns using traditional methods.

What's more interesting is that the owners from Jashore that provided more incentives and benefits to their workers had even higher Class-1 bricks (on average, 5 percentage points higher) and lower coal spending (on average, 0.42 Taka less per brick) compared to kilns that did not offer additional incentives.

How can you reap the same benefits?

The workers on your kiln are crucial for the success of this new practice. They have to learn the new practices and at first they may not want to change from the old way of doing things. If your workers invest the time to master the new skills it will lead to huge benefits for you . Now, you can imagine when they are learning the new practices they might more slowly which might reduce their pay. If they do not feel motivated to adopt the new practices, they may take shortcuts or not learn it properly unless you find a way to include them in the success you will have from these new practices.

You may also consider the time and effort you are putting in to having your workers trained on these new practices. They are learning many new skills which will make your kiln successful. You will benefit if you can use the same workers next season, because they will already have the experience and training on these new practices. If you can encourage workers to return, it will be very beneficial to your kiln operation and production.

Because all workers on your kiln must be successfully adopt these practices and work together to increase your production and profit, we recommend any incentives or extra bonus be offered to all workers.

We have some suggestions that other kiln owners like you have used and found to be successful at increasing their kiln performance, getting better performance from workers, and commitments from workers to return to the same kiln:

1. Providing some extra monetary incentives to the workers to motivate them to follow this new practice properly. This will be easily covered by your increased profit /production soon. Because all workers on your kiln must be successfully adopt these practices and work together to increase your production and profit, we recommend incentives be offered to all workers. Successful kiln owners have used incentives differently for different categories of workers, for example, firing workers are given lump sum bonuses after a circuit, whereas unloaders and loaders are given bonuses in terms of 1000 bricks.

2. There are easy improvements you can make for your workers to make them happier and healthier to motivate them be more productive. If your kiln gets a reputation for being a good place to work, where workers are well-taken care of, your workers are more likely to return next season and more workers will want to work for you.

How can you make incentives and benefits work for you?

When offering these incentives, it is very important that the workers themselves receive the benefit. Otherwise, they will not be motivated to adopt the new practices, trust will be lost, and your kiln will not benefit. You may encourage the sardars to provide these benefits to workers so that the workers will adopt the practices. Some owners provide benefits directly to the workers to make sure they receive them. A common practice of successful owners is to announce a particular day and time and request all workers and sardars be present, then owners hand over bonuses/bakhshish by themselves. This practice is successful because everyone will give credit to the owner for the extra benefits.

It is also important that you provide the incentives and benefits in a timely manner and early in the season. If it is too late, the workers may not be encouraged to follow the new practices and you will not see the benefit in time.

[Ask: Any questions on what we have talked about so far?]

What are examples of monetary incentives and good working conditions that you can provide?

We have put together a list of suggestions from successful kiln owners for you to think about:

1. You may offer a ‘Bakhshish’ from the higher earnings that you will get by adopting our suggested practices. For example, you can offer a Bakhshish to your workers such as 5-10%, which can be shared across all the workers. One successful kiln owner has provided 10000 Tk to the loading Sardar for adopting the new system and he committed to providing it subsequently in the next rounds of brick stacking. If you inform them at the beginning of each circuit about the

Bakhshish and the importance of following the new practices to achieve a higher amount, it will motivate their performance during the circuit.

2. You may offer a bonus (onudan) to the workers if your kiln achieves a certain level of class-1 bricks in each circuit. We have provided a guideline for the bonuses depending on the share of class-1 bricks. For example, you may offer BDT 5000 if your kiln achieves 80-85% class-1 bricks in a cycle, BDT 6000 if you achieve 85-90% class-1 bricks, and BDT 7000 if you achieve >90% class-1 bricks. You can adjust the schedule given your kiln's performance. We suggest you inform workers at the beginning of the circuit about the bonus to motivate their performance and deliver the payment at the end of the circuit once the brick quality has been assessed.

3. You can also provide 'Bakhshish' of extra Taka 50 per 1000 bricks if your kiln achieves 80-85% class-1 bricks, extra Taka 100 per 1000 bricks if your kiln achieves 85-90% class-1 bricks, or extra Taka 150 per 1000 bricks if your kiln achieves >90% class-1 bricks.

4. Some of the recommended practices will require more time involvement for the workers. For example, in the new method, workers need to increase the ash layers by 9-12 inches from the previous setting. In the new method, fire travels faster and more loading of bricks is necessary to keep up the fire travel in a circuit. In both cases, you can consider increasing the wages of the workers by Taka 10-50 per 1000 bricks to account for the changes.

5. You may offer a return bonus if workers return to your kiln the next season. Inform them of the bonus offer before the end of the current season, so that it can encourage them to return the next year. For example, some kiln owners have offered a bonus equal to 20% of the workers current wages if they return the following season, which will be paid only after they return.

6. You might see that some of your workers want to leave for other working options during the firing season, especially on agricultural fields. To prevent workers who have been trained on these new and improved practices from leaving in the middle of an active season, kiln owners have provided instant bonuses in cash. By making your kiln a more desirable and better paying place to work, the workers will not want to leave for other options.

7. Many kiln owners have successfully retained a higher presence of workers by offering 'attendance bonuses.' You can offer some bonuses for the top 5 workers who are most regular in your kilns to motivate all the workers to avoid shirking.

Power Calculations

Based on our pilot results, we have estimated effect sizes for the "intention-to-treat" (ITT) effect of each experimental arm, as well as an estimate of adopting (IV) that accounts for imperfect compliance with the intervention (both from kilns assigned to the treatment arm that did not take-up the intervention practices and from control kilns that sought to learn the intervention practices) by using random assignment to both arms as an instrument for adoption. These results for each of the three outcomes are summarized in Table S58 below. We first calculate the minimum detectable effect size (MDES) assuming both arms have equal effect sizes, a significance level of 0.05 and power of 0.9. Then, because there is suggestive evidence from our pilot that the incentive arm encouraged better adherence to the improved operating practices and resulted in better outcomes, we also calculate our statistical power for detecting differences between the incentive and technical arms.

Fig. S14 presents the minimum detectable effect sizes against the sample size per treatment arm for the percent of class-1 bricks produced, CO/CO_2 ratio, and specific energy consumption. The estimated ITT effects for each arm from the pilot study are indicated in red (incentive arm) and blue (technical arm). These scenarios indicate that with a sample size of 100 kilns per experimental arm (300 total kilns), we are powered for all three outcomes with 90% power in most cases. For class-1 bricks the incentive arm performed much better, producing 7.12 percentage points more class-1 bricks than the control group and we would be powered to detect an effect size of this magnitude with only 25 kilns per arm. The effect size for the technical arm was much smaller (2.1 percentage points higher than the control group) and with 100 kilns per arm, we would not be powered to detect such a small difference. However, 2.1 percentage points is an extremely conservative estimate for a potential effect size. The minimum detectable effect size for 100 kilns per arm at 90% power is 3.56 percentage points. This is half the magnitude of the incentive arm and still relatively conservative, particularly when considering the TOT estimate of 9.22 percentage points among adopters.

For the CO/CO_2 ratio, with 100 kilns per arm, we almost are powered for the more conservative ITT effect attained by the incentive arm but more than sufficiently powered to detect the larger effect size attained by the technical arm. With 100 kilns per arm at 90% power, we are powered to detect an effect size of -0.0064 in the CO/CO_2 ratio, while we would need only 65 kilns per arm to detect an effect as large as -0.008, which is what the technical arm attained in the pilot. Somewhat surprisingly, the measured CO/CO_2 ratio in the pilot was lower in the technical arm than in the incentive arm. This may simply reflect that the CO/CO_2 ratio is a cross-sectional measure that we captured based on data from a few hours in each kiln and so may not accurately reflect the performance over the whole season. Indeed, the first CO/CO_2 ratio was measured before the incentive arm was even rolled out. Nevertheless, the calculations suggest that we will have sufficient power to be able to detect changes in CO/CO_2 ratio with the interventions.

Similar to the percent of Class-1 bricks, our pilot results suggest kilns assigned to the incentive arm had a much lower specific energy consumption (SEC). While we will not be powered to detect effect sizes as small as what the pilot found in the technical arm, we are powered to detect effect sizes smaller than what the technical arm attained. With 100 kilns per arm at 90% power, we are powered to detect an effect size of -0.065 in SEC, while we would need 70 kilns per arm to detect an effect as large as -0.083, which is the ITT effect for the incentive arm compared to the control group. We summarize the minimum detectable effect sizes for a study with 100 kilns per arm with power of 80% and 90% in Table S59.

It is also of interest to assess the power for detecting differences between the two arms. Although we were not powered in the pilot to statistically detect differences in the exploratory outcomes between the technical and incentive arms, our pilot provides suggestive evidence that kilns assigned to the incentive arm performed better than the technical-only arm, although statistically, we cannot rule out equivalent effects. Using these effect sizes and assuming 100 kilns per arm, we estimated the power we can expect to attain for each outcome, which is presented in Table S59. Given the small differences between the two arms, we are underpowered except for the percent of class-1 bricks, where we estimate having 80% power to detect a difference of 5 percentage points.

Kiln Performance Monitoring Protocol

Kiln performance monitoring was carried out in 276 kilns to collect outcomes for the trial (see Fig. S13 for the field activities timeline). Each monitoring visit was spread over 3 days (from 2 pm on Day 1 to around 10 am on Day 3). The monitoring teams consisted of one engineer and one research assistant. They were further assisted by one or two workers/helpers.

Timing of Monitoring

The performance of a brick kiln varies throughout a brick-firing season. Circuit-wise performance data were collected from a zigzag kiln located near Kolkata in India.[5] Data on the time taken to complete one kiln circuit and the SFC for a circuit are plotted in Fig. S15.

The brick-firing season can be divided into three phases:

1. Initial Phase (November to Mid-February): This is the winter period, during which the kiln structure and ground are wet from the water absorbed during the rainy season and green bricks loaded in the kiln have higher moisture content. As a result, the SFC and the time required to complete one circuit are higher.

2. Mid-Phase (Mid-February to end April): This is the spring and summer period. After a few circuits have been completed, the kiln structure and ground dry up; due to the dry weather, green bricks loaded in the kiln have lower moisture. The kiln achieves a steady state, and SFC is lowest.

3. End Phase (May-June): By this time, pre-monsoon rains are common and SFC again rises.

Based on this information, kiln performance monitoring was carried out during the mid-phase of the kiln operation when the kiln is operating at steady state. All kilns were monitored between February 20, 2023, and May 11, 2023.

To ensure that kiln performance was monitored when kiln operation was not disturbed and was representative of normal kiln operation, the following criteria were applied:

- The weather at the time of monitoring was dry.
- The kiln was not experiencing any shortage of labor to operate the kiln.
- The kiln had an adequate quantity of coal and green bricks for normal operation.
- The fire was located in the straight portion (which has a zigzag brick setting) of the kiln circuit.

Each monitoring team was equipped with following equipment and materials:

1. A platform balance scale (50-100 kg, with LC of 10 gm)
2. A container for fuel measurement
3. Flue gas analyzer and equipment
4. Fully charged and cleaned flue gas analyzer

[5] Personal communication between Greentech and Ashok Tewari, Owner, LMB Brick Kiln, Howrah, Kolkata.

5. Flue gas analyzer probe packed in PVC pipe case
6. Flue gas charger
7. 2 ft steel tube for placement of the probe
8. Napkin/cloth/tissues for cleaning the analyzer
9. Cloth and umbrella for protecting the flue gas analyzer
10. KANE Live program downloaded and installed on the mobile device/tablet.
11. Steel measuring tape (5 m)
12. Steel scale (12 in)
13. Tarpaulin sheets to cover an area of 10 m x 10 m
14. Zip polythene bags (2 kg size), labels, permanent marker, cello tape for sealing fuel sample bags.
15. Computer tablet for data recording and entry in ODK
16. Hardback notebook and pens
17. Placards for marking unloaded brick stacks
18. Bicycle pump for cleaning the probe
19. Set of multiplugs for electrical connections
20. Screwdrivers/tester.

The complete schedule of activities during the monitoring period is reported in Table S60

Supplementary Figures

Fig. S1. Year 2 Adoption by Treatment Arm. This figure presents the raw means of adopting double/triple zigzag brick stacking and single fireman continuous feeding by treatment arm across two firing seasons. Results from the RCT firing season (2022-2023) are shown in grey and results from a follow-up conducted during the subsequent year's firing season (2023-2024) are shown in orange.

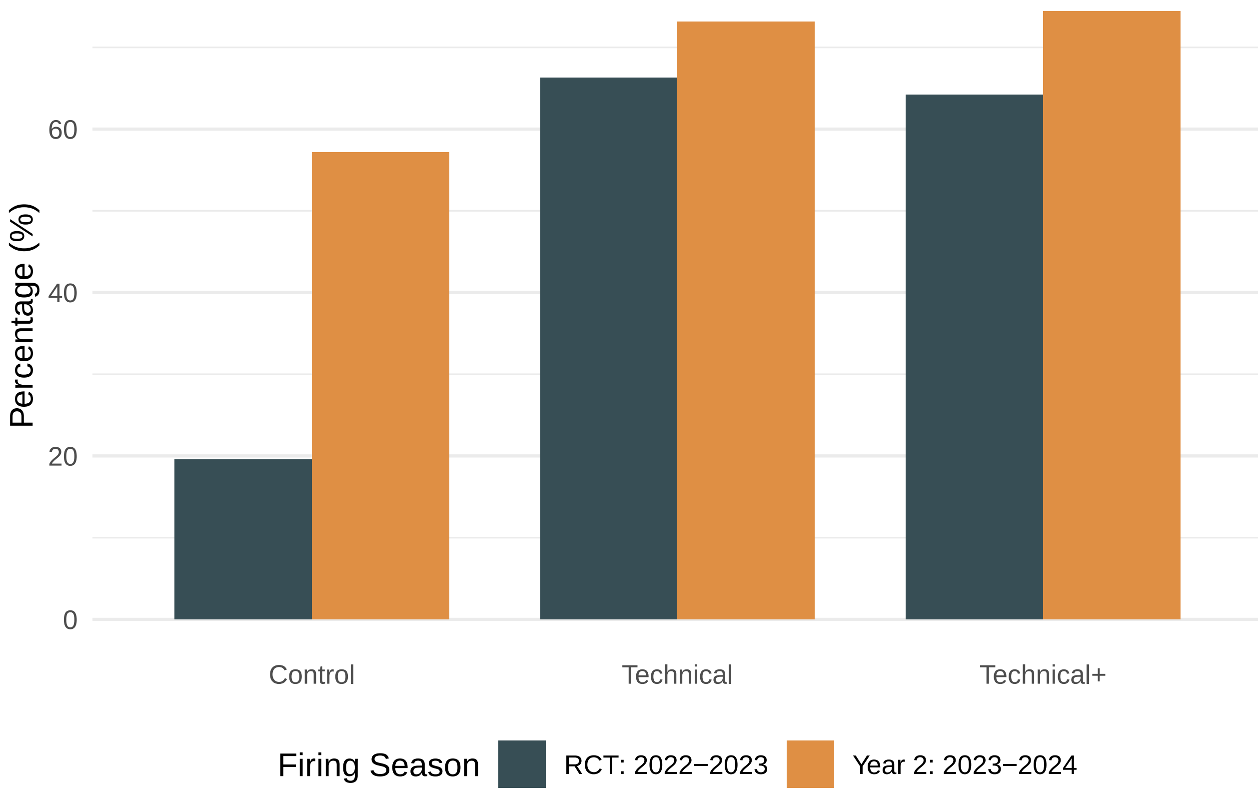


Fig. S2. Mean Suspended Particulate Matter by Adoption. Suspended particulate matter was measured in a subsample of 12 kilns (8 adopters, 4 non-adopters, where adoption is defined as adopting both the improved stacking and improved coal feeding practices).

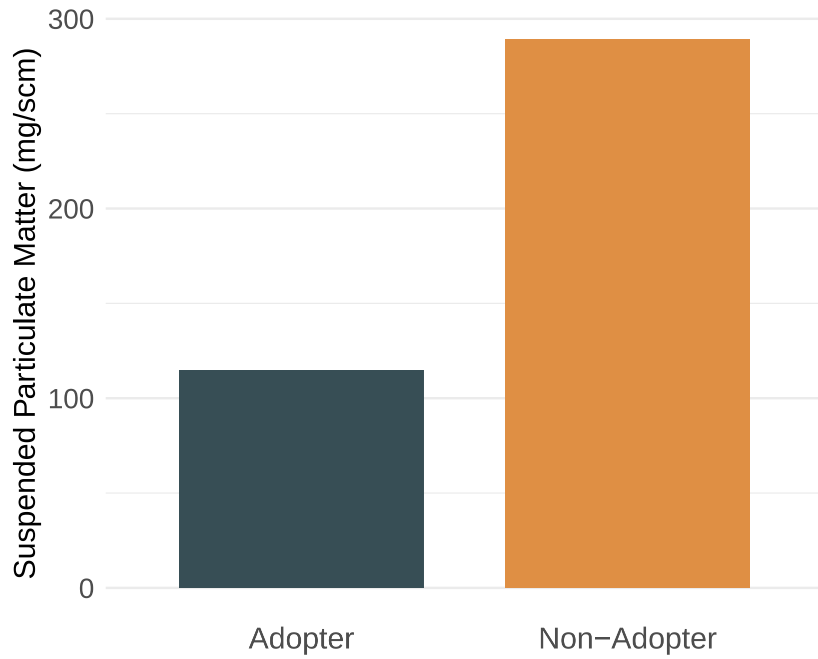


Fig. S3. Intervention Impact on Distribution of Brick Quality (Endline). This figure presents regression results for the intention-to-treat (ITT) and instrumental variable (IV) specifications for each classification of brick quality as a percentage of total production, using data reported by kiln owners at endline. 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 among compliers 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% confidence intervals around the regression coefficient.

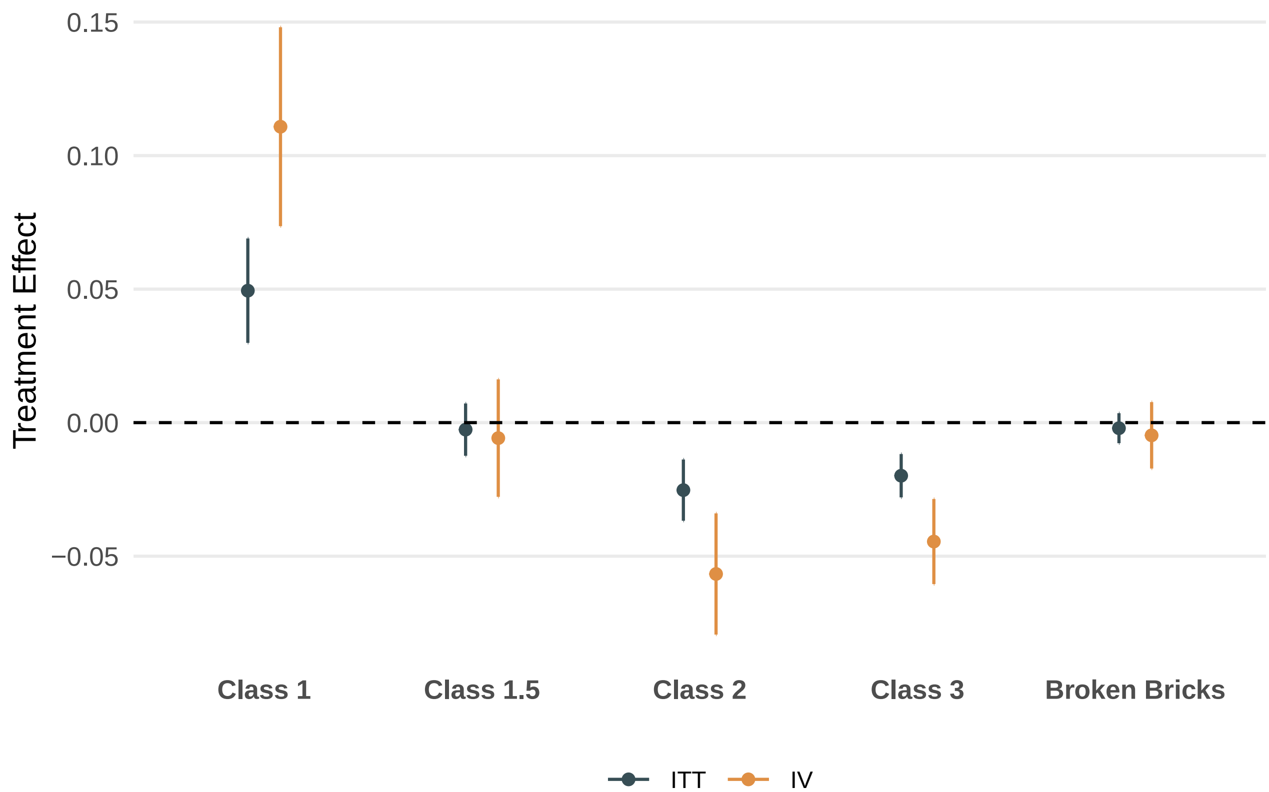


Fig. S4. Alternative Approach to Estimating CO_2 Emissions. This figure compares the ITT and IV results of the primary approach to estimating CO_2 emissions, in which the measure is derived from specific energy consumption to an alternative approach that uses the carbon fraction in the fuel mixture with the flue gas data, as described in the Materials and Methods.

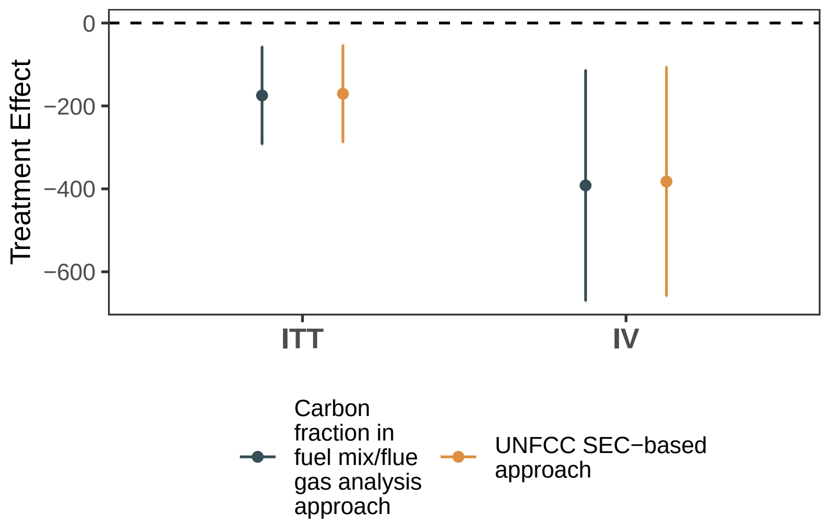


Fig. S5. Dense zigzag brick stacking with single zigzag path. This picture shows the standard dense brick setting practice (left) and the resulting airflow in a single zigzag path. See Technical Intervention Details for details.

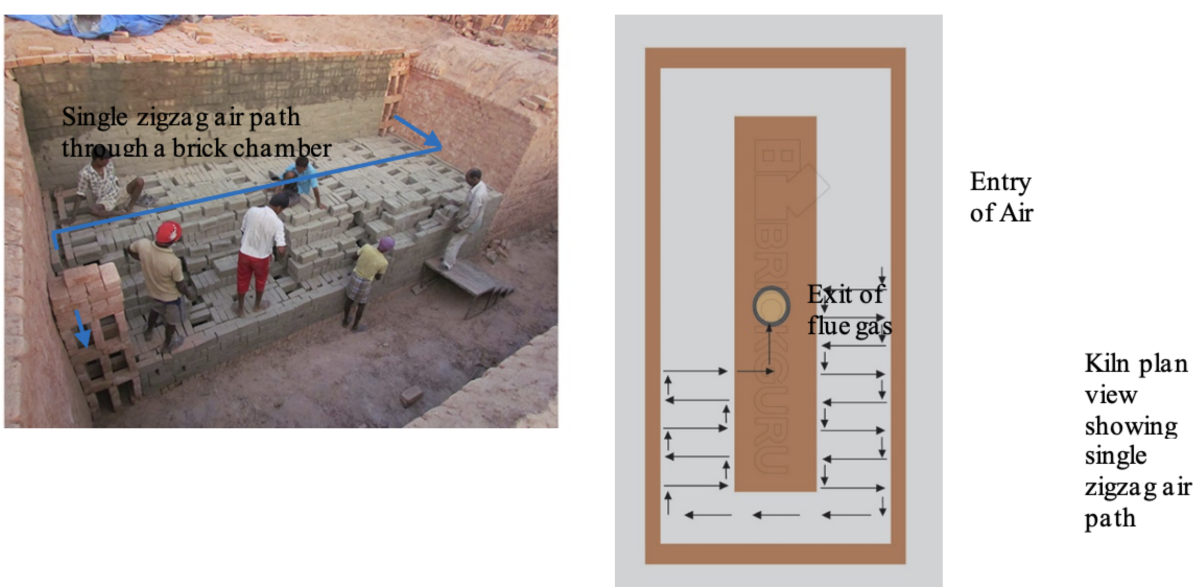


Fig. S6. Less Dense zigzag brick stacking with double/triple zigzag path. This picture shows the less dense brick setting practice recommended by the technical intervention (left) and the resulting airflow in a two zigzag paths. See Technical Intervention Details for details.

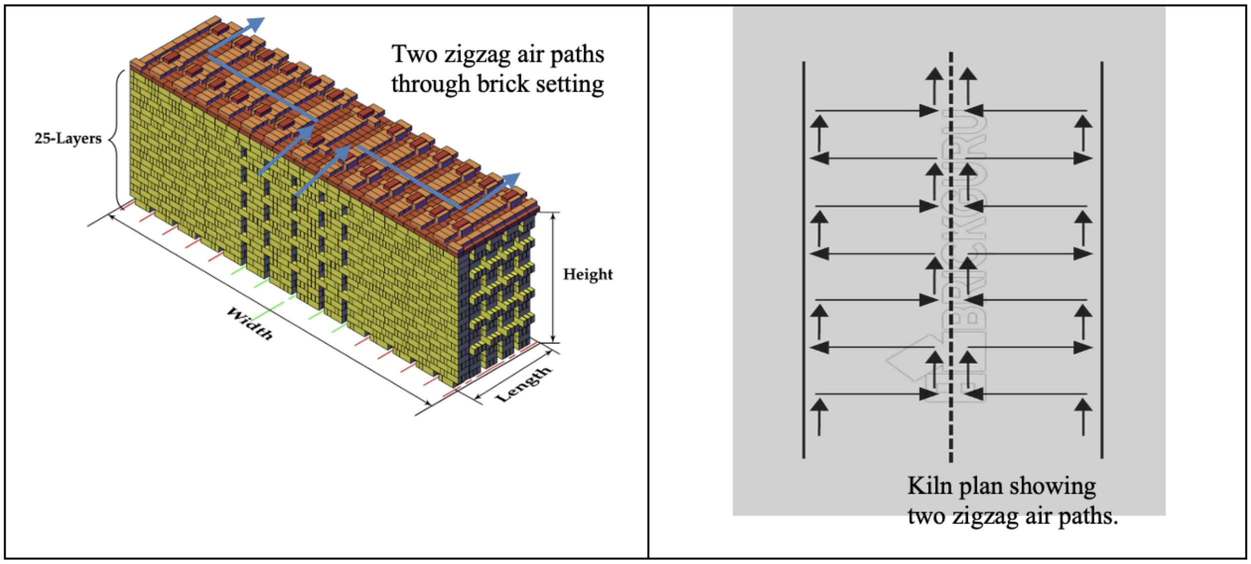


Fig. S7. Intermittent fuel feeding by 2 or 3 firemen simultaneously. This picture shows the standard practice of 2-3 firemen feeding coal simultaneously into the kiln. See Technical Intervention Details for details.

Fig. S8. Continuous fuel feeding by a single fireman. This picture shows the practice recommended by the technical intervention of a single fireman feeding coal. See Technical Intervention Details for details.

Fig. S9. Ash layer on top of the brick setting. This picture shows the ash layer used for insulation on top of the kiln and indicates the intervention recommended practice of an ash layer of at least 9 inches. See Technical Intervention Details for details.

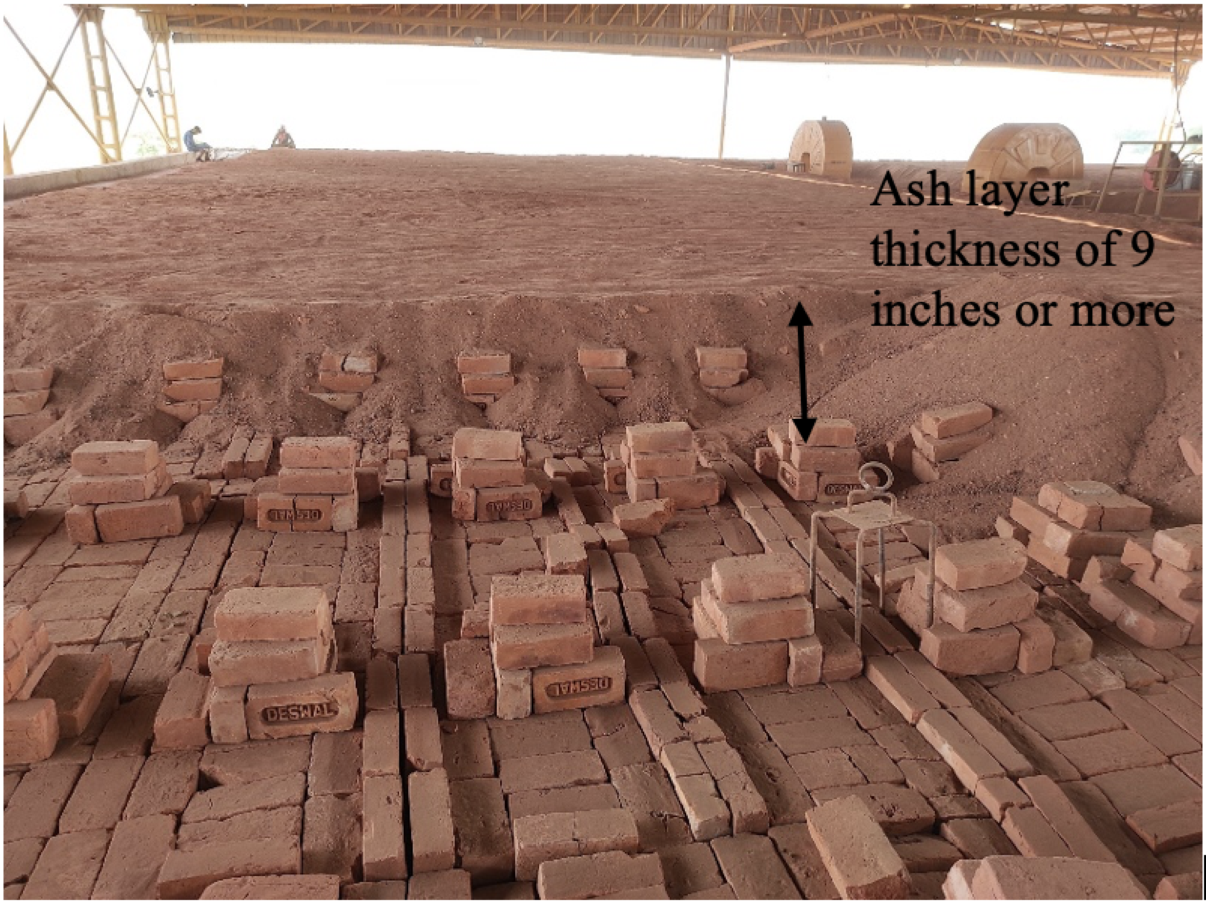


Fig. S10. Sawdust for feeding in newly inducted chambers in the fuel feeding zone. This picture depicts the practice of using sawdust in the front chambers of firing, as recommended by the technical intervention. See Technical Intervention Details for details.

Fig. S11. Map of Study Kilns, Khulna Division, Bangladesh. The study was conducted in the 6 districts indicated on the map: Jahsore, Khulna, Jhenaidah, Chuadanga, Kushtia, and Narail. Kilns assigned to control arm are shown in red, the technical arm in green, and the technical+incentive arm in blue.

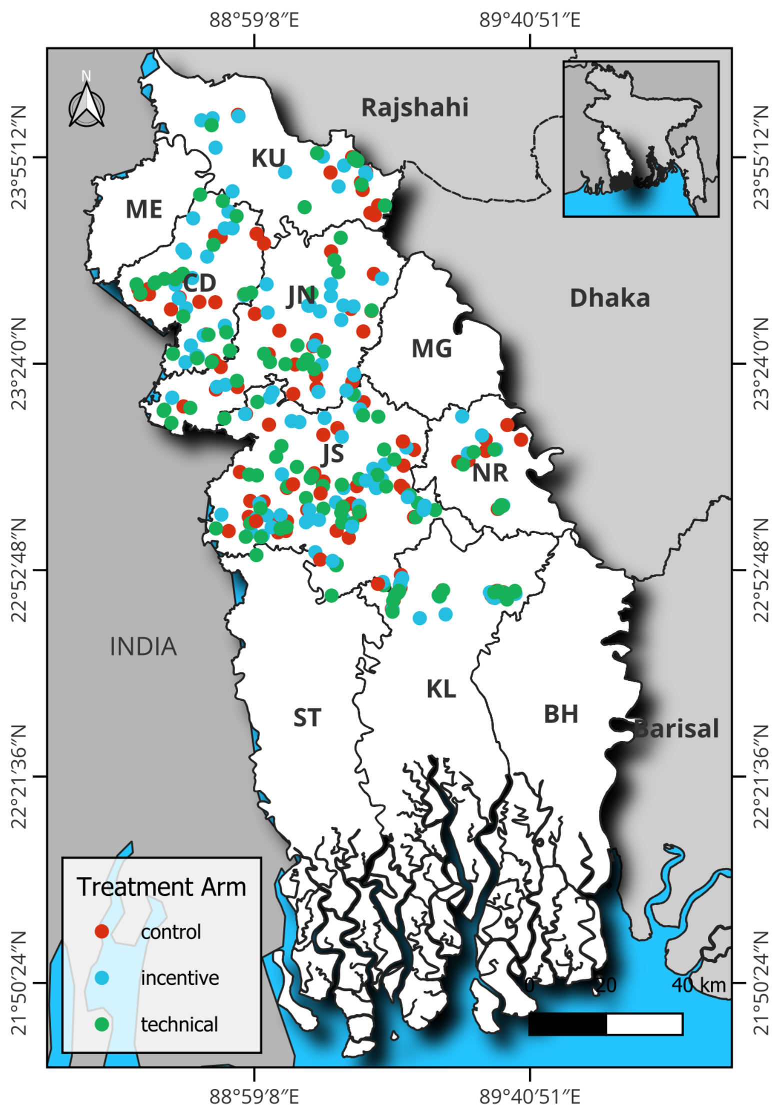


Fig. S12. Flowchart of sample size from baseline data to final analytic sample. Flowchart of sample size from baseline data collection to final analytic sample. Reasons for dropout at each stage, as well as number of kilns that dropped out for each reason, are reported. See Materials and Methods for details.

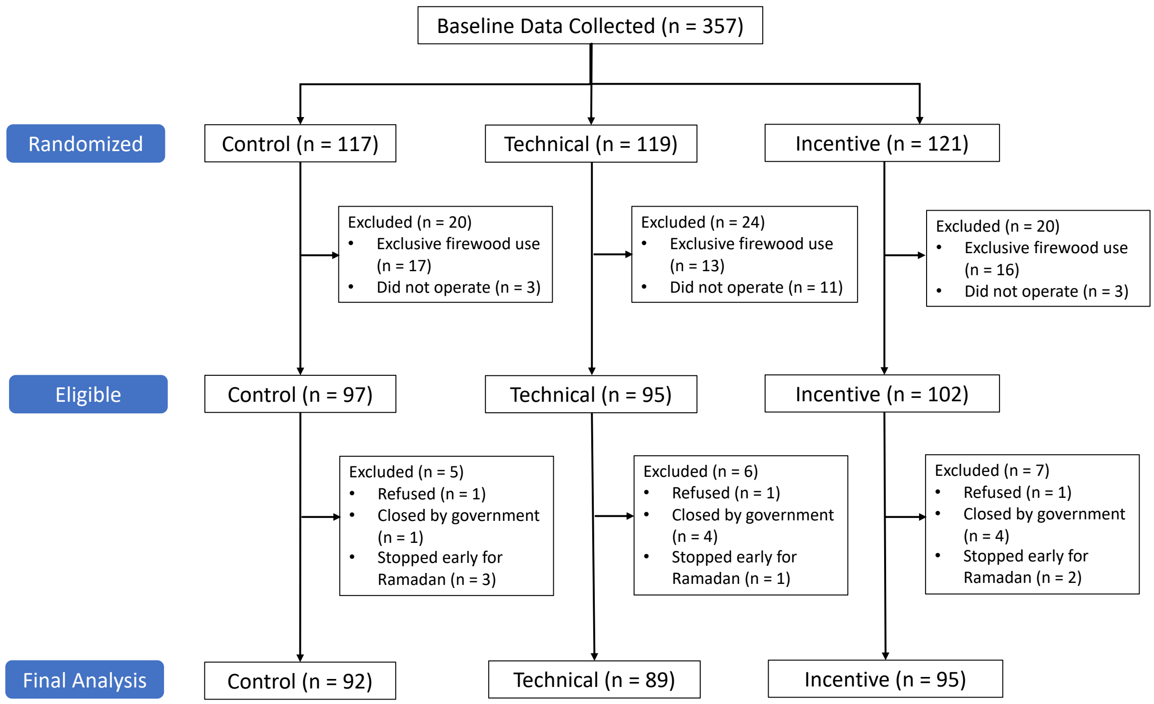


Fig. S13. Timeline of fieldwork activities. This figure presents the timeline of field activities and data collection during the 2022-2023 brick firing season. See Materials and Methods for details.

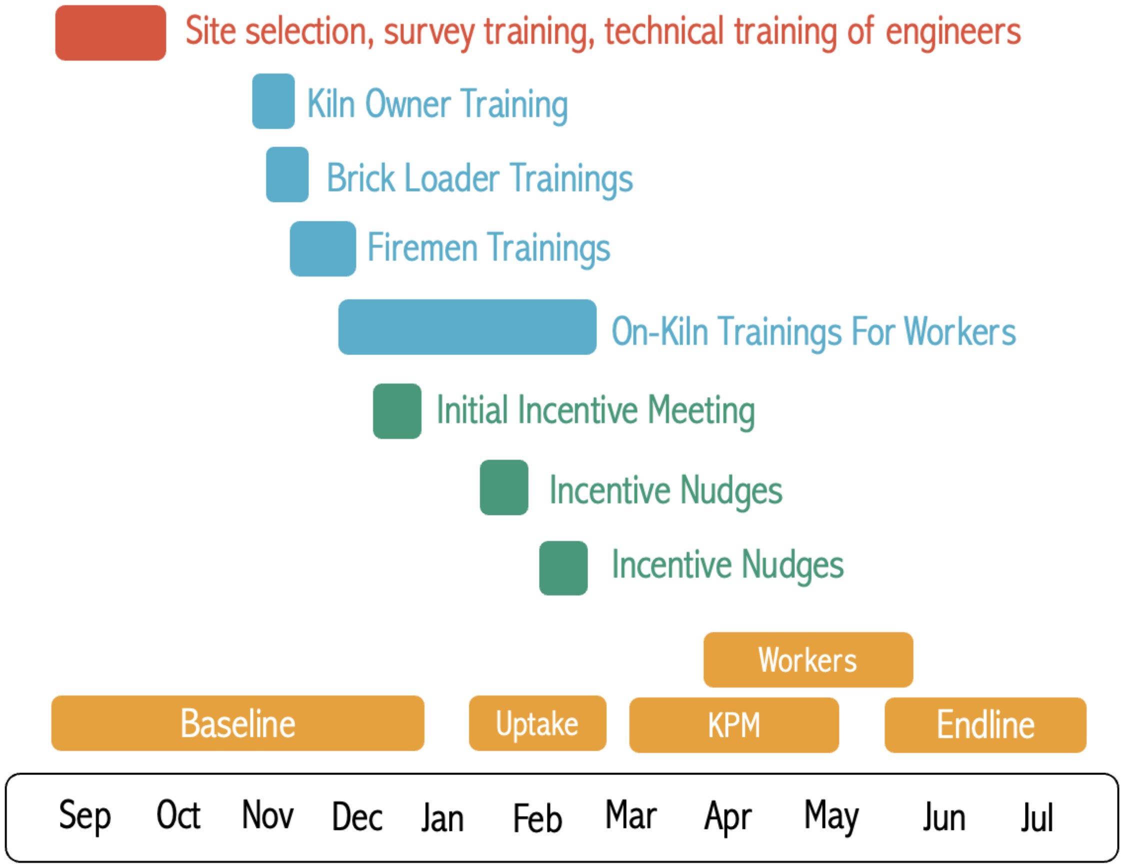


Fig. S14. Minimum Detectable Effect Sizes for RCT Outcomes. This figure presents the minimum detectable effect sizes for three outcomes (Class-1 bricks, CO/CO_2, and specific energy consumption) estimated with the power calculations conducted prior to the study implementation. Based on these power calculations, we aimed to enroll 300 kilns total (100 per arm) to be powered to detect effects with 80% power. See Materials and Methods for details.

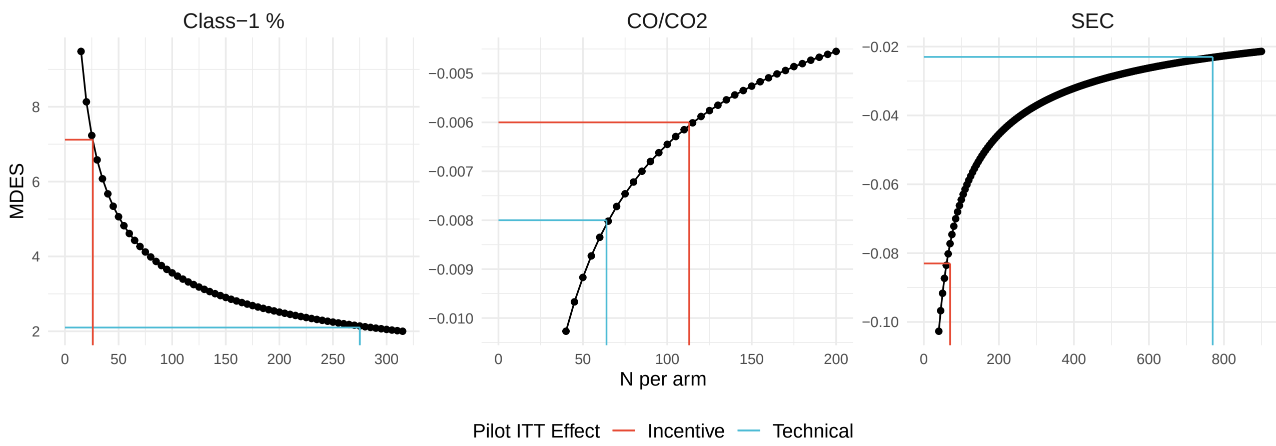
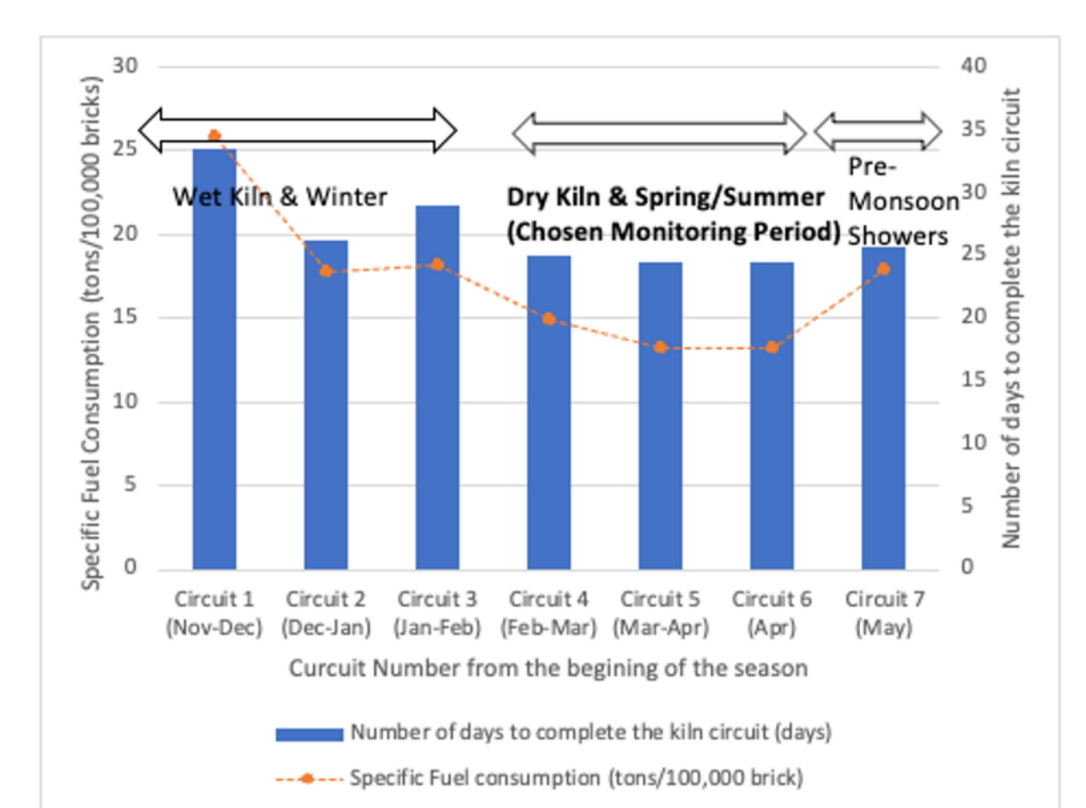


Fig. S15. Circuit-wise variation in the number of days required to complete the circuit and specific fuel consumption. This figure depicts the fuel requirements (per 100,000 bricks) across the brick firing season. At the beginning of the season (November-December), efficiency is lowest and then reaches a steady state around February.



Supplementary Tables

Table S1. Adoption By Intervention Component

	Adopter	Stacking	Feeding	Ash Layer	Cavity Wall	Sawdust	Total Practices
Technical Arm	0.45***	0.42***	0.45***	0.05	0.05	-0.02	0.95***
	(0.06)	(0.06)	(0.06)	(0.05)	(0.05)	(0.06)	(0.17)
Technical+ Arm	0.44***	0.44***	0.44***	0.09*	0.07	-0.10+	0.95***
	(0.06)	(0.06)	(0.06)	(0.05)	(0.05)	(0.06)	(0.16)
N	276	276	276	276	276	276	276

+ $p < 0.1$, * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Note: Heteroskedasticity-robust standard errors are in parentheses. Regression includes randomization strata fixed effects. Adoption (column 1) is defined as adopting both the improved stacking (column 2) and improved coal feeding (column 3) practices.

Table S2. Interaction between control and treatment kilns

Characteristic	**N**	**Value**
How control kilns learned about intervention		
Owner's association	18	78% (14)
Intervention team	18	39% (7)
Another kiln owner	18	67% (12)
Friend or relative	18	5.6% (1)
Another kiln worker	18	5.6% (1)
Who control kilns requested support from		
Another kiln's loading team	18	33% (6)
Intervention team	18	28% (5)
Another kiln's firing team	18	22% (4)
Another kiln owner	18	17% (3)
Treatment kilns contact		
Contacted about intervention	184	30% (55)
Provided support to adopt intervention	184	30% (56)

Note: This table presents summary statistics, % (n), for how control kiln adopters (n = 18) learned about the intervention and requested technical support. This table also presents summary statistics for whether intervention kilns (n = 184) were contacted about the intervention.

Table S3. Summary of Outcomes By Treatment Arm

Outcome	**Control**	**Technical+**	**Technical**
Specific Fuel Consumption (tons/100,000 bricks)	16.1 (3.3)	14.2 (3.0)	14.2 (2.7)
Specific Energy Consumption (MJ/kg fired brick)	1.07 (0.20)	0.94 (0.18)	0.95 (0.18)
CO/CO_2 (Mean ratio)	0.032 (0.014)	0.031 (0.018)	0.030 (0.016)
CO_2 Emissions (tons/season)	1,903 (505)	1,725 (428)	1,757 (368)
$PM_{2.5}$ (kg/season)	5.02 (1.33)	4.55 (1.13)	4.64 (0.97)
Value of Production (BDT/brick)	10.44 (0.19)	10.62 (0.20)	10.61 (0.21)
Fuel Spending (BDT/brick)	3.74 (0.71)	3.37 (0.66)	3.26 (0.77)
Total Fuel Costs (million BDT)	22.7 (5.9)	21.0 (5.3)	20.3 (5.1)
Annual Production (100,000 bricks)	62 (15)	63 (13)	63 (12)
Circuits Completed (Total number)	5.01 (1.31)	5.09 (1.19)	5.18 (1.11)
Class 1 (%)	78 (7)	84 (7)	84 (7)
Class 1.5 (%)	4.1 (4.6)	3.9 (5.8)	3.4 (3.9)
Class 2 (%)	8.2 (3.7)	4.9 (3.5)	5.0 (3.2)
Class 3 (%)	6.5 (3.6)	3.9 (3.4)	4.1 (3.6)
Broken Bricks (%)	3.24 (2.12)	3.07 (1.94)	3.19 (2.57)
Any benefits: any worker	74 (80%)	77 (81%)	70 (79%)
Any benefits: firing team	74 (80%)	76 (80%)	69 (78%)
Any benefits: loading team	37 (40%)	34 (36%)	36 (40%)
Any meals provided	75 (82%)	76 (80%)	77 (87%)
Cooking fuel provided	67 (73%)	79 (83%)	73 (82%)
Rest shed provided	83 (90%)	88 (93%)	79 (89%)
N	92	95	89

Note: This table presents the outcome means (standard deviations) by study arm. The first column presents the baseline mean and standard deviation in the Control arm, the second column presents the baseline mean and standard deviation in the Technical+ Arm, and the third column presents the baseline mean and standard deviation in the Technical Arm. The sample includes the 276 kilns for which outcome data was collected.

Balance Tests

Table S4. Original Sample Results (N = 328)

Balance Variable	Technical+ Mean	Technical+ Std. Dev.	Technical Mean	Technical Std. Dev.	Control Mean	Control Std. Dev.	T+ - C (p-val)	T - C (p-val)	T+ - T (p-val)
Owner Experience (Years)	14.1	8.2	15.5	10.1	14.3	9.7	0.82	0.4	0.25
Jashore Intervention Knowledge	0.29	0.46	0.32	0.47	0.28	0.45	0.98	0.57	0.55
Jashore Owner Interaction	0.48	0.51	0.50	0.51	0.61	0.50	0.69	0.79	0.86
Zigzag Year	2015	4	2014	4	2014	4	0.62	0.67	0.36
Water Adjacent	0.62	0.49	0.60	0.49	0.62	0.49	0.96	0.79	0.84
Bricks Fired (Lakhs)	8.0	1.0	8.0	1.2	8.0	1.2	0.8	0.89	0.68
Circuits Completed	5.9	1.6	5.8	1.5	5.9	1.8	0.76	0.61	0.37
Class 1 Production Share (%)	64.6	11.4	65.9	10.5	64.9	10.8	0.85	0.33	0.26
Production Cost Estimate BDT (per 1K Bricks)	8,754.4	1,155.4	8,529.8	1,192.9	8,666.2	1,032.8	0.51	0.36	0.14
Fired Brick Weight (kg)	3.37	0.25	3.41	0.22	3.41	0.23	0.19	0.98	0.2
Total Workers	108.6	27.8	107.8	31.5	109.3	34.2	0.91	0.74	0.81
Higher Secondary+	0.60	0.49	0.61	0.49	0.60	0.49	0.97	0.87	0.9
Highland	0.72	0.45	0.72	0.45	0.72	0.45	0.99	0.97	0.96
Joint Ownership	0.31	0.47	0.34	0.48	0.37	0.49	0.34	0.68	0.58
Shared Sardar	0.12	0.32	0.13	0.34	0.14	0.35	0.57	0.82	0.73
	N = 112		N = 108		N = 108				

Note: This table presents the results of balance tests run on baseline characteristics. The first two columns present the baseline mean and standard deviation in the Technical+ Arm, the second two present the baseline mean and standard deviation in the Technical Arm, and the third two present the baseline mean and standard deviation in the Control Arm. The last three columns present the p-value for a t-test of the difference in means between (1) Technical+ and Control, (2) Technical and Control, and (3) Technical+ and Technical. T-tests control for the randomization strata. The sample includes the original 328 kilns enrolled in the study.

Table S5. Jashore Expansion Sample Results (N = 29)

Balance Variable	Technical+ Mean	Technical+ Std. Dev.	Technical Mean	Technical Std. Dev.	Control Mean	Control Std. Dev.	T+ - C (p-val)	T - C (p-val)	T+ - T (p-val)
Owner Experience (Years)	17.0	6.4	17.2	8.5	20.9	10.3	0.38	0.39	0.97
Jashore Intervention Knowledge	1.0	0.0	0.73	0.47	1.0	0.0	0.28	0.066	0.05
Jashore Owner Interaction	0.33	0.50	0.62	0.52	0.33	0.50	0.94	0.32	0.36
Zigzag Year	2014	2	2015	2	2014	2	0.61	0.49	0.22
Water Adjacent	0.44	0.53	0.64	0.50	0.67	0.50	0.2	0.9	0.14
Bricks Fired (Lakhs)	7.83	0.61	7.4	1.3	8.00	0.75	0.61	0.18	0.3
Circuits Completed	6.4	1.4	6.5	1.5	6.4	1.7	0.81	1.0	0.84
Class 1 Production Share (%)	69.4	1.7	68.6	4.5	68.9	4.9	0.15	0.52	0.053
Production Cost Estimate BDT (per 1K Bricks)	9,055.6	300.5	9,000.0	591.6	9,044.4	133.3	0.94	0.83	0.82
Fired Brick Weight (kg)	3.37	0.11	3.38	0.11	3.34	0.13	0.68	0.58	0.89
Total Workers	98.0	29.3	117.5	26.5	98.2	28.8	0.99	0.15	0.17
Higher Secondary+	0.56	0.53	0.45	0.52	0.33	0.50	0.41	0.58	0.73
Highland	0.89	0.33	0.73	0.47	0.89	0.33	0.86	0.34	0.28
Joint Ownership	0.33	0.50	0.18	0.40	0.44	0.53	0.69	0.22	0.42
	N = 9		N = 11		N = 9				

Note: This table presents the results of balance tests run on baseline characteristics. The first two columns present the baseline mean and standard deviation in the Technical+ Arm, the second two present the baseline mean and standard deviation in the Technical Arm, and the third two present the baseline mean and standard deviation in the Control Arm. The last three columns present the p-value for a t-test of the difference in means between (1) Technical+ and Control, (2) Technical and Control, and (3) Technical+ and Technical. T-tests control for the randomization strata. The sample includes the additional 29 kilns enrolled to meet sample size requirements.

Table S6. Combined Sample Results (N = 357)

Balance Variable	Technical+ Mean	Technical+ Std. Dev.	Technical Mean	Technical Std. Dev.	Control Mean	Control Std. Dev.	T+ - C (p-val)	T - C (p-val)	T+ - T (p-val)
Owner Experience (Years)	14.3	8.1	15.7	9.9	14.8	9.8	0.62	0.53	0.23
Jashore Intervention Knowledge	0.36	0.48	0.37	0.49	0.36	0.48	0.94	0.84	0.77
Jashore Owner Interaction	0.44	0.50	0.53	0.51	0.53	0.51	0.78	0.68	0.51
Zigzag Year	2015	3	2014	4	2014	4	0.68	0.77	0.48
Water Adjacent	0.60	0.49	0.61	0.49	0.62	0.49	0.68	0.83	0.84
Bricks Fired (Lakhs)	8.0	1.0	8.0	1.2	8.0	1.2	0.74	0.81	0.94
Circuits Completed	6.0	1.6	5.8	1.5	5.9	1.8	0.76	0.67	0.42
Class 1 Production Share (%)	64.9	11.1	66.2	10.1	65.2	10.5	0.95	0.37	0.36
Production Cost Estimate BDT (per 1K Bricks)	8,776.8	1,116.8	8,573.3	1,157.1	8,695.3	997.6	0.5	0.36	0.14
Fired Brick Weight (kg)	3.37	0.24	3.41	0.21	3.40	0.22	0.22	0.94	0.19
Total Workers	107.8	27.9	108.6	31.1	108.5	33.9	0.93	0.95	0.88
Higher Secondary+	0.60	0.49	0.60	0.49	0.58	0.50	0.75	0.78	0.97
Highland	0.74	0.44	0.72	0.45	0.74	0.44	0.97	0.75	0.72
Joint Ownership	0.31	0.47	0.33	0.47	0.38	0.49	0.29	0.44	0.78
Shared Sardar	0.11	0.31	0.12	0.32	0.13	0.34	0.58	0.81	0.74
	N = 121		N = 119		N = 117				

Note: This table presents the results of balance tests run on baseline characteristics. The first two columns present the baseline mean and standard deviation in the Technical+ Arm, the second two present the baseline mean and standard deviation in the Technical Arm, and the third two present the baseline mean and standard deviation in the Control Arm. The last three columns present the p-value for a t-test of the difference in means between (1) Technical+ and Control, (2) Technical and Control, and (3) Technical+ and Technical. T-tests control for the randomization strata. The sample includes the combined 357 kilns enrolled (original 328 kilns plus additional 28 kilns added in Jashore district).

Table S7. Operated Sample Results (N = 340)

Balance Variable	Technical+ Mean	Technical+ Std. Dev.	Technical Mean	Technical Std. Dev.	Control Mean	Control Std. Dev.	T+ - C (p-val)	T - C (p-val)	T+ - T (p-val)
Owner Experience (Years)	14.4	8.1	15.6	9.9	14.8	9.9	0.69	0.6	0.32
Jashore Intervention Knowledge	0.36	0.48	0.37	0.48	0.37	0.49	0.77	0.86	0.92
Jashore Owner Interaction	0.42	0.50	0.53	0.51	0.53	0.51	0.79	0.67	0.5
Zigzag Year	2015	3	2014	4	2014	4	0.47	0.86	0.4
Water Adjacent	0.61	0.49	0.61	0.49	0.63	0.48	0.66	0.87	0.78
Bricks Fired (Lakhs)	8.01	0.98	7.9	1.2	8.0	1.2	0.94	0.44	0.36
Circuits Completed	6.0	1.6	5.9	1.5	6.0	1.8	0.92	0.86	0.77
Class 1 Production Share (%)	64.8	11.1	66.6	8.8	65.5	10.5	0.88	0.19	0.17
Production Cost Estimate BDT (per 1K Bricks)	8,788.1	1,126.2	8,578.0	1,203.8	8,674.1	999.8	0.36	0.54	0.16
Fired Brick Weight (kg)	3.38	0.24	3.41	0.21	3.40	0.22	0.43	0.79	0.3
Total Workers	107.4	27.7	109.2	31.5	109.2	33.7	0.78	0.92	0.69
Higher Secondary+	0.59	0.49	0.58	0.50	0.57	0.50	0.6	0.82	0.77
Highland	0.73	0.45	0.72	0.45	0.73	0.45	0.99	0.77	0.77
Joint Ownership	0.31	0.47	0.32	0.47	0.38	0.49	0.3	0.4	0.86
Shared Sardar	0.11	0.31	0.11	0.32	0.13	0.34	0.58	0.64	0.93
	N = 118		N = 108		N = 114				

Note: This table presents the results of balance tests run on baseline characteristics. The first two columns present the baseline mean and standard deviation in the Technical+ Arm, the second two present the baseline mean and standard deviation in the Technical Arm, and the third two present the baseline mean and standard deviation in the Control Arm. The last three columns present the p-value for a t-test of the difference in means between (1) Technical+ and Control, (2) Technical and Control, and (3) Technical+ and Technical. T-tests control for the randomization strata. The sample includes the 340 kilns that were operated during the 2022-2023 firing season (out of 357 originally enrolled).

Table S8. No Government Interference Sample Results (N = 348)

Balance Variable	Technical+ Mean	Technical+ Std. Dev.	Technical Mean	Technical Std. Dev.	Control Mean	Control Std. Dev.	T+ - C (p-val)	T - C (p-val)	T+ - T (p-val)
Owner Experience (Years)	14.4	8.2	15.6	9.9	14.8	9.9	0.66	0.57	0.28
Jashore Intervention Knowledge	0.38	0.49	0.38	0.49	0.35	0.48	0.87	0.78	0.9
Jashore Owner Interaction	0.44	0.50	0.52	0.51	0.52	0.51	0.79	0.68	0.51
Zigzag Year	2015	3	2014	4	2014	4	0.69	0.69	0.43
Water Adjacent	0.59	0.49	0.59	0.49	0.62	0.49	0.68	0.83	0.84
Bricks Fired (Lakhs)	8.0	1.0	8.0	1.2	8.0	1.2	0.7	0.71	1.0
Circuits Completed	6.0	1.6	5.8	1.5	5.9	1.8	0.82	0.53	0.36
Class 1 Production Share (%)	65.2	10.9	66.3	10.0	65.2	10.5	0.92	0.36	0.45
Production Cost Estimate BDT (per 1K Bricks)	8,773.4	1,123.6	8,558.4	1,174.4	8,684.1	994.5	0.44	0.38	0.13
Fired Brick Weight (kg)	3.37	0.24	3.41	0.22	3.40	0.22	0.26	0.86	0.21
Total Workers	107.1	28.1	108.1	30.4	108.2	33.9	0.84	0.98	0.86
Higher Secondary+	0.59	0.49	0.59	0.49	0.58	0.50	0.74	0.77	0.97
Highland	0.74	0.44	0.73	0.45	0.73	0.44	0.96	0.8	0.83
Joint Ownership	0.32	0.47	0.33	0.47	0.38	0.49	0.26	0.4	0.77
Shared Sardar	0.1	0.3	0.11	0.32	0.12	0.33	0.64	0.89	0.73
	N = 117		N = 115		N = 116				

Note: This table presents the results of balance tests run on baseline characteristics. The first two columns present the baseline mean and standard deviation in the Technical+ Arm, the second two present the baseline mean and standard deviation in the Technical Arm, and the third two present the baseline mean and standard deviation in the Control Arm. The last three columns present the p-value for a t-test of the difference in means between (1) Technical+ and Control, (2) Technical and Control, and (3) Technical+ and Technical. T-tests control for the randomization strata. The sample includes the 348 kilns that remained open during the 2022-2023 firing season and were not shutdown by the government (out of 357 originally enrolled).

Table S9. Analytic Sample Results (N = 276)

Balance Variable	Technical+ Mean	Technical+ Std. Dev.	Technical Mean	Technical Std. Dev.	Control Mean	Control Std. Dev.	T+ - C (p-val)	T - C (p-val)	T+ - T (p-val)
Owner Experience (Years)	15.4	8.5	16.5	10.1	14.6	9.7	0.64	0.26	0.46
Jashore Intervention Knowledge	0.37	0.49	0.37	0.49	0.36	0.48	0.82	0.91	0.92
Jashore Owner Interaction	0.44	0.51	0.58	0.50	0.52	0.51	0.77	0.48	0.33
Zigzag Year	2015	4	2014	4	2014	3	0.96	0.22	0.2
Water Adjacent	0.60	0.49	0.62	0.49	0.63	0.49	0.45	0.92	0.4
Bricks Fired (Lakhs)	8.0	1.0	7.9	1.2	8.1	1.1	0.36	0.12	0.45
Circuits Completed	6.1	1.5	6.0	1.5	6.1	1.8	0.9	0.59	0.45
Class 1 Production Share (%)	65.4	11.0	67.2	8.3	65.8	10.3	0.84	0.087	0.18
Production Cost Estimate BDT (per 1K Bricks)	8,810.4	1,215.1	8,581.1	1,284.3	8,683.2	1,039.5	0.29	0.77	0.22
Fired Brick Weight (kg)	3.38	0.24	3.40	0.19	3.39	0.23	0.56	0.85	0.43
Total Workers	107.9	28.9	111.2	31.5	110.8	34.8	0.75	0.67	0.46
Higher Secondary+	0.60	0.49	0.56	0.50	0.53	0.50	0.14	0.45	0.49
Highland	0.72	0.45	0.71	0.46	0.72	0.45	0.83	0.73	0.58
Joint Ownership	0.32	0.47	0.31	0.47	0.37	0.49	0.46	0.35	0.83
Shared Sardar	0.11	0.31	0.11	0.32	0.11	0.31	0.68	0.99	0.66
	N = 95		N = 89		N = 92				

Note: This table presents the results of balance tests run on baseline characteristics. The first two columns present the baseline mean and standard deviation in the Technical+ Arm, the second two present the baseline mean and standard deviation in the Technical Arm, and the third two present the baseline mean and standard deviation in the Control Arm. The last three columns present the p-value for a t-test of the difference in means between (1) Technical+ and Control, (2) Technical and Control, and (3) Technical+ and Technical. T-tests control for the randomization strata. The sample includes the 276 kilns with outcome data collected for analysis.

Table S10. Attrition Tests

Balance Variable	Technical+ Mean	Technical+ Std. Dev.	Technical Mean	Technical Std. Dev.	Control Mean	Control Std. Dev.	T+ - C (p-val)	T - C (p-val)	T+ - T (p-val)
Exclusive Firewood Use	0.13	0.34	0.11	0.31	0.15	0.35	0.76	0.42	0.62
Not Operated This Season	0.025	0.156	0.092	0.291	0.026	0.159	0.98	0.028	0.029
Not Operated or Exclusive Firewood Use	0.16	0.37	0.2	0.4	0.17	0.38	0.79	0.45	0.29
Demolished or Stopped by Gov	0.033	0.180	0.034	0.181	0.0085	0.0925	0.16	0.16	1.0
Dropped out (all reasons)	0.21	0.41	0.25	0.44	0.21	0.41	0.93	0.4	0.46

Note: This table presents the results of attrition tests run on the various reasons kilns dropped out of the study sample. The first two columns present the baseline mean and standard deviation in the Technical+ Arm, the second two present the baseline mean and standard deviation in the Technical Arm, and the third two present the baseline mean and standard deviation in the Control Arm. The last three columns present the p-value for a t-test of the difference in means between (1) Technical+ and Control, (2) Technical and Control, and (3) Technical+ and Technical. T-tests control for the randomization strata. The sample includes the 357 originally enrolled in the study.

Arm-Specific Regression Results

Table S11. Specific Energy Consumption (MJ/kg fired brick)

	Intention-to-Treat (Separate)	Intention-to-Treat (Bundled)	Instrumental Variable	Instrumental Variable (Technical)	Instrumental Variable (Technical+)
Adopted Intervention			-0.25***	-0.22***	-0.27***
			(0.05)	(0.05)	(0.06)
Bundled Treatment		-0.11***			
		(0.02)			
Technical Arm	-0.10***				
	(0.03)				
Technical+ Arm	-0.12***				
	(0.03)				
Control Mean	1.07	1.07	1.07	1.07	1.07
Percent Change	-9.4% (T)	-10.5%	-23.5%	-20.9%	-25.5%
	-11.5% (T+)				
N	276	276	276	181	187

+ p < 0.1, * p < 0.05, ** p < 0.01, *** p < 0.001

Note: Heteroskedasticity-robust standard errors are in parentheses. Regressions include randomization strata fixed effects. Outcome data are derived from measurements collected during kiln performance monitoring. Adoption is defined as adopting double/triple zigzag brick stacking and single fireman continuous feeding.

Table S12. CO_2 Emissions (tons)

	Intention-to-Treat (Separate)	Intention-to-Treat (Bundled)	Instrumental Variable	Instrumental Variable (Technical)	Instrumental Variable (Technical+)
Adopted Intervention			-382.26**	-339.39*	-409.54*
			(140.86)	(146.36)	(161.82)
Bundled Treatment		-170.70**			
		(60.05)			
Technical Arm	-153.12*				
	(64.46)				
Technical+ Arm	-187.51**				
	(68.27)				
Control Mean	1903.12	1903.12	1903.12	1903.12	1903.12
Percent Change	-8.0% (T)	-9.0%	-20.1%	-17.8%	-21.5%
	-9.9% (T+)				
N	276	276	276	181	187

+ p < 0.1, * p < 0.05, ** p < 0.01, *** p < 0.001

Note: Heteroskedasticity-robust standard errors are in parentheses. Regressions include randomization strata fixed effects. Outcome data are derived from measurements collected during kiln performance monitoring. Adoption is defined as adopting double/triple zigzag brick stacking and single fireman continuous feeding.

Table S13. $PM_{2.5}$ Emissions (tons)

	Intention-to-Treat (Separate)	Intention-to-Treat (Bundled)	Instrumental Variable	Instrumental Variable (Technical)	Instrumental Variable (Technical+)
Adopted Intervention			-1.01**	-0.90*	-1.08*
			(0.37)	(0.39)	(0.43)
Bundled Treatment		-0.45**			
		(0.16)			
Technical Arm	-0.40*				
	(0.17)				
Technical+ Arm	-0.50**				
	(0.18)				
Control Mean	5.02	5.02	5.02	5.02	5.02
Percent Change	-8.0% (T)	-9.0%	-20.1%	-17.8%	-21.5%
	-9.9% (T+)				
N	276	276	276	181	187

+ $p < 0.1$, * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Note: Heteroskedasticity-robust standard errors are in parentheses. Regressions include randomization strata fixed effects. Outcome data are derived from measurements collected during kiln performance monitoring. Adoption is defined as adopting double/triple zigzag brick stacking and single fireman continuous feeding.

Table S14. Fuel Costs (BDT/brick)

	Intention-to-Treat (Separate)	Intention-to-Treat (Bundled)	Instrumental Variable	Instrumental Variable (Technical)	Instrumental Variable (Technical+)
Adopted Intervention			-0.81***	-0.91***	-0.69***
			(0.17)	(0.21)	(0.18)
Bundled Treatment		-0.36***			
		(0.08)			
Technical Arm	-0.41***				
	(0.10)				
Technical+ Arm	-0.31***				
	(0.09)				
Control Mean	3.74	3.74	3.74	3.74	3.74
Percent Change	-11.1% (T)	-9.6%	-21.6%	-24.2%	-18.4%
	-8.2% (T+)				
N	276	276	276	181	187

+ $p < 0.1$, * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Note: Heteroskedasticity-robust standard errors are in parentheses. Regressions include randomization strata fixed effects. Outcome data are derived from measurements collected during kiln performance monitoring. Adoption is defined as adopting double/triple zigzag brick stacking and single fireman continuous feeding.

Table S15. Total Fuel Costs (million BDT)

	Intention-to-Treat (Separate)	Intention-to-Treat (Bundled)	Instrumental Variable	Instrumental Variable (Technical)	Instrumental Variable (Technical+)
Adopted Intervention			-4.35**	-5.02**	-3.43+
			(1.64)	(1.84)	(1.84)
Bundled Treatment		-1.94**			
		(0.71)			
Technical Arm	-2.33**				
	(0.79)				
Technical+ Arm	-1.57+				
	(0.80)				
Control Mean	22.71	22.71	22.71	22.71	22.71
Percent Change	-10.3% (T)	-8.5%	-19.2%	-22.1%	-15.1%
	-6.9% (T+)				
N	276	276	276	181	187

+ p < 0.1, * p < 0.05, ** p < 0.01, *** p < 0.001

Note: Heteroskedasticity-robust standard errors are in parentheses. Regressions include randomization strata fixed effects. Outcome data are derived from measurements collected during kiln performance monitoring. Adoption is defined as adopting double/triple zigzag brick stacking and single fireman continuous feeding.

Table S16. Class 1 Bricks (%)

	Intention-to-Treat (Separate)	Intention-to-Treat (Bundled)	Instrumental Variable	Instrumental Variable (Technical)	Instrumental Variable (Technical+)
Adopted Intervention			0.142***	0.140***	0.143***
			(0.016)	(0.017)	(0.020)
Bundled Treatment		0.063***			
		(0.009)			
Technical Arm	0.062***				
	(0.010)				
Technical+ Arm	0.064***				
	(0.010)				
Control Mean	0.78	0.78	0.78	0.78	0.78
Percent Change	8.0% (T)	8.1%	18.2%	17.9%	18.3%
	8.2% (T+)				
N	276	276	276	181	187

+ p < 0.1, * p < 0.05, ** p < 0.01, *** p < 0.001

Note: Heteroskedasticity-robust standard errors are in parentheses. Regressions include randomization strata fixed effects. Outcome data are derived from measurements collected during kiln performance monitoring. Adoption is defined as adopting double/triple zigzag brick stacking and single fireman continuous feeding.

Table S17. Endline Total Value of Production (BDT)

	Intention-to-Treat (Separate)	Intention-to-Treat (Bundled)	Instrumental Variable	Instrumental Variable (Technical)	Instrumental Variable (Technical+)
Adopted Intervention			36.70	41.99	36.26
			(40.60)	(44.23)	(47.57)
Bundled Treatment		16.36			
		(18.54)			
Technical Arm	17.75				
	(20.49)				
Technical+ Arm	15.04				
	(21.15)				
Control Mean	639.41	639.41	639.41	639.41	639.41
Percent Change	2.8% (T)	2.6%	5.7%	6.6%	5.7%
	2.4% (T+)				
N	276	276	276	181	187

+ p < 0.1, * p < 0.05, ** p < 0.01, *** p < 0.001

Note: Heteroskedasticity-robust standard errors are in parentheses. Regressions include randomization strata fixed effects. Outcome data are derived from kiln owner self-reports at endline. Adoption is defined as adopting double/triple zigzag brick stacking and single fireman continuous feeding.

Table S18. Specific Fuel Consumption (tons/100,000 bricks)

	Intention-to-Treat (Separate)	Intention-to-Treat (Bundled)	Instrumental Variable	Instrumental Variable (Technical)	Instrumental Variable (Technical+)
Adopted Intervention			-4.13***	-4.27***	-4.00***
			(0.91)	(0.97)	(1.08)
Bundled Treatment		-1.84***			
		(0.41)			
Technical Arm	-1.91***				
	(0.42)				
Technical+ Arm	-1.77***				
	(0.46)				
Control Mean	15.97	15.97	15.97	15.97	15.97
Percent Change	-12.0% (T)	-11.5%	-25.8%	-26.7%	-25.0%
	-11.1% (T+)				
N	276	276	276	181	187

+ p < 0.1, * p < 0.05, ** p < 0.01, *** p < 0.001

Note: Heteroskedasticity-robust standard errors are in parentheses. Regressions include randomization strata fixed effects. Outcome data are derived from measurements collected during kiln performance monitoring. Adoption is defined as adopting double/triple zigzag brick stacking and single fireman continuous feeding.

Table S19. Specific Coal Consumption (tons/100,000 bricks)

	Intention-to-Treat (Separate)	Intention-to-Treat (Bundled)	Instrumental Variable	Instrumental Variable (Technical)	Instrumental Variable (Technical+)
Adopted Intervention			-2.49***	-2.42**	-2.45**
			(0.67)	(0.74)	(0.79)
Bundled Treatment		-1.11***			
		(0.32)			
Technical Arm	-1.11**				
	(0.35)				
Technical+ Arm	-1.11**				
	(0.37)				
Control Mean	14.54	14.54	14.54	14.54	14.54
Percent Change	-7.6% (T)	-7.6%	-17.1%	-16.7%	-16.9%
	-7.6% (T+)				
N	276	276	276	181	187

+ p < 0.1, * p < 0.05, ** p < 0.01, *** p < 0.001

Note: Heteroskedasticity-robust standard errors are in parentheses. Regressions include randomization strata fixed effects. Outcome data are derived from measurements collected during kiln performance monitoring. Adoption is defined as adopting double/triple zigzag brick stacking and single fireman continuous feeding.

Table S20. Endline Fuel Costs Per Brick (BDT/brick)

	Intention-to-Treat (Separate)	Intention-to-Treat (Bundled)	Instrumental Variable	Instrumental Variable (Technical)	Instrumental Variable (Technical+)
Adopted Intervention			-0.28	-0.29	-0.31
			(0.19)	(0.19)	(0.23)
Bundled Treatment		-0.13			
		(0.09)			
Technical Arm	-0.13				
	(0.09)				
Technical+ Arm	-0.13				
	(0.10)				
Control Mean	3.93	3.93	3.93	3.93	3.93
Percent Change	-3.2% (T)	-3.2%	-7.2%	-7.4%	-7.9%
	-3.2% (T+)				
N	276	276	276	181	187

+ p < 0.1, * p < 0.05, ** p < 0.01, *** p < 0.001

Note: Heteroskedasticity-robust standard errors are in parentheses. Regressions include randomization strata fixed effects. Outcome data are derived from kiln owner self-reports at endline. Adoption is defined as adopting double/triple zigzag brick stacking and single fireman continuous feeding.

Table S21. Coal Costs (BDT/brick)

	Intention-to-Treat (Separate)	Intention-to-Treat (Bundled)	Instrumental Variable	Instrumental Variable (Technical)	Instrumental Variable (Technical+)
Adopted Intervention			-0.72***	-0.78***	-0.63**
			(0.18)	(0.21)	(0.20)
Bundled Treatment		-0.32***			
		(0.08)			
Technical Arm	-0.36***				
	(0.10)				
Technical+ Arm	-0.28**				
	(0.10)				
Control Mean	3.65	3.65	3.65	3.65	3.65
Percent Change	-9.8% (T)	-8.7%	-19.6%	-21.4%	-17.2%
	-7.7% (T+)				
N	276	276	276	181	187

+ p < 0.1, * p < 0.05, ** p < 0.01, *** p < 0.001

Note: Heteroskedasticity-robust standard errors are in parentheses. Regressions include randomization strata fixed effects. Outcome data are derived from measurements collected during kiln performance monitoring. Adoption is defined as adopting double/triple zigzag brick stacking and single fireman continuous feeding.

Table S22. Total Coal Costs (million BDT)

	Intention-to-Treat (Separate)	Intention-to-Treat (Bundled)	Instrumental Variable	Instrumental Variable (Technical)	Instrumental Variable (Technical+)
Adopted Intervention			-3.74*	-4.27*	-2.94
			(1.65)	(1.81)	(1.91)
Bundled Treatment		-1.67*			
		(0.72)			
Technical Arm	-1.99*				
	(0.79)				
Technical+ Arm	-1.35				
	(0.84)				
Control Mean	22.11	22.11	22.11	22.11	22.11
Percent Change	-9.0% (T)	-7.5%	-16.9%	-19.3%	-13.3%
	-6.1% (T+)				
N	276	276	276	181	187

+ p < 0.1, * p < 0.05, ** p < 0.01, *** p < 0.001

Note: Heteroskedasticity-robust standard errors are in parentheses. Regressions include randomization strata fixed effects. Outcome data are derived from measurements collected during kiln performance monitoring. Adoption is defined as adopting double/triple zigzag brick stacking and single fireman continuous feeding.

Table S23. Mean CO/CO_2 Ratio

	Intention-to-Treat (Separate)	Intention-to-Treat (Bundled)	Instrumental Variable	Instrumental Variable (Technical)	Instrumental Variable (Technical+)
Adopted Intervention			-0.0020	-0.0032	-0.0004
			(0.0039)	(0.0045)	(0.0048)
Bundled Treatment		-0.0009			
		(0.0018)			
Technical Arm	-0.0014				
	(0.0021)				
Technical+ Arm	-0.0004				
	(0.0021)				
Control Mean	0.03	0.03	0.03	0.03	0.03
Percent Change	-4.5% (T)	-2.8%	-6.4%	-10.2%	-1.2%
	-1.3% (T+)				
N	276	276	276	181	187

+ p < 0.1, * p < 0.05, ** p < 0.01, *** p < 0.001

Note: Heteroskedasticity-robust standard errors are in parentheses. Regressions include randomization strata fixed effects. Outcome data are derived from measurements collected during kiln performance monitoring. Adoption is defined as adopting double/triple zigzag brick stacking and single fireman continuous feeding.

Table S24. Annual Production (100,000 bricks)

	Intention-to-Treat (Separate)	Intention-to-Treat (Bundled)	Instrumental Variable	Instrumental Variable (Technical)	Instrumental Variable (Technical+)
Adopted Intervention			1.77	2.31	1.80
			(3.84)	(4.16)	(4.50)
Bundled Treatment		0.79			
		(1.73)			
Technical Arm	0.89				
	(1.91)				
Technical+ Arm	0.69				
	(1.98)				
Control Mean	61.52	61.52	61.52	61.52	61.52
Percent Change	1.4% (T)	1.3%	2.9%	3.7%	2.9%
	1.1% (T+)				
N	276	276	276	181	187

+ p < 0.1, * p < 0.05, ** p < 0.01, *** p < 0.001

Note: Heteroskedasticity-robust standard errors are in parentheses. Regressions include randomization strata fixed effects. Outcome data are derived from measurements collected during kiln performance monitoring. Adoption is defined as adopting double/triple zigzag brick stacking and single fireman continuous feeding.

Table S25. Circuits Completed (Total number)

	Intention-to-Treat (Separate)	Intention-to-Treat (Bundled)	Instrumental Variable	Instrumental Variable (Technical)	Instrumental Variable (Technical+)
Adopted Intervention			0.18	0.16	0.16
			(0.34)	(0.38)	(0.40)
Bundled Treatment		0.08			
		(0.15)			
Technical Arm	0.09				
	(0.17)				
Technical+ Arm	0.07				
	(0.17)				
Control Mean	5.01	5.01	5.01	5.01	5.01
Percent Change	1.8% (T)	1.6%	3.6%	3.2%	3.2%
	1.4% (T+)				
N	276	276	276	181	187

+ p < 0.1, * p < 0.05, ** p < 0.01, *** p < 0.001

Note: Heteroskedasticity-robust standard errors are in parentheses. Regressions include randomization strata fixed effects. Outcome data are derived from measurements collected during kiln performance monitoring. Adoption is defined as adopting double/triple zigzag brick stacking and single fireman continuous feeding.

Table S26. Total Value of Production (BDT)

	Intention-to-Treat (Separate)	Intention-to-Treat (Bundled)	Instrumental Variable	Instrumental Variable (Technical)	Instrumental Variable (Technical+)
Adopted Intervention			42.84	47.82	43.99
			(40.53)	(44.15)	(47.62)
Bundled Treatment		19.10			
		(18.56)			
Technical Arm	19.87				
	(20.52)				
Technical+ Arm	18.38				
	(21.22)				
Control Mean	642.66	642.66	642.66	642.66	642.66
Percent Change	3.1% (T)	3.0%	6.7%	7.4%	6.8%
	2.9% (T+)				
N	276	276	276	181	187

+ p < 0.1, * p < 0.05, ** p < 0.01, *** p < 0.001

Note: Heteroskedasticity-robust standard errors are in parentheses. Regressions include randomization strata fixed effects. Total value of production is calculated by applying the objective brick quality data measured during the kiln performance assessment to the annual production reported at endline. Adoption is defined as adopting double/triple zigzag brick stacking and single fireman continuous feeding.

Table S27. Value of Production Per Brick (BDT/brick)

	Intention-to-Treat (Separate)	Intention-to-Treat (Bundled)	Instrumental Variable	Instrumental Variable (Technical)	Instrumental Variable (Technical+)
Adopted Intervention			0.39***	0.38***	0.41***
			(0.04)	(0.05)	(0.05)
Bundled Treatment		0.18***			
		(0.02)			
Technical Arm	0.17***				
	(0.03)				
Technical+ Arm	0.18***				
	(0.03)				
Control Mean	10.44	10.44	10.44	10.44	10.44
Percent Change	1.6% (T)	1.7%	3.8%	3.6%	3.9%
	1.8% (T+)				
N	276	276	276	181	187

+ p < 0.1, * p < 0.05, ** p < 0.01, *** p < 0.001

Note: Heteroskedasticity-robust standard errors are in parentheses. Regressions include randomization strata fixed effects. Outcome data are derived from measurements collected during kiln performance monitoring. Adoption is defined as adopting double/triple zigzag brick stacking and single fireman continuous feeding.

Table S28. Endline Value Per Brick (BDT)

	Intention-to-Treat (Separate)	Intention-to-Treat (Bundled)	Instrumental Variable	Instrumental Variable (Technical)	Instrumental Variable (Technical+)
Adopted Intervention			0.30***	0.29***	0.29***
			(0.05)	(0.06)	(0.06)
Bundled Treatment		0.13***			
		(0.03)			
Technical Arm	0.14***				
	(0.03)				
Technical+ Arm	0.13***				
	(0.03)				
Control Mean	10.38	10.38	10.38	10.38	10.38
Percent Change	1.3% (T)	1.3%	2.9%	2.8%	2.8%
	1.3% (T+)				
N	276	276	276	181	187

+ p < 0.1, * p < 0.05, ** p < 0.01, *** p < 0.001

Note: Heteroskedasticity-robust standard errors are in parentheses. Regressions include randomization strata fixed effects. Outcome data are derived from kiln owner self-reports at endline. Adoption is defined as adopting double/triple zigzag brick stacking and single fireman continuous feeding.

Table S29. Total Value of Production (BDT)

	Intention-to-Treat (Separate)	Intention-to-Treat (Bundled)	Instrumental Variable	Instrumental Variable (Technical)	Instrumental Variable (Technical+)
Adopted Intervention			42.84	47.82	43.99
			(40.53)	(44.15)	(47.62)
Bundled Treatment		19.10			
		(18.56)			
Technical Arm	19.87				
	(20.52)				
Technical+ Arm	18.38				
	(21.22)				
Control Mean	642.66	642.66	642.66	642.66	642.66
Percent Change	3.1% (T)	3.0%	6.7%	7.4%	6.8%
	2.9% (T+)				
N	276	276	276	181	187

+ p < 0.1, * p < 0.05, ** p < 0.01, *** p < 0.001

Note: Heteroskedasticity-robust standard errors are in parentheses. Regressions include randomization strata fixed effects. Total value of production is calculated by applying the objective brick quality data measured during the kiln performance assessment to the annual production reported at endline. Adoption is defined as adopting double/triple zigzag brick stacking and single fireman continuous feeding.

Table S30. Endline Class 1 Bricks (%)

	Intention-to-Treat (Separate)	Intention-to-Treat (Bundled)	Instrumental Variable	Instrumental Variable (Technical)	Instrumental Variable (Technical+)
Adopted Intervention			0.11***	0.11***	0.11***
			(0.02)	(0.02)	(0.02)
Bundled Treatment		0.05***			
		(0.01)			
Technical Arm	0.05***				
	(0.01)				
Technical+ Arm	0.05***				
	(0.01)				
Control Mean	0.76	0.76	0.76	0.76	0.76
Percent Change	6.7% (T)	6.5%	14.6%	14.1%	14.3%
	6.4% (T+)				
N	276	276	276	181	187

+ p < 0.1, * p < 0.05, ** p < 0.01, *** p < 0.001

Note: Heteroskedasticity-robust standard errors are in parentheses. Regressions include randomization strata fixed effects. Outcome data are derived from kiln owner self-reports at endline. Adoption is defined as adopting double/triple zigzag brick stacking and single fireman continuous feeding.

Table S31. Endline Specific Fuel Consumption (tons/100,000 bricks)

	Intention-to-Treat (Separate)	Intention-to-Treat (Bundled)	Instrumental Variable	Instrumental Variable (Technical)	Instrumental Variable (Technical+)
Adopted Intervention			-3.04**	-2.86**	-3.46**
			(1.04)	(1.08)	(1.27)
Bundled Treatment		-1.36**			
		(0.46)			
Technical Arm	-1.24**				
	(0.47)				
Technical+ Arm	-1.47**				
	(0.52)				
Control Mean	17.27	17.27	17.27	17.27	17.27
Percent Change	-7.2% (T)	-7.9%	-17.6%	-16.6%	-20.0%
	-8.5% (T+)				
N	276	276	276	181	187

+ $p < 0.1$, * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Note: Heteroskedasticity-robust standard errors are in parentheses. Regressions include randomization strata fixed effects. Outcome data are derived from kiln owner self-reports at endline. Adoption is defined as adopting double/triple zigzag brick stacking and single fireman continuous feeding.

Table S32. Heterogeneous Treatment Effects

	Specific Energy Consumption			Class 1 Bricks (%)		
	Experience	Education	Location	Experience	Education	Location
Bundled Treatment	-0.07	-0.08*	-0.10*	0.04**	0.07***	0.06***
	(0.04)	(0.03)	(0.04)	(0.01)	(0.01)	(0.01)
Owner Experience	0.00			0.00		
	(0.00)			(0.00)		
Treatment X Owner Experience	-0.00			0.00		
	(0.00)			(0.00)		
Higher Secondary+		0.02			0.02	
		(0.04)			(0.02)	
Treatment X Higher Secondary+		-0.06			-0.02	
		(0.05)			(0.02)	
Highland			-0.02			0.01
			(0.05)			(0.02)
Treatment X Highland			-0.02			-0.00
			(0.05)			(0.02)
N	276	276	276	276	276	276

+ p < 0.1, * p < 0.05, ** p < 0.01, *** p < 0.001

Note: Heteroskedasticity-robust standard errors are in parentheses. Regression includes randomization strata fixed effects. Kiln characteristics (owner experience, education, and kiln location) are from baseline data and outcomes are derived from the kiln performance monitoring. Kiln owner experience is measured in years, higher secondary+ is a binary indicator that equals 1 if the owner has attained higher secondary schooling or more, and highland indicates a kiln is located on highland (as opposed to lowland).

Changes In Other Costs

Table S33. Sawdust Spending (BDT/ton)

	Intention-to-Treat (Separate)	Intention-to-Treat (Bundled)	Instrumental Variable	Instrumental Variable (Technical)	Instrumental Variable (Technical+)
Adopted Intervention			-4940.88*	-4543.22*	-5683.20*
			(2081.33)	(2132.59)	(2483.10)
Bundled Treatment		-2206.90*			
		(886.32)			
Technical Arm	-1921.35*				
	(914.09)				
Technical+ Arm	-2479.92*				
	(956.84)				
Control Mean	3573.64	3573.64	3573.64	3573.64	3573.64
Percent Change	-53.8% (T)	-61.8%	-138.3%	-127.1%	-159.0%
	-69.4% (T+)				
N	276	276	276	181	187

+ p < 0.1, * p < 0.05, ** p < 0.01, *** p < 0.001

Note: Heteroskedasticity-robust standard errors are in parentheses. Regressions include randomization strata fixed effects. Outcome data are derived from measurements collected during endline and kiln performance monitoring. Adoption is defined as adopting double/triple zigzag brick stacking and single fireman continuous feeding.

Table S34. Soil (BDT per 1000 bricks)

	Intention-to-Treat (Separate)	Intention-to-Treat (Bundled)	Instrumental Variable	Instrumental Variable (Technical)	Instrumental Variable (Technical+)
Adopted Intervention			27.43	0.88	52.79
			(28.60)	(33.02)	(34.87)
Bundled Treatment		12.34			
		(12.64)			
Technical Arm	1.59				
	(14.89)				
Technical+ Arm	22.62				
	(15.36)				
Control Mean	902.3	902.3	902.3	902.3	902.3
Percent Change	0.2% (T)	1.4%	3.0%	0.1%	5.9%
	2.5% (T+)				
N	276	276	276	181	187

+ p < 0.1, * p < 0.05, ** p < 0.01, *** p < 0.001

Note: Heteroskedasticity-robust standard errors are in parentheses. Regressions include randomization strata fixed effects. Outcome data are derived from measurements collected during endline and kiln performance monitoring. Adoption is defined as adopting double/triple zigzag brick stacking and single fireman continuous feeding.

Table S35. Molding (BDT per 1000 bricks)

	Intention-to-Treat (Separate)	Intention-to-Treat (Bundled)	Instrumental Variable	Instrumental Variable (Technical)	Instrumental Variable (Technical+)
Adopted Intervention			9.89	10.17	9.02
			(32.69)	(39.35)	(37.92)
Bundled Treatment		4.39			
		(14.54)			
Technical Arm	6.58				
	(17.36)				
Technical+ Arm	2.30				
	(16.59)				
Control Mean	1026.79	1026.79	1026.79	1026.79	1026.79
Percent Change	0.6% (T)	0.4%	1.0%	1.0%	0.9%
	0.2% (T+)				
N	276	276	276	181	187

+ p < 0.1, * p < 0.05, ** p < 0.01, *** p < 0.001

Note: Heteroskedasticity-robust standard errors are in parentheses. Regressions include randomization strata fixed effects. Outcome data are derived from measurements collected during endline and kiln performance monitoring. Adoption is defined as adopting double/triple zigzag brick stacking and single fireman continuous feeding.

Table S36. Coal preparation (BDT per season)

	Intention-to-Treat (Separate)	Intention-to-Treat (Bundled)	Instrumental Variable	Instrumental Variable (Technical)	Instrumental Variable (Technical+)
Adopted Intervention			17494.21	31382.76	4816.06
			(16369.83)	(19278.21)	(18556.09)
Bundled Treatment		7750.48			
		(7400.13)			
Technical Arm	13239.60				
	(8852.78)				
Technical+ Arm	2502.05				
	(8255.78)				
Control Mean	214463.91	214463.91	214463.91	214463.91	214463.91
Percent Change	6.2% (T)	3.6%	8.2%	14.6%	2.2%
	1.2% (T+)				
N	276	276	276	181	187

+ p < 0.1, * p < 0.05, ** p < 0.01, *** p < 0.001

Note: Heteroskedasticity-robust standard errors are in parentheses. Regressions include randomization strata fixed effects. Outcome data are derived from measurements collected during endline and kiln performance monitoring. Adoption is defined as adopting double/triple zigzag brick stacking and single fireman continuous feeding.

Table S37. Brick loading (BDT per 1000 bricks)

	Intention-to-Treat (Separate)	Intention-to-Treat (Bundled)	Instrumental Variable	Instrumental Variable (Technical)	Instrumental Variable (Technical+)
Adopted Intervention			13.59	9.55	16.67
			(11.50)	(12.81)	(13.51)
Bundled Treatment		6.07			
		(5.10)			
Technical Arm	5.85				
	(5.81)				
Technical+ Arm	6.27				
	(5.90)				
Control Mean	307.52	307.52	307.52	307.52	307.52
Percent Change	1.9% (T)	2.0%	4.4%	3.1%	5.4%
	2.0% (T+)				
N	276	276	276	181	187

+ p < 0.1, * p < 0.05, ** p < 0.01, *** p < 0.001

Note: Heteroskedasticity-robust standard errors are in parentheses. Regressions include randomization strata fixed effects. Outcome data are derived from measurements collected during endline and kiln performance monitoring. Adoption is defined as adopting double/triple zigzag brick stacking and single fireman continuous feeding.

Table S38. Firemen cost (BDT per season)

	Intention-to-Treat (Separate)	Intention-to-Treat (Bundled)	Instrumental Variable	Instrumental Variable (Technical)	Instrumental Variable (Technical+)
Adopted Intervention			45656.58	37695.26	63099.23
			(43496.33)	(49501.40)	(49902.29)
Bundled Treatment		20386.10			
		(19625.66)			
Technical Arm	18452.90				
	(22541.56)				
Technical+ Arm	22234.53				
	(22297.62)				
Control Mean	1069347.83	1069347.83	1069347.83	1069347.83	1069347.83
Percent Change	1.7% (T)	1.9%	4.3%	3.5%	5.9%
	2.1% (T+)				
N	276	276	276	181	187

+ p < 0.1, * p < 0.05, ** p < 0.01, *** p < 0.001

Note: Heteroskedasticity-robust standard errors are in parentheses. Regressions include randomization strata fixed effects. Outcome data are derived from measurements collected during endline and kiln performance monitoring. Adoption is defined as adopting double/triple zigzag brick stacking and single fireman continuous feeding.

Table S39. Brick unloading (BDT per 1000 bricks)

	Intention-to-Treat (Separate)	Intention-to-Treat (Bundled)	Instrumental Variable	Instrumental Variable (Technical)	Instrumental Variable (Technical+)
Adopted Intervention			8.35	7.80	8.23
			(8.94)	(10.45)	(10.34)
Bundled Treatment		3.73			
		(3.98)			
Technical Arm	3.35				
	(4.63)				
Technical+ Arm	4.09				
	(4.54)				
Control Mean	204.54	204.54	204.54	204.54	204.54
Percent Change	1.6% (T)	1.8%	4.1%	3.8%	4.0%
	2.0% (T+)				
N	276	276	276	181	187

+ $p < 0.1$, * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Note: Heteroskedasticity-robust standard errors are in parentheses. Regressions include randomization strata fixed effects. Outcome data are derived from measurements collected during endline and kiln performance monitoring. Adoption is defined as adopting double/triple zigzag brick stacking and single fireman continuous feeding.

Supplementary CO/CO_2 Analysis

Table S40. Max CO/CO_2 Ratio

	Intention-to-Treat (Separate)	Intention-to-Treat (Bundled)	Instrumental Variable	Instrumental Variable (Technical)	Instrumental Variable (Technical+)
Adopted Intervention			-0.0082	-0.0112	-0.0053
			(0.0064)	(0.0074)	(0.0075)
Bundled Treatment		-0.0037			
		(0.0030)			
Technical Arm	-0.0048				
	(0.0035)				
Technical+ Arm	-0.0025				
	(0.0035)				
Control Mean	0.06	0.06	0.06	0.06	0.06
Percent Change	-8.6% (T)	-6.5%	-14.7%	-19.9%	-9.5%
	-4.5% (T+)				
N	276	276	276	181	187

+ $p < 0.1$, * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Note: Heteroskedasticity-robust standard errors are in parentheses. Regressions include randomization strata fixed effects. Outcome data are derived from measurements collected during kiln performance monitoring. Adoption is defined as adopting double/triple zigzag brick stacking and single fireman continuous feeding.

Table S41. SD CO/CO_2 Ratio

	Intention-to-Treat (Separate)	Intention-to-Treat (Bundled)	Instrumental Variable	Instrumental Variable (Technical)	Instrumental Variable (Technical+)
Adopted Intervention			-0.0029*	-0.0030+	-0.0031*
			(0.0014)	(0.0016)	(0.0016)
Bundled Treatment		-0.0013*			
		(0.0007)			
Technical Arm	-0.0013+				
	(0.0008)				
Technical+ Arm	-0.0013+				
	(0.0007)				
Control Mean	0.01	0.01	0.01	0.01	0.01
Percent Change	-14.2% (T)	-14.3%	-32.1%	-32.3%	-33.7%
	-14.4% (T+)				
N	276	276	276	181	187

+ p < 0.1, * p < 0.05, ** p < 0.01, *** p < 0.001

Note: Heteroskedasticity-robust standard errors are in parentheses. Regressions include randomization strata fixed effects. Outcome data are derived from measurements collected during kiln performance monitoring. Adoption is defined as adopting double/triple zigzag brick stacking and single fireman continuous feeding.

Table S42. IQR CO/CO_2 Ratio

	Intention-to-Treat (Separate)	Intention-to-Treat (Bundled)	Instrumental Variable	Instrumental Variable (Technical)	Instrumental Variable (Technical+)
Adopted Intervention			-0.0035	-0.0033	-0.0040
			(0.0022)	(0.0025)	(0.0025)
Bundled Treatment		-0.0016			
		(0.0010)			
Technical Arm	-0.0015				
	(0.0011)				
Technical+ Arm	-0.0016				
	(0.0011)				
Control Mean	0.01	0.01	0.01	0.01	0.01
Percent Change	-12.3% (T)	-12.9%	-28.9%	-27.6%	-33.4%
	-13.4% (T+)				
N	276	276	276	181	187

+ p < 0.1, * p < 0.05, ** p < 0.01, *** p < 0.001

Note: Heteroskedasticity-robust standard errors are in parentheses. Regressions include randomization strata fixed effects. Outcome data are derived from measurements collected during kiln performance monitoring. Adoption is defined as adopting double/triple zigzag brick stacking and single fireman continuous feeding.

Table S43. Mean CO/CO_2Ratio (dropping abnormal feeding)

	Intention-to-Treat (Separate)	Intention-to-Treat (Bundled)	Instrumental Variable	Instrumental Variable (Technical)	Instrumental Variable (Technical+)
Adopted Intervention			-0.0025	-0.0039	-0.0006
			(0.0043)	(0.0049)	(0.0053)
Bundled Treatment		-0.0011			
		(0.0019)			
Technical Arm	-0.0015				
	(0.0022)				
Technical+ Arm	-0.0006				
	(0.0023)				
Control Mean	0.03	0.03	0.03	0.03	0.03
Percent Change	-4.8% (T)	-3.3%	-7.7%	-12.1%	-2.0%
	-1.9% (T+)				
N	256	256	256	164	174

+ $p < 0.1$, * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Note: Heteroskedasticity-robust standard errors are in parentheses. Regressions include randomization strata fixed effects. Outcome data are derived from measurements collected during kiln performance monitoring. Adoption is defined as adopting double/triple zigzag brick stacking and single fireman continuous feeding. Sample excludes kilns with total feeding time below 33%, which indicates abnormal operation.

Table S44. Max CO/CO_2 Ratio (dropping abnormal feeding)

	Intention-to-Treat (Separate)	Intention-to-Treat (Bundled)	Instrumental Variable	Instrumental Variable (Technical)	Instrumental Variable (Technical+)
Adopted Intervention			-0.0078	-0.0108	-0.0043
			(0.0068)	(0.0079)	(0.0081)
Bundled Treatment		-0.0034			
		(0.0031)			
Technical Arm	-0.0046				
	(0.0036)				
Technical+ Arm	-0.0022				
	(0.0035)				
Control Mean	0.06	0.06	0.06	0.06	0.06
Percent Change	-8.2% (T)	-6.0%	-14.1%	-19.4%	-7.7%
	-4.0% (T+)				
N	256	256	256	164	174

+ $p < 0.1$, * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Note: Heteroskedasticity-robust standard errors are in parentheses. Regressions include randomization strata fixed effects. Outcome data are derived from measurements collected during kiln performance monitoring. Adoption is defined as adopting double/triple zigzag brick stacking and single fireman continuous feeding. Sample excludes kilns with total feeding time below 33%, which indicates abnormal operation.

Table S45. SD CO/CO_2 Ratio (dropping abnormal feeding)

	Intention-to-Treat (Separate)	Intention-to-Treat (Bundled)	Instrumental Variable	Instrumental Variable (Technical)	Instrumental Variable (Technical+)
Adopted Intervention			-0.0031*	-0.0031+	-0.0030+
			(0.0015)	(0.0017)	(0.0017)
Bundled Treatment		-0.0013+			
		(0.0007)			
Technical Arm	-0.0013+				
	(0.0008)				
Technical+ Arm	-0.0013+				
	(0.0007)				
Control Mean	0.01	0.01	0.01	0.01	0.01
Percent Change	-14.7% (T)	-14.5%	-33.6%	-33.5%	-33.2%
	-14.3% (T+)				
N	256	256	256	164	174

+ p < 0.1, * p < 0.05, ** p < 0.01, *** p < 0.001

Note: Heteroskedasticity-robust standard errors are in parentheses. Regressions include randomization strata fixed effects. Outcome data are derived from measurements collected during kiln performance monitoring. Adoption is defined as adopting double/triple zigzag brick stacking and single fireman continuous feeding. Sample excludes kilns with total feeding time below 33%, which indicates abnormal operation.

Table S46. IQR CO/CO_2 Ratio (dropping abnormal feeding)

	Intention-to-Treat (Separate)	Intention-to-Treat (Bundled)	Instrumental Variable	Instrumental Variable (Technical)	Instrumental Variable (Technical+)
Adopted Intervention			-0.0039+	-0.0041+	-0.0039
			(0.0023)	(0.0024)	(0.0027)
Bundled Treatment		-0.0017+			
		(0.0010)			
Technical Arm	-0.0018+				
	(0.0011)				
Technical+ Arm	-0.0016				
	(0.0012)				
Control Mean	0.01	0.01	0.01	0.01	0.01
Percent Change	-15.0% (T)	-14.0%	-32.5%	-33.6%	-32.1%
	-13.0% (T+)				
N	256	256	256	164	174

+ p < 0.1, * p < 0.05, ** p < 0.01, *** p < 0.001

Note: Heteroskedasticity-robust standard errors are in parentheses. Regressions include randomization strata fixed effects. Outcome data are derived from measurements collected during kiln performance monitoring. Adoption is defined as adopting double/triple zigzag brick stacking and single fireman continuous feeding. Sample excludes kilns with total feeding time below 33%, which indicates abnormal operation.

Table S47. Mean CO/CO_2 Ratio (dropping abnormal values)

	Intention-to-Treat (Separate)	Intention-to-Treat (Bundled)	Instrumental Variable	Instrumental Variable (Technical)	Instrumental Variable (Technical+)
Adopted Intervention			-0.0023	-0.0022	-0.0016
			(0.0039)	(0.0046)	(0.0048)
Bundled Treatment		-0.0011			
		(0.0018)			
Technical Arm	-0.0011				
	(0.0021)				
Technical+ Arm	-0.0010				
	(0.0022)				
Control Mean	0.03	0.03	0.03	0.03	0.03
Percent Change	-3.4% (T)	-3.3%	-7.3%	-6.9%	-5.1%
	-3.2% (T+)				
N	264	264	264	171	181

+ $p < 0.1$, * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Note: Heteroskedasticity-robust standard errors are in parentheses. Regressions include randomization strata fixed effects. Outcome data are derived from measurements collected during kiln performance monitoring. Adoption is defined as adopting double/triple zigzag brick stacking and single fireman continuous feeding. Sample excludes kilns with O2, CO2, and CO outside normal ranges for more than 50% of the monitored time, which indicates abnormal operation.

Table S48. Max CO/CO_2 Ratio (dropping abnormal values)

	Intention-to-Treat (Separate)	Intention-to-Treat (Bundled)	Instrumental Variable	Instrumental Variable (Technical)	Instrumental Variable (Technical+)
Adopted Intervention			-0.0097	-0.0106	-0.0085
			(0.0064)	(0.0076)	(0.0075)
Bundled Treatment		-0.0044			
		(0.0030)			
Technical Arm	-0.0047				
	(0.0036)				
Technical+ Arm	-0.0041				
	(0.0035)				
Control Mean	0.06	0.06	0.06	0.06	0.06
Percent Change	-8.3% (T)	-7.7%	-17.1%	-18.7%	-15.0%
	-7.2% (T+)				
N	264	264	264	171	181

+ $p < 0.1$, * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Note: Heteroskedasticity-robust standard errors are in parentheses. Regressions include randomization strata fixed effects. Outcome data are derived from measurements collected during kiln performance monitoring. Adoption is defined as adopting double/triple zigzag brick stacking and single fireman continuous feeding. Sample excludes kilns with O2, CO2, and CO outside normal ranges for more than 50% of the monitored time, which indicates abnormal operation.

Table S49. SD CO/CO_2 Ratio (dropping abnormal values)

	Intention-to-Treat (Separate)	Intention-to-Treat (Bundled)	Instrumental Variable	Instrumental Variable (Technical)	Instrumental Variable (Technical+)
Adopted Intervention			-0.0032*	-0.0030+	-0.0036*
			(0.0014)	(0.0017)	(0.0016)
Bundled Treatment		-0.0015*			
		(0.0007)			
Technical Arm	-0.0013				
	(0.0008)				
Technical+ Arm	-0.0016*				
	(0.0007)				
Control Mean	0.01	0.01	0.01	0.01	0.01
Percent Change	-14.2% (T)	-15.7%	-34.7%	-32.4%	-39.1%
	-17.1% (T+)				
N	264	264	264	171	181

+ $p < 0.1$, * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Note: Heteroskedasticity-robust standard errors are in parentheses. Regressions include randomization strata fixed effects. Outcome data are derived from measurements collected during kiln performance monitoring. Adoption is defined as adopting double/triple zigzag brick stacking and single fireman continuous feeding. Sample excludes kilns with O2, CO2, and CO outside normal ranges for more than 50% of the monitored time, which indicates abnormal operation.

Table S50. IQR CO/CO_2 Ratio (dropping abnormal values)

	Intention-to-Treat (Separate)	Intention-to-Treat (Bundled)	Instrumental Variable	Instrumental Variable (Technical)	Instrumental Variable (Technical+)
Adopted Intervention			-0.0033	-0.0030	-0.0039
			(0.0023)	(0.0026)	(0.0026)
Bundled Treatment		-0.0015			
		(0.0011)			
Technical Arm	-0.0014				
	(0.0012)				
Technical+ Arm	-0.0016				
	(0.0012)				
Control Mean	0.01	0.01	0.01	0.01	0.01
Percent Change	-11.3% (T)	-12.3%	-27.1%	-25.0%	-32.4%
	-13.2% (T+)				
N	264	264	264	171	181

+ $p < 0.1$, * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Note: Heteroskedasticity-robust standard errors are in parentheses. Regressions include randomization strata fixed effects. Outcome data are derived from measurements collected during kiln performance monitoring. Adoption is defined as adopting double/triple zigzag brick stacking and single fireman continuous feeding. Sample excludes kilns with O2, CO2, and CO outside normal ranges for more than 50% of the monitored time, which indicates abnormal operation.

Table S51. Mean CO/CO_2 Ratio (dropping abnormal feeding & values)

	Intention-to-Treat (Separate)	Intention-to-Treat (Bundled)	Instrumental Variable	Instrumental Variable (Technical)	Instrumental Variable (Technical+)
Adopted Intervention			-0.0014	-0.0019	-0.0004
			(0.0039)	(0.0045)	(0.0048)
Bundled Treatment		-0.0006			
		(0.0018)			
Technical Arm	-0.0008				
	(0.0021)				
Technical+ Arm	-0.0005				
	(0.0022)				
Control Mean	0.03	0.03	0.03	0.03	0.03
Percent Change	-2.6% (T)	-2.0%	-4.4%	-5.9%	-1.3%
	-1.4% (T+)				
N	272	272	272	178	186

+ $p < 0.1$, * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Note: Heteroskedasticity-robust standard errors are in parentheses. Regressions include randomization strata fixed effects. Outcome data are derived from measurements collected during kiln performance monitoring. Adoption is defined as adopting double/triple zigzag brick stacking and single fireman continuous feeding. Sample excludes kilns with O2, CO2, CO outside normal ranges for more than 50% of the monitored time and with total feeding time below 33%, which indicates abnormal operation.

Table S52. Max CO/CO_2 Ratio (dropping abnormal feeding & values)

	Intention-to-Treat (Separate)	Intention-to-Treat (Bundled)	Instrumental Variable	Instrumental Variable (Technical)	Instrumental Variable (Technical+)
Adopted Intervention			-0.0076	-0.0092	-0.0061
			(0.0063)	(0.0074)	(0.0074)
Bundled Treatment		-0.0035			
		(0.0030)			
Technical Arm	-0.0040				
	(0.0035)				
Technical+ Arm	-0.0030				
	(0.0035)				
Control Mean	0.06	0.06	0.06	0.06	0.06
Percent Change	-7.1% (T)	-6.2%	-13.7%	-16.4%	-10.9%
	-5.3% (T+)				
N	272	272	272	178	186

+ $p < 0.1$, * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Note: Heteroskedasticity-robust standard errors are in parentheses. Regressions include randomization strata fixed effects. Outcome data are derived from measurements collected during kiln performance monitoring. Adoption is defined as adopting double/triple zigzag brick stacking and single fireman continuous feeding. Sample excludes kilns with O2, CO2, CO outside normal ranges for more than 50% of the monitored time and with total feeding time below 33%, which indicates abnormal operation.

Table S53. SD CO/CO_2 Ratio (dropping abnormal feeding & values)

	Intention-to-Treat (Separate)	Intention-to-Treat (Bundled)	Instrumental Variable	Instrumental Variable (Technical)	Instrumental Variable (Technical+)
Adopted Intervention			-0.0029*	-0.0026	-0.0033*
			(0.0014)	(0.0017)	(0.0015)
Bundled Treatment		-0.0013*			
		(0.0007)			
Technical Arm	-0.0012				
	(0.0008)				
Technical+ Arm	-0.0014*				
	(0.0007)				
Control Mean	0.01	0.01	0.01	0.01	0.01
Percent Change	-12.7% (T)	-14.2%	-31.5%	-28.7%	-35.5%
	-15.6% (T+)				
N	272	272	272	178	186

+ p < 0.1, * p < 0.05, ** p < 0.01, *** p < 0.001

Note: Heteroskedasticity-robust standard errors are in parentheses. Regressions include randomization strata fixed effects. Outcome data are derived from measurements collected during kiln performance monitoring. Adoption is defined as adopting double/triple zigzag brick stacking and single fireman continuous feeding. Sample excludes kilns with O2, CO2, CO outside normal ranges for more than 50% of the monitored time and with total feeding time below 33%, which indicates abnormal operation.

Table S54. IQR CO/CO_2 Ratio (dropping abnormal feeding & values)

	Intention-to-Treat (Separate)	Intention-to-Treat (Bundled)	Instrumental Variable	Instrumental Variable (Technical)	Instrumental Variable (Technical+)
Adopted Intervention			-0.0032	-0.0028	-0.0039
			(0.0022)	(0.0025)	(0.0025)
Bundled Treatment		-0.0014			
		(0.0010)			
Technical Arm	-0.0013				
	(0.0011)				
Technical+ Arm	-0.0016				
	(0.0011)				
Control Mean	0.01	0.01	0.01	0.01	0.01
Percent Change	-10.6% (T)	-11.9%	-26.4%	-23.2%	-32.1%
	-13.2% (T+)				
N	272	272	272	178	186

+ p < 0.1, * p < 0.05, ** p < 0.01, *** p < 0.001

Note: Heteroskedasticity-robust standard errors are in parentheses. Regressions include randomization strata fixed effects. Outcome data are derived from measurements collected during kiln performance monitoring. Adoption is defined as adopting double/triple zigzag brick stacking and single fireman continuous feeding. Sample excludes kilns with O2, CO2, CO outside normal ranges for more than 50% of the monitored time and with total feeding time below 33%, which indicates abnormal operation.

Table S55. Above 33 Pct Fuel Feeding Sample Results (N = 255)

Balance Variable	Technical+ Mean	Technical+ Std. Dev.	Technical Mean	Technical Std. Dev.	Control Mean	Control Std. Dev.	T+ - C (p-val)	T - C (p-val)	T+ - T (p-val)
Owner Experience (Years)	15.7	8.5	17.0	10.2	13.9	9.6	0.25	0.074	0.4
Jashore Intervention Knowledge	0.37	0.49	0.40	0.49	0.35	0.48	0.82	0.72	0.88
Jashore Owner Interaction	0.44	0.51	0.58	0.50	0.58	0.50	0.47	0.8	0.32
Zigzag Year	2015	4	2014	4	2015	3	0.58	0.055	0.17
Water Adjacent	0.61	0.49	0.60	0.49	0.62	0.49	0.6	1.0	0.6
Bricks Fired (Lakhs)	8.06	0.97	7.9	1.1	8.1	1.1	0.72	0.15	0.23
Circuits Completed	6.1	1.5	6.0	1.5	6.2	1.9	0.98	0.53	0.43
Class 1 Production Share (%)	65.3	10.6	67.1	8.3	65.4	10.4	0.42	0.031	0.24
Production Cost Estimate BDT (per 1K Bricks)	8,842.3	1,220.9	8,606.3	1,317.3	8,673.5	1,060.4	0.19	0.97	0.23
Fired Brick Weight (kg)	3.38	0.24	3.40	0.19	3.40	0.23	0.4	0.95	0.4
Total Workers	108.8	28.7	111.5	30.3	110.8	35.2	0.89	0.57	0.47
Higher Secondary+	0.60	0.49	0.57	0.50	0.56	0.50	0.27	0.47	0.72
Highland	0.72	0.45	0.73	0.45	0.69	0.46	0.48	0.73	0.74
Joint Ownership	0.32	0.47	0.29	0.46	0.38	0.49	0.32	0.18	0.68
Shared Sardar	0.11	0.31	0.12	0.33	0.099	0.300	0.91	0.64	0.55
	N = 92		N = 82		N = 81				

Note: This table presents the results of balance tests run on baseline characteristics. The first two columns present the baseline mean and standard deviation in the Technical+ Arm, the second two present the baseline mean and standard deviation in the Technical Arm, and the third two present the baseline mean and standard deviation in the Control Arm. The last three columns present the p-value for a t-test of the difference in means between (1) Technical+ and Control, (2) Technical and Control, and (3) Technical+ and Technical. T-tests control for the randomization strata. The sample includes the 255 kilns with total feeding time above 33% (which indicates normal operation).

Table S56. Under 50 Out Of Range Sample Results (N = 264)

Balance Variable	Technical+ Mean	Technical+ Std. Dev.	Technical Mean	Technical Std. Dev.	Control Mean	Control Std. Dev.	T+ - C (p-val)	T - C (p-val)	T+ - T (p-val)
Owner Experience (Years)	15.5	8.5	17.0	10.2	15.0	9.8	0.75	0.24	0.34
Jashore Intervention Knowledge	0.36	0.48	0.38	0.49	0.35	0.48	0.89	0.89	0.98
Jashore Owner Interaction	0.46	0.51	0.6	0.5	0.54	0.51	0.87	0.46	0.39
Zigzag Year	2015	4	2014	4	2014	4	0.9	0.2	0.24
Water Adjacent	0.61	0.49	0.64	0.48	0.64	0.48	0.48	0.73	0.3
Bricks Fired (Lakhs)	8.0	1.0	7.9	1.2	8.1	1.1	0.33	0.17	0.59
Circuits Completed	6.1	1.6	6.0	1.5	6.1	1.9	0.88	0.7	0.54
Class 1 Production Share (%)	65.1	10.9	67.5	8.2	66.0	10.3	0.98	0.071	0.11
Production Cost Estimate BDT (per 1K Bricks)	8,817.1	1,225.1	8,574.9	1,307.8	8,725.6	1,025.2	0.35	0.6	0.19
Fired Brick Weight (kg)	3.38	0.24	3.40	0.19	3.39	0.22	0.53	0.91	0.44
Total Workers	108.0	29.1	112.5	31.2	111.4	35.4	0.68	0.54	0.3
Higher Secondary+	0.60	0.49	0.59	0.49	0.53	0.50	0.11	0.21	0.75
Highland	0.71	0.46	0.72	0.45	0.72	0.45	0.93	0.84	0.76
Joint Ownership	0.32	0.47	0.30	0.46	0.36	0.48	0.55	0.29	0.63
Shared Sardar	0.11	0.31	0.12	0.33	0.11	0.32	0.61	0.88	0.49
	N = 93		N = 83		N = 88				

Note: This table presents the results of balance tests run on baseline characteristics. The first two columns present the baseline mean and standard deviation in the Technical+ Arm, the second two present the baseline mean and standard deviation in the Technical Arm, and the third two present the baseline mean and standard deviation in the Control Arm. The last three columns present the p-value for a t-test of the difference in means between (1) Technical+ and Control, (2) Technical and Control, and (3) Technical+ and Technical. T-tests control for the randomization strata. The sample includes the 272 kilns with O2, CO2, CO outside normal ranges for less than 50% of the monitored time (which indicates normal operation).

Table S57. Under 50 Out Of Range Or Above 33 Pct Fuel Feeding Sample Results (N = 272)

Balance Variable	Technical+ Mean	Technical+ Std. Dev.	Technical Mean	Technical Std. Dev.	Control Mean	Control Std. Dev.	T+ - C (p-val)	T - C (p-val)	T+ - T (p-val)
Owner Experience (Years)	15.5	8.5	16.8	10.1	14.6	9.7	0.6	0.19	0.37
Jashore Intervention Knowledge	0.37	0.49	0.38	0.49	0.36	0.48	0.82	0.89	0.94
Jashore Owner Interaction	0.44	0.51	0.58	0.50	0.52	0.51	0.77	0.48	0.33
Zigzag Year	2015	4	2014	4	2014	3	0.99	0.17	0.17
Water Adjacent	0.61	0.49	0.62	0.49	0.63	0.49	0.52	0.85	0.42
Bricks Fired (Lakhs)	8.0	1.0	7.9	1.2	8.1	1.1	0.35	0.11	0.44
Circuits Completed	6.1	1.5	6.0	1.5	6.1	1.8	0.91	0.72	0.59
Class 1 Production Share (%)	65.2	10.9	67.3	8.3	65.8	10.3	0.88	0.084	0.17
Production Cost Estimate BDT (per 1K Bricks)	8,819.0	1,218.6	8,595.6	1,299.0	8,683.2	1,039.5	0.28	0.81	0.24
Fired Brick Weight (kg)	3.38	0.24	3.40	0.19	3.39	0.23	0.61	0.81	0.44
Total Workers	108.1	29.0	111.7	31.0	110.8	34.8	0.75	0.54	0.36
Higher Secondary+	0.60	0.49	0.58	0.50	0.53	0.50	0.14	0.26	0.75
Highland	0.71	0.45	0.73	0.45	0.72	0.45	0.87	0.91	0.78
Joint Ownership	0.32	0.47	0.30	0.46	0.37	0.49	0.49	0.26	0.65
Shared Sardar	0.11	0.31	0.12	0.32	0.11	0.31	0.68	0.84	0.53
	N = 94		N = 86		N = 92				

Note: This table presents the results of balance tests run on baseline characteristics. The first two columns present the baseline mean and standard deviation in the Technical+ Arm, the second two present the baseline mean and standard deviation in the Technical Arm, and the third two present the baseline mean and standard deviation in the Control Arm. The last three columns present the p-value for a t-test of the difference in means between (1) Technical+ and Control, (2) Technical and Control, and (3) Technical+ and Technical. T-tests control for the randomization strata. The sample includes the 272 kilns with O2, CO2, CO outside normal ranges for less than 50% of the monitored time and total feeding time above 33% (which indicates normal operation).

Table S58. Estimated Effect Sizes from Pilot Study

Outcome	**Control Group Mean**	**Technical ITT**	**Incentive ITT**	**TOT**
Class-1 (%)	66	2.1	7.12	9.22
CO/CO_2 (ratio)	0.04	-0.008	-0.006	-0.014
SEC (MJ/kg-fired brick)	1.28	-0.023	-0.083	-0.107

Table S59. Minimum Detectable Effect Sizes and Power for 100 kilns per arm

	MDES		**Power b/w treatment arms**
	Power: 0.9	Power: 0.8	
Class-1 (%)	3.56	3.08	0.81
CO/CO_2 (ratio)	-0.0064	-0.0056	0.19
SEC (MJ/kg-fired brick)	-0.065	-0.056	0.23

Table S60. Activity Schedule

Day & Time	**Activity**
Day 1	
08:00	The two-member team and helpers with all necessary equipment and materials arrive at the brick kiln site.
08:00 – 09:00	Meet brick kiln manager and brief him on the key tasks the team will be performing over next 2 days and the support required from kiln management. After initial briefing, request that he introduce the team to loading and unloading supervisors and the head fireman/firing supervisor. Tour the kiln with the kiln manager. Find key information on the kiln through questions and observations:

Continued on next page

Table S60 – *Continued from previous page*

Day & Time	**Activity**
	• Is the kiln's operation normal, or are there any operational issues—e.g. a shortage of workers, shortage of green bricks, etc.? • Observe the location of the fuel feeding/firing zone. The fuel feeding zone should be in the straight part of the kiln circuit. Check brick loading and unloading locations. • List the fuels being used. • How many chambers are being completed in a day (24-hour period)? • What is the approximate quantity of fuel used in 24 hours? • The type of brick setting and number of bricks loaded in one chamber. • Where is crushed fuel stored, and what is the quantity? Is there sufficient space for storing the weighed fuel for monitoring? • Time of the last chamber shifting and time when the next shifting is planned. • What is the typical schedule for the unloading operation, and where are unloaded bricks stacked? This is the basic information required for kiln monitoring, which can be used to fine tune the monitoring plan.
09:00 onward	One team member, with assistance from workers, starts the process of weighing and storing fuel:

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Table S60 – *Continued from previous page*

Day & Time	Activity
	• Using buckets of known volume and weight and a balance scale, individually weigh 5 buckets of each fuel and note the weight. Take the average of the 5 measurements to calculate the average weight of fuel/bucket and the density of each type of fuel. • Ask the kiln manager the amount of fuel required for 24 hours (also cross-check with your estimations). Calculate the number of buckets required of each fuel to obtain 1.1 times the 24-hour requirement. • Spread the tarpaulin on the ground. • Start the process of collecting the required quantities of fuel on the tarpaulin. This will require help from at least 2 workers and can take 3-4 hours. Use tokens to count the number of buckets. • When the fuel collection is complete, enter the initial quantity of each type of fuel on the ODK form. • Collect fuel samples in zip bags and label each with the number generated by the ODK, date of collection, and name of the fuel.
09:00 onward	The second team member prepares to start the 24-hour fuel consumption trial: • Observe kiln operations and complete Sections 1 to 4 on the ODK form. • Talk to firemen and coal persons and explain what the 24-hour fuel consumption trial will entail. Ask that they not add excess coal to containers/drums before the next chamber shifting. • Usually, a chamber shifting takes place sometime between 10:00 and 13:00 hrs. The aim should be to start the trial by lunchtime on day 1. • Supervise the start of the 24 hours fuel consumption trial.
11:00 onward	Ask the unloading sardar where they intend to stack fired bricks the next day and request that he organize the stacks so that it is easy to count the number of bricks. Check the unloading plan for the next day with him.
14:00 – 18:00 hrs	Carry out flue gas analysis (Option 1).

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Table S60 – *Continued from previous page*

Day & Time	Activity
	• Ensure that flue gas monitoring is not done immediately after the shifting of a chamber and that there is a gap of at least 1 hour. • The duration of flue gas monitoring is 2 hours. The total time required is close to 2.5 hours, which includes setting up the instrument and packing it after the measurements. • The measurements are collected at the shunt. Lift the shunt a few inches and place the pipe, which acts as the monitoring port. Insert and position the probe (at this point, the probe is not connected to the flue gas analyzer) inside the pipe. Ensure that there is no leakage of air from around the pipe by covering it with ash. Also ensure that the gap between the probe and the pipe is sealed with clay. • Switch on and self-calibrate the flue gas analyzer in open air. After self-calibration, connect the flue gas analyzer with the probe and ensure that the flue gas analyzer reading is displayed correctly on the computer tablet (using the KANE Live program). Flue gas analyzer readings are to be saved periodically both on the tablet and in the flue gas analyzer's memory. Ensure that the flue gas analyzer and the tablet remain connected by Bluetooth during the entire 2 hours of monitoring. The flue gas analyzer should be placed vertically and protected from dust and heat (by the cloth and umbrella). • While one team member is setting up the flue-gas analyzer, the second team member should be stationed near the fuel feeding zone to observe fuel feeding during the flue gas monitoring. • The clock on the flue gas analyzer should match the watch of the person monitoring the fuel feeding operation. • Once both team members are ready, flue gas monitoring begins. The team member stationed at the fuel feeding zone should record the fuel feeding status during the entire flue gas monitoring period. • Photograph the flue gas monitoring and fuel feeding operations, which are to be uploaded on the ODK. • After completion of the 2-hour monitoring, disconnect the probe, turn off the flue gas analyzer, and clean the flue gas analyzer, pipe, and tube externally. • After returning to the base, clean the moisture trap, check/replace the filter, and put the flue gas analyzer on the charger. Blow the flue gas probe with the bicycle pump to clean it. Periodically connect the probe and check for leaks.

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Table S60 – *Continued from previous page*

Day & Time	Activity
14:00 -18:00	After the unloading operation for the day has been completed, count the number of bricks (row wise) for each stack and record in a table format in the notebook. Place placards on unloaded brick stacks and/or mark using lime wash. Instruct the kiln manager/unloading sardar to stack the bricks in the marked stacks or in a separate new stack the next day. Broken bricks should be collected separately in a new heap. • Before leaving the site, check the firing operation to ensure that only fuel from the weighed lot is being used. Also instruct the firing supervisor to tell all firemen and coal loaders that only fuel from the weighed lot is to be used during the night. • Photograph the fan, chimney, and loading chamber to be uploaded on the ODK.
Day 2	
08:00 onwards	One team member should observe unloading operations. • Ensure that (a) unloading only takes place from the straight region of the trench and not from the gully region; (b) unloaded bricks are being stacked in the marked stacks; and (c) almost an equal number of bricks are being unloaded from the top and bottom parts of the kiln stacking. If that is not the case, ask that the kiln manager and unloading sardar ensure that by the end of the day's unloading, an almost equal number of bricks from the top and bottom parts of the kiln stacking are unloaded. • Photograph of the unloading to be uploaded on the ODK.
08:30 -11:30	If the flue gas analysis was not carried out on Day 1, it can be carried out during this time slot (Option 2)
09:00 onward	Completion of the 24-hour monitoring:

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Table S60 – *Continued from previous page*

Day & Time	Activity
	• The other team member should observe the fuel feeding and talk to firemen to find out when the next chamber shifting is likely to take place. Also check the quantity of weighed fuel available, and ask that they not add excess coal to the containers before the next chamber shifting. • On completion of fuel measurement monitoring: Note the end time and sketch the kiln and mark the position of the fire. Also put a marker on the kiln and take a photograph. Note the number of chambers that have been completed/closed during the 24-hour monitoring. • Ensure that all drums that have remaining pre-weighed fuel are emptied and calculate the quantity of remaining fuel using the standard bucket measurement. • Check the remaining pre-weighed fuel on the tarpaulin in the fuel storage area and estimate the quantity using the standard bucket measurement. • Record the remaining weight of each fuel type on the ODK. • Record the number of chambers completed during 24 hours on the ODK. • Usually, the total duration of the monitoring is 24±2 hours. In some cases, if the monitoring was started on the afternoon of Day 1, the monitoring period can be reduced in order to finish monitoring during the 2 days. However, the monitoring period should not be less than 20 hours
14:00-16:00	After the unloading operation for the day has been completed, count the unloaded bricks by class.

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Table S60 – *Continued from previous page*

Day & Time	**Activity**
	• Count the number of bricks by rows, subtract the initial numbers, and calculate the number of bricks stacked on that day by quality class. • Arrange the broken bricks in a cuboid shape and measure to calculate the volume and, from that, the number of bricks (1 cubic ft = 8.5 bricks) • Enter the number of unloaded bricks of each quality on the ODK. • Randomly select and weigh 20 samples of unloaded Class 1 bricks in a lot size of 5 and enter on the ODK.
16:00-17:00	Check that all data have been recorded and photographs taken and that the data are correctly recorded on the ODK. Meet with the Kiln Manager/Owner, thank them for their cooperation, brief them regarding the preliminary results—e.g., specific fuel consumption, % distribution of the quantity of bricks, and interpretation of the flue gas analysis results.