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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 10.3% (p-value<0.001) and decreased CO2 and PM2.5 emissions by 171 metric tons and 0.45 metric tons, respectively, per kiln per year. Valuing the CO2 reductions using a social cost of carbon of $185/MT, we find that the social benefits outweigh costs by a factor of 190 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 data appendix is available at
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A randomized controlled trials registry entry is available at
https://www.socialscienceregistry.org/trials/10127

1. Introduction

Informal industries, such as brick manufacturing, are central to the economies of low- and middle-income countries (LMIC)(*1*). In Bangladesh (our study location), they account for as much as 40% of GDP and 80% of employment (*2*). Because it typically operates outside strict government oversight, the informal sector includes many highly polluting industries, including brick manufacturing (*3*–*5*).[2] In South Asia, most brick manufacturing takes place in informal, traditional coal-fired kilns (*6*–*8*). They are among the largest sources of greenhouse gas emissions in South Asia (*6*, *9*, *10*), degrading local air quality (*10*–*14*), health (*6*, *9*, *15*–*17*) and agricultural productivity (*18*, *19*).

Regulating informal sector pollution is particularly difficult.[3] In Bangladesh, efforts to improve the brick kiln industry over the past 30 years have largely been ineffective (*21*–*24*), in part because government regulations have not been adequate (*15*) or enforced (*21*, *23*–*25*). The other dominant approach has been to promote technologically advanced kilns. Modern kilns are five to ten times more expensive to construct and operate (*6*, *7*, *24*)---and therefore particularly onerous for informal firms with limited access to formal credit and technical expertise to adopt (*26*). Perhaps unsurprisingly, the diffusion of such modern kilns has been minimal despite significant promotion efforts, and even more importantly, these kilns have often failed to achieve their purported emissions benefits (*21*, *27*–*30*).

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[2] Other examples include leather tanning, metal working and resource extraction (*3*, *5*).

[3] The two most often cited challenges are (a) the difficulty of locating and monitoring entities with no formal registration or other ties to the regulatory apparatus and (b) the difficulty of monitoring emissions from a widely dispersed and small-scale set of industrial units (*3*, *20*).

This background informed our strategy for designing an intervention to improve the environmental performance of Bangladeshi brick kilns. Specifically, we designed an intervention that was incentive-compatible for existing zigzag kiln owners[4] and that did not rely on state action. Several relatively modest modifications to the operational practices of informal kilns met these criteria. These practices required no new capital investment and can reduce black carbon, CO_2, and $PM_{2.,5}$, while also increasing kiln profitability by reducing costs and increasing brick quality (*32–35*). However, most zigzag kilns in Bangladesh are incorrectly operated, leaving these social and private benefits unrealized (*6*, *21*, *24*, *30*).

Our pilot work suggested that kiln owners were unaware of proper operating practices and their profitability (*22*). 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 kilns with technical training and support to improve kiln performance. Because the improved operational practices changed workers' tasks, we also provided additional information and nudges to owners about incentivizing workers to adopt the improved practices. We implemented the study as a randomized controlled trial (RCT) with a control group and two intervention groups. The first intervention provided technical support (the "technical arm"), and the second provided technical

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[4] Zigzag kilns, a type of traditional kiln in the informal sector, are the dominant kiln technology in Bangladesh, representing 81% of the 7,881 registered brick kilns. The other traditional kiln is called a fixed-chimney kiln (17.4% of all registered kilns). There are 150 modern, formal kilns (hybrid Hoffmann and tunnel kilns) registered in Bangladesh, making up fewer than 2% of total kilns (*31*).

support as well as information and nudges to incentivize worker adherence (the “technical+incentive” arm). To our knowledge, this is the first randomized controlled trial examining energy efficiency in informal brick kilns.

2. Materials and Methods

2.1 Experimental Design

During the 2022–2023 brick firing season,[5] we conducted an RCT with three experimental arms: (1) a technical arm, (2) a technical+incentive information 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 brick production.

Kilns assigned to the technical arm received information, intensive 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, 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

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[5] 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).

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+incentive 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 Appendix A for details on the interventions.

2.2 Sampling, Data Collection and Measurement

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).[6] Kiln performance monitoring to collect

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[6] 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, outcome data from the kiln performance monitoring assessment, which required kilns to be firing, was collected from 276 kilns. The sample remains balanced (Table S8) and attrition for either stopping early or government demolition was uncorrelated with treatment (Table S12).

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).[7]

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, measuring 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

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[7] 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.

Our primary outcomes are adoption of the technical intervention; specific energy consumption (a measure of the energy used to fire 1 kg of bricks); the ratio of CO/CO_2 (which captures the completeness of combustion (*36*)); and 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). These outcomes are based on detailed and objective data collected during the kiln performance monitoring. Secondary outcomes include additional measures of efficiency—specific fuel consumption (the quantity of coal used to fire 100,000 bricks); CO_2 emissions (calculated by applying IPCC conversion factors to specific energy consumption (*37*)); $PM_{2.5}$ emissions (calculated by applying $PM_{2.5}$ emissions factors (*38*) to specific energy consumption); and measures of working conditions and the use of incentives and amenities for workers (for more details, see Appendix A).[8] 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.

2.3 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+incentive 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

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[8] Since the overwhelming majority of fuel used was coal, we use the terms fuel and coal interchangeably (though some kilns use sawdust and small amounts of firewood).

was in either treatment arm and zero otherwise. To quantify treatment effects among adopters, 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.[9] 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).

3. Results

Adoption of improved zigzag kiln operation practices

Fig. 1 presents results for adoption by study arm: 66.3% of kilns in the technical arm (59 of 89 kilns) and 64.2% of kilns in the technical+incentive arm (61 of 95 kilns) adopted the intervention. Strikingly, 19.6% of control kilns (18 of 92 kilns) also adopted the intervention even though they were not provided any of the intervention components. The control group take-up provides some revealed preference evidence of the value of the intervention to kiln owners---these owners sent managers and workers to intervention kilns to learn the practices. 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+incentive

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[9] In settings with one-sided non-compliance (specifically, when the population comprises only “compliers” and “never takers” in the language of Imbens and Angrist (*39*)), the Treatment-on-the-Treated (ToT) parameter is equal to the average treatment effect among compliers (sometimes referred to as the 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).

arm relative to the control arm, ($p<0.001$) (Table S2). 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+incentive arm). Perhaps most encouragingly, among the 18 control kilns that had adopted 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, bringing total adoption to 56.5% of control kilns (Figure S1).[10]

In what follows, for sake of brevity we discuss the experimental results from the specification that combines the two treatment arms (the arm-specific treatment effects and associated standard errors are also provided in Tables S10 - S16).

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[10] As a condition for participating in the RCT with the potential of being randomly assigned to the treatment group, the intervention was offered to all control kilns in the subsequent firing season (that is, to all control kilns that had not adopted the operational practices in the first year of the experiment and met the original inclusion criteria for the intervention (e.g., used coal and operated their kiln). Of the 65 kilns that were trained, 28 (43%) adopted the two most important practices. All control kilns that had adopted during the RCT continued to use the improved practices in the subsequent firing season, bringing total control kiln adoption to 56.5%.

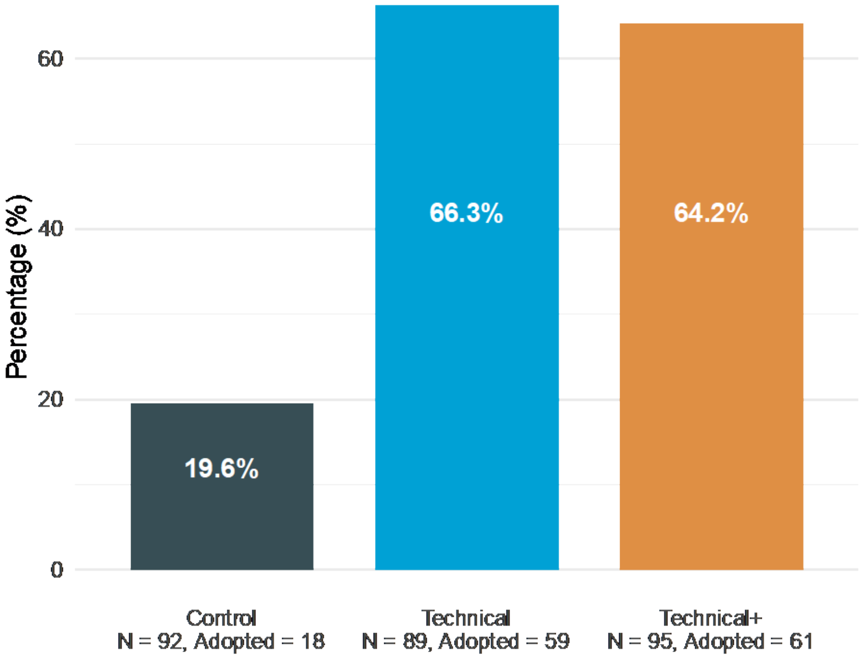

Fig. 1. Adoption by study arm. This figure presents the raw means of adopting double/triple zigzag brick stacking and single fireman continuous feeding by treatment arm.

Intervention Impact on 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. 2A and Table S10) in the treatment arms, equivalent to a 10.3% 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 22.4% relative to the control mean (Table S10). These results are meaningful from an energy perspective: for instance, the IV 0.25 reduction in energy use brings specific energy consumption in line with the previously reported lowest specific energy consumption values among brick kilns in South Asia for the most efficient coal-burning kilns (*33*). We also find a reduction in fuel use of 1.8

tons/l00,000 bricks (95% CI: [1,2.6], p-value <0.001), which represents an 11% decrease in fuel use relative to the control mean of 16.3 tons/l00,000 bricks (Table S17).

Assignment to the intervention reduced CO_2 emissions by 171 tons over the season (9.8%, 95% CI: [53,289], p-value<0.001), and the IV estimates suggest even larger reductions among adopters of 382 tons (21.5%, 95% CI: [105,660], p-value<0.001) (Fig. 2A and Table S11). The intervention also reduced $PM_{2.5}$ emissions by 0.45 tons over the season (8.8%, 95% CI: [0.139,0.763], p-value<0.001) and the IV estimates are more than double the ITT estimates at 1 ton (19.3%, 95% CI: [0.28,1.7], p-value<0.001) (Fig. 2A and Table S11).[11] Suspended particulate matter (SPM) was measured in a small sample of kilns (8 adopted, 4 non-adopters, see Appendix A) and shows lower values SPM among adopting kilns, however we caution over-interpretation of these data due to the small sample (Fig S2).

Both the ITT and IV results show small and statistically insignificant reductions in the mean CO/CO_2 ratio (Table S22), a measure of combustion efficiency (*36*) that was pre-registered. The measurements collected were noisy (and not all were physically plausible given the expected ranges of O_2, CO_2, and CO). In Appendix E, we test the sensitivity of the CO/CO_2 findings to alternative specifications that drop kilns with implausible values and explore alternative outcomes based on the CO/CO_2 (which were not prespecified; Tables E1 – E14). These results provide suggestive evidence that the intervention significantly reduced both the maximum

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[11] 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.

(Tables E1, E9, E13) and the variance (Tables E2, E3, E6, E7, E10, E14, E15) of the CO/CO_2 ratio, which is indicative of improved combustion efficiency.

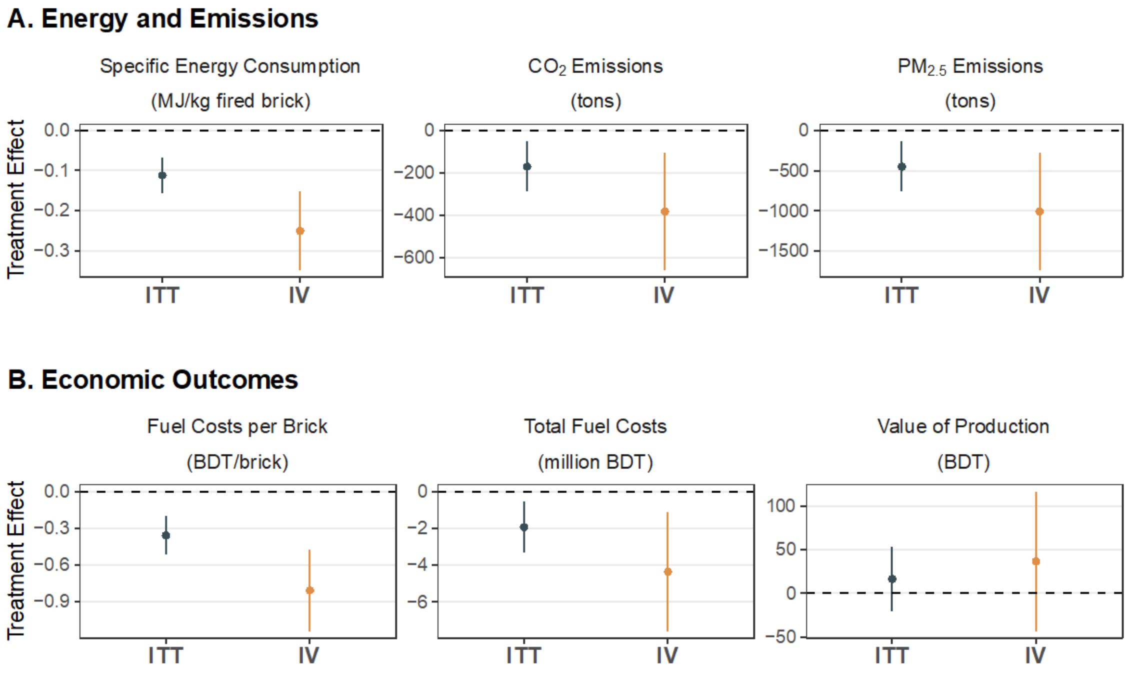

Fig. 2. Intervention impact on energy, emissions, and economic outcomes. Panel A presents the intervention's impact on outcomes related to energy use and emissions. Panel B reports the findings for economic outcomes for kiln owners. Both panels show regression results for the intention-to-treat (ITT) 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.

Economic Outcomes

Fuel is kiln owners' most expensive input and a key promise 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 and 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. 2B and Table S13). These magnitudes are large and imply 9.5% and 20.8% reductions in fuel costs/brick for the ITT and IV results, respectively. 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 adopters (USD 37,153; 95% CI: [1.1,7.6], p-value<0.001, Fig. 2B and Table S14).

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) 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), a 8.2% increase, while also reducing the percentage of inferior bricks (Classes 2 and 3, see Fig. 3). The IV estimates suggest a 14.2 percentage point (95% CI: [11.0,17.3], p-value<0.001) increase or 19% (Fig. 3 and Table S15) among adopters. 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 S28).

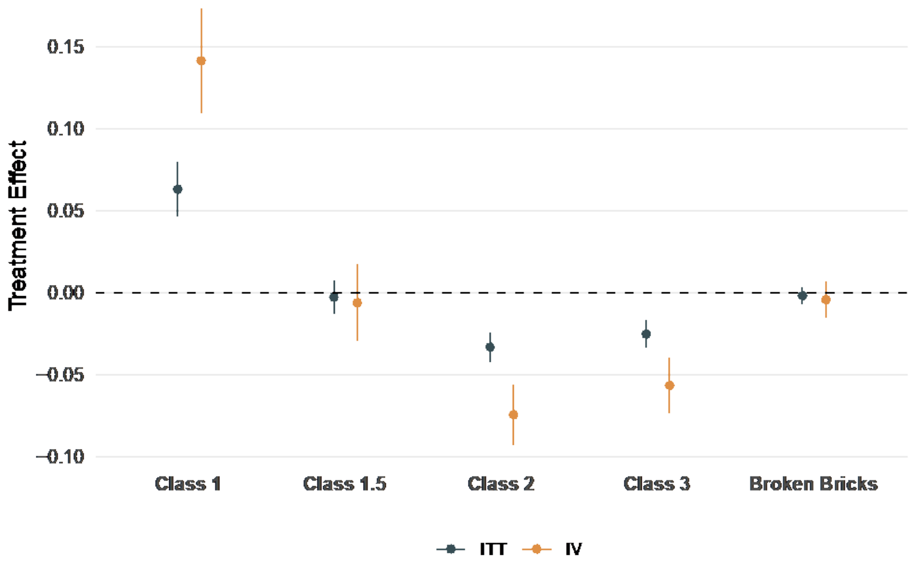

Fig. 3. Intervention impact on distribution of brick quality. This figure presents regression results for the intention-to-treat (ITT) and instrumental variable (IV) specifications for each classification of brick quality as a percentage of total production. The ITT specification, shown on the left in 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.

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 and summing across the various classes, using the kiln owner's self-reported data on the entire season's production.[12] In Fig. 2B we

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[12] 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 (see Table S25). We prespecified a

present the results for total value of production over the firing season and see positive, but noisy effects of the intervention (both ITT and IV specifications). While the intervention resulted in a larger fraction of Class 1 bricks (Fig. 3), there was no difference in total brick production over the season (Fig. 2B); consequently, we may be underpowered to detect significant differences in the value of production.

Rebound effects

By effectively reducing the price of energy, energy efficiency interventions can potentially increase total energy use if overall production increases (*40–42*). We find a small and statistically insignificant effect of the intervention on total annual brick production (Table S23), which suggests there was not a rebound effect on brick production in our setting.[13]

Work Conditions

Because the operational changes promoted by the intervention substantively changed workers' tasks, the technical+incentive 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

"normalized" version in which we divide the value of production by the total quantity of bricks (see Supplementary Section C for more details). As a result, 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 the Supplementary Information (Table S26 with monitoring data and S27 using kiln owner self-reports at endline).

[13] 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 Information 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.

specifications suggest that the intervention had no effect on explicit incentives that kiln owners report providing to workers (Fig. G4).

Costs

The primary cost for the RCT was the training expense and technical support throughout the season. These included venue costs, staff costs for engineers, material (e.g. handouts, pens), travel and food for participants, as well as “train the trainers” sessions in which the technical lead trained the project engineers. Training was provided at the district level (i.e. to all treatment kilns in the same district) and the total cost was approximately USD 30,544 or about USD 166 (30,544/184) per treatment kiln.

4. Limitations

A limitation of our study is that although we were powered (based on pilot data, see Appendix A for details) to detect differences in the mean CO/CO_2, the estimated effects were noisier (and hence less precise) than anticipated. However, the increased sample size posed unanticipated additional difficulties with flue gas measurement, and this increased measurement variability (we describe the measurement protocol in more detail in Appendix D and provide more discussion of these challenges in Appendix E). Even after conducting supplementary analysis excluding unreliable data (these were not prespecified; see Tables E1 – E15), there were few differences in the mean CO/CO_2 but some suggestive evidence that the intervention decreased both the maximum value and variance, which is indicative of improved combustion efficiency. Ultimately, these efforts suggest that 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. Nonetheless, the strength and internal consistency of the results on energy use, brick quality, and fuel savings support the overall conclusions of the study.

5. Discussion and Conclusion

We designed an intervention to improve informal brick kiln operations in Bangladesh. The intervention aimed to reduce emissions and costs and increase revenue by introducing a set of operational practices to improve kiln efficiency. We tested the intervention using a randomized controlled trial on a sample of 276 kilns in Khulna division. Demand for the intervention was high with 65% of treatment kilns adopting the key improved practices. Furthermore, 20% of control kilns also adopted these practices despite not receiving any training or the support, which provides compelling revealed-preference evidence of the value of the intervention to kiln owners. Additional adoption in all study arms in the post-intervention period (to about three-quarters in the treatment arms and over one-half of the control arm) provides further evidence that kiln owners valued the intervention.

The efficiency improvements that we promoted achieved large effects, which we captured with high quality and detailed assessments collected from each kiln during 30-hour kiln performance monitoring assessments. Treatment assignment reduced energy use by 10% and coal use by 11% and the instrumental variable estimates suggest reductions that are approximately twice as large (20% and 24% respectively) for adopters. Fuel is the costliest input for brick kilns, and the reductions in fuel use decreased costs per brick by 9.5% (20.8% for adopters). These benefits were achieved without evidence of contemporaneous rebound effects, a common concern in the energy efficiency literature (*35, 36, 37–42*). Finally, the intervention also increased the quality of the bricks produced as measured by the fraction of Class 1 bricks (the highest quality brick gradation) by 8.2% (18.9% for adopters). Information reported by kiln owners also confirms these results.

The intervention yielded significant social benefits, reducing both CO_2 by 171 MT and $PM_{2.5}$ emissions by 0.45 MT (382 MT and 1 MT among adopters, respectively). If all 6,352 zigzag kilns (*31*) in Bangladesh adopted these efficiency improvements, our results imply that CO_2 would be reduced by 2.4 million MT over a single brick firing season, a 2% reduction in Bangladesh's annual CO_2 emissions (*43*). For context, 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 (*44*).[14] 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 adopters 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*).[15]

Assuming a social cost of carbon of $185/MT (*52*), our results also suggest a single year valuation of the reduced carbon emissions of USD 31,635 per kiln (USD 70,670 among adopters). This compares favorably with the cost of delivering the intervention (USD $166 per

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[14] We obtained these estimates by multiplying the reduction in CO_2 emissions among adopters (382 MT) by the total number of zigzag kilns in the country (6,352) to get 2,426,464 tons CO_2 emissions, which is equivalent to 2% of Bangladesh's total annual emissions. Then, we used the EPA's CO_2 equivalence calculator, available at https://www.epa.gov/energy/greenhouse-gas-equivalencies-calculator, to convert the CO_2 into the equivalent amounts required to power homes in the US or that would be sequestered by seedlings, for context.

[15] We explore whether other input costs changed due to the intervention (Tables S32-S38) and find 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.

kiln), implying a benefit-cost ratio of 190 (31,635/166).[16] Given we have not accounted for the health benefits of reduced $PM_{2.5}$ emissions, this calculation presumably underestimates the total social benefits substantially as well (*45*).

An important caveat is that we observed no significant differences in adoption or efficiency between the two treatment arms, despite both the information provided to owners in the technical+incentive 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 (*46*). 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 (*47*).

Our findings add to the fledgling literature measuring the effects of innovative approaches to reducing emissions and pollution in low income countries (*3*, *5*, *20*, *48–50*). 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 (*51–56*). Past research has

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[16] The benefit-cost ratio implied by the IV estimates is even larger: 425. The 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 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 57.

found that better-managed firms in the United Kingdom were less energy intensive (*54*), but few firm-level interventions in LMICs have been effective (*51*). 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 informal enterprises.

Our approach is promising for scaling both within Bangladesh and possibly across South Asia, where brick production is similar. Our study also provides lessons for implementing interventions in other polluting industries in the informal sector, particularly in contexts with weak regulatory enforcement–environments in which aligning private incentives with public policy goals may be necessary. 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.

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