Reducing Occupational Heat Stress

Pre-Analysis Plan

March 30, 2026

This document outlines the analysis plan for the cluster randomized controlled trial of an integrated ZZK2.0 refresher training and work conditions improvements for brick kiln owners and workers, for the "Reducing Occupational Heat Stress and Improving Work Conditions: A Cluster Randomized Controlled Trial" project. The document provides a pre-specified methodology and plan for analyzing the results of the experiment.

1 Study Overview

Millions of people living in poverty in Bangladesh are threatened by accelerating climate change and worsening air quality. The brick kiln sector in Bangladesh poses two major threats. It is a major contributor to air pollution, while also subjecting workers to unsafe and exploitative labor conditions (Das et al., 2017). Its ∼7,000 brick kilns produce 27 billion bricks each year, generating 11% of the country's particulate matter, 22% of black carbon, and 17% of total annual CO2 emissions (Eil et al., 2020). In major cities in Bangladesh during the wintertime when air quality is worse, brick kilns contribute 30 to 58% of the small particulate matter (PM 2.5) (Eil et al., 2020). Exposure to air pollutants contributes to morbidity, mortality, childhood pneumonia and adverse birth and cognitive outcomes (Landrigan et al., 2018). Despite the promotion of zigzag kilns (ZZK) since 2013, most conversions have been implemented poorly (Eil et al., 2020; Alam and Barman, 2019).

Our randomized controlled trial (RCT) with 276 kilns in Khulna Division during the 2022–2023 season introduced Zigzag 2.0 (ZZK 2.0), a package of technical training and operational support for kiln owners and managers (Brooks et al., 2025). Adoption of the two most critical practices, improved brick stacking and more frequent coal feeding, resulted in 24% less coal use per 100,000 bricks produced and reductions of 21% in both CO2 and PM2.5 emissions (Brooks et al., 2025). Importantly, Zigzag 2.0 also delivered economic wins to owners in the form of reduced spending on coal and greater production of the highest quality bricks. Owners perceived these improvements, which increased sustained uptake—in fact, one year later nearly 99% of kilns which had adopted Zigzag 2.0 continued to follow the practices. At the request of the Ministry of Environment, Forest and Climate Change, this intervention has now been scaled to 500+ kilns nationwide in 2024–2025.

In contrast, the conditions faced by kiln workers remain understudied and under-addressed. Workers, often impoverished seasonal migrants, are routinely exposed to unsafe, coercive, and exploitative conditions (Miller et al., 2024). In our recent survey, about 70% reported lacking basic personal protective equipment (PPE), such as gloves, boots, or masks (Miller et al., 2024). This gap exposes them to frequent burns, head injuries, eye irritation, and chronic respiratory illness from smoke inhalation (Sanjel et al., 2016).

Work conditions compound these risks. Shifts typically last 12–16 hours, often near coal-fired chambers burning above 800°C (Maithel et al., 2017). Kilns rarely provide shaded rest areas, safe drinking water, or heat breaks, creating conditions ripe for dehydration, heat exhaustion, and long-term cardiovascular and renal disease (Flouris et al., 2024). Many workers and their families also live onsite at kilns in inadequate housing that lacks basic sanitation and privacy, further compounding health risks and exposure to hazardous conditions. Heat exposure is a particularly acute and growing concern: as climate change intensifies, kiln workers face rising ambient temperatures layered on top of extreme occupational heat from coal-fired chambers, placing them at severe risk of heat stroke, acute kidney injury, and chronic kidney disease of non-traditional origin (Flouris et al., 2024). Despite the scale of this risk, there is virtually no rigorous evidence on whether low-cost heat mitigation strategies—such as shaded rest areas, hydration access, and scheduled work breaks—can meaningfully reduce physiological heat strain in this population.

The labor system itself is marked by coercion. Many workers in our Khulna Division sample entered through debt-bondage contracts, leaving them unable to exit even when wages are withheld or benefits denied—practices reported by over 10% of workers (Miller et al., 2024). Moreover, child labor is pervasive—reported in more than 70% of kilns in our previous study—with families often migrating together and children contributing to manual tasks under hazardous conditions (Miller et al., 2024). The informal nature of the industry prevents effective labor regulation, and the absence of formal contracts (reported by 71% of workers) strips them of any legal protections (Das et al., 2017). This combination of physical hazards, economic coercion, and social vulnerability represents a critical human rights and public health issue.

Our past ZZK 2.0 energy-efficiency intervention brought measurable reductions in emissions and fuel use (Brooks et al., 2025), yet work conditions remain hazardous. In other settings, occupational health interventions in South Asia have focused on PPE distribution or training but without rigorous evaluation in coercive labor settings (Shoaib et al., 2024). Improving work conditions for this vulnerable population requires filling key knowledge gaps. First, it is unknown whether low-cost workplace interventions such as shaded rest areas, hydration access, or PPE can actually reduce physiological heat stress and improve worker health and well-being. Second, brick kilns operate through complex management hierarchies—with owners often distant from daily operations while managers and sardars (labor contractors and supervisors) control recruitment, payment, and work conditions. There is limited evidence on whether and how interventions can work through these management structures to significantly reduce coercive labor conditions, or whether owners and their managers can be motivated to make improvements that reduce labor exploitation (Miller et al., 2024). Third, we lack evidence on whether integrating worker protections into profitable improvements to kiln operation (Zigzag 2.0) can create synergistic benefits for both worker well-being and productivity, which is particularly relevant in a context with limited enforcement of labor regulations. Finally, the absence of gender-disaggregated data limits our ability to identify and protect those at greatest risk.

This study builds directly on the success of Zigzag 2.0, enhancing it with a new package of worker-centered interventions ("Zigzag 2.0+") that target occupational safety, heat stress, and labor exploitation. Specifically, the new package integrates worker protection measures—including personal protective equipment (PPE) provision, heat mitigation strategies, workplace and living condition improvements, and wage payment monitoring—into the existing Zigzag 2.0 technical training and operational support framework. We hypothesize that combining worker welfare improvements with a profitable business model can take advantage of owners' economic incentives to generate meaningful improvements in labor conditions. By implementing this intervention as a randomized controlled trial, we aim to generate causal evidence on whether simple, low-cost workplace improvements can protect workers, reduce physiological heat strain, and enhance well-being, without undermining kiln productivity.

Our cluster randomized controlled trial has the following objectives:

1. Summarize occupational environmental conditions at kilns in terms of PM2.5, temperature, and wet-bulb globe temperature.
2. Assess differences in physiological heat strain indicators (core body temperature, hydration status) between treatment and control workers resulting from heat mitigation interventions.
3. Measure impacts on worker-reported heat stress symptoms (feeling faint, dehydration, confusion, fatigue, nausea, cramps).

2 Research Design

2.1 Sampling and Randomization

We used our database of past study kilns to create a list of 215 kilns which had already adopted ZZK2.0 in Jashore, Jhenaidah and Shatkhira districts of Khulna Division (selected due to the high number of adopters). Field teams approached these kilns, secured their consent to participate in the trial, and conducted a baseline survey. From the list of the adopted zigzag kilns, we stratified the kilns into five strata, based on prior project enrollment groups: pilot, RCT-control, RCT-technical arm, RCT-incentive information arm, and scaling.[1]

Within each stratum, we aimed to assign approximately 60% of kilns to the treatment group and 40% to the control group. For the four strata with consistent baseline data (all except the "scaling" arm), we used a re-randomization procedure to ensure balance on a broad set of pre-specified covariates, including kiln owner characteristics, kiln structural features, and past production metrics. Specifically, we repeatedly generated random assignments until we found one for which the absolute value of the Welch t-statistic for the difference in means between the treatment and control groups was less than 1.2 for every covariate. For the 'scaling' stratum, where covariate data was unavailable, we conducted a simple (unrestricted) randomization.

This procedure resulted in an initial sample of 127 kilns assigned to the treatment group and 88 kilns to the control group. During baseline data collection, we then subsequently observed an approximate 20% non-operation rate among these kilns. Given available budget and implementation

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[1] These strata are determined based on our research's group prior work in the Khulna Division of Bangladesh and reflect the different timing and nature of the ZZK2.0 delivery. Pilot refers to kilns that were included in the pilot study of ZZK 2.0 conducted in Jashore district among 30 kilns in the 2021-2022 brick firing season (Brooks et al., 2024). RCT kilns were enrolled in the randomized controlled trial of ZZK 2.0 conducted across 6 districts of Khulna Division during the 2022-2023 brick firing season Brooks et al. (2025). We created separate strata for kilns that were assigned to the control arm, technical-only arm, and incentive information arm, to reflect the different information and training provided on ZZK 2.0 as well as regarding work conditions. Scaling kilns are those that received technical training on ZZK2.0 during the 2023-2024 brick firing season during our team's ramp up on ZZK2.0 across Khulna and Dhaka Divisions, at the request of the Bangladesh Government.

capacity, we therefore expanded our sample by identifying 36 additional operating kilns in close-by districts. This sixth "expansion" stratum included kilns which had adopted ZZK2.0 both through our previous programs, or independently had done so. Because baseline covariate data were not available for most expansion kilns, we assigned them to treatment and control groups using simple (unrestricted) randomization with the same 60/40 target allocation. 148 assigned to the treatment group and 103 to the control group, across six strata (five from the initial randomization and the expansion stratum). The final targeted sample includes 251 kilns: 103 kilns assigned to the control group, and 148 kilns to the treatment group, a strategy that maximizes statistical power accounting for imperfect uptake among the treatment group, yielding a sample size of 103*5=515 workers in the control group and 148*5=740 workers in the treatment group.

2.2 Intervention

Owners in kilns in the intervention arm will receive an integrated ZZK 2.0+ intervention which includes: (1) a training session combining Zigzag 2.0 technical refresher with worker condition improvement (WCI) orientation, (2) individualized action planning meetings to develop kiln-specific implementation plans, and (3) ongoing field support throughout the brick production season. The WCI package is designed to enhance occupational safety, improve payment practices, and improve living conditions for kiln workers. The intervention will be delivered through a 4-hour integrated training session in November-December 2025, after baseline data has been collected. These trainings will be delivered at central kiln locations with 15-20 kilns per session. These initial group sessions will be followed by monthly site visits (60-90 minutes each) including: observation of PPE use, facility conditions; form collection; troubleshooting conversations, quarterly review meetings (2 hours) with clusters of owners to share progress, challenges and adaptive solutions, phone support available between visits for urgent technical and implementation issues.

Relationship to companion PAP and bundled intervention description. This trial evaluates a single, integrated ZZK 2.0+ package delivered as a bundled, multi-component intervention. We pre-specify two related PAPs for the same experiment: this PAP focuses on heat-stress outcomes, while a companion PAP focuses on broader work conditions and labor outcomes. Both PAPs describe the full intervention package, but each emphasizes the components most directly relevant to its primary outcomes. In this heat-stress PAP, we emphasize workplace/living-condition improvements and heat-mitigation measures, while noting that PPE provision and wage-payment monitoring were also delivered as part of the package.

Intervention Components (Specified using the TIDieR framework)

Component 1: Personal Protective Equipment (PPE) and Occupational Safety

What (materials):

- Improved wooden shoes (khoroms) for the firemen
- Dust masks (cloth or disposable) for coal crushers, loaders, unloaders and molders
- Protective gloves for coal handlers, brick loaders and unloaders

- Local protective headwear (Bida) for unloaders
- Caps and towels (gamcha) for heat/dust protection for all workers
- First aid kits containing: bandages, antiseptic, pain relievers, burn ointment, oral rehydration salts (ORS)

What (procedures):

- Owners procure PPE supplies before season starts based on worker counts
- PPE distributed to workers at the beginning of the season or upon arrival
- First aid kits placed in accessible central locations (e.g., manager's office, rest areas)
- ORS sachets made available during hot months (March-May)

Who provides: Kiln owners purchase and distribute; field staff provide procurement guidelines and supplier contacts

Dose/intensity: One complete PPE set per worker at season start; replacement items available as needed; first aid supplies replenished monthly

Component 2: Wage Payment Monitoring System

What (materials):

- Standardized weekly wage tracking forms documenting: worker names, job categories, agreed wages, amounts paid, dates, payment method, signatures

What (procedures):

- Managers/owners complete forms weekly
- Forms submitted to field staff during monthly visits
- Owners conduct at least monthly direct check-ins with workers of different groups(separate from sardars) about payment satisfaction
- Any reported discrepancies documented and followed up within one week

Who provides: Field staff train managers on form completion; managers implement weekly; field staff collect and review

Dose/intensity: Weekly form completion throughout 6-month season (24 forms per kiln); monthly owner-worker engagement sessions

Component 3: Workplace and Living Condition Improvements

What (materials):

- Toilet cleaning supplies: Harpic or similar cleaning agent, brushes, soap bars

- Handwashing stations: soap bars or soapy water containers placed near toilets and work areas
- Drinking water: clean water sources positioned near resting areas
- Infrastructure improvements (where feasible): temporary shaded rest areas with mats; ventilation improvements to worker housing (windows, vents); fans in rest areas (if possible)

What (procedures):

- Cleaning supplies provided at start of season and replenished monthly
- Designated cleaning responsibilities assigned (either hired cleaner or rotation among workers)
- Weekly checks by managers to ensure supplies are available and facilities functional

Who provides: Owners procure and provide supplies; field staff provide facility improvement guidance and cost estimates

Dose/intensity: Continuous availability of cleaning/hygiene supplies throughout season; infrastructure improvements implemented within first 2 months

Component 4: Heat Mitigation Strategies

What (materials/procedures):

- Shaded rest areas near high-heat work zones (molding, firing areas)
- Drinking water stations positioned within 50 meters of all work areas
- ORS sachets provided for free and consumption encouraged during hot months (March-May)
- Work breaks: encourage at least 15-minute rest breaks every 2-3 hours during peak heat (11am-3pm)

Who provides: Owners establish infrastructure; managers enforce break policies; field staff provide heat safety orientation materials

Dose/intensity: Continuous access to shade and water; daily ORS availability in hot months; break policies communicated at season start and reinforced monthly

Component 5: Child Labor Awareness and pathway to prevention

Note: This is a supplementary component of our intervention which we are piloting in this project. We do not anticipate that child labor can change much during a single season because our preliminary qualitative work suggests that the most effective way to reduce child labor is to discourage parents from bringing their children to kilns for a brick season (and once present, children are unlikely to be sent home). However, we include this component as part of our intervention to better establish awareness about child labor, and while unlikely, secondary changes to reduce child labor within a single brick season remain possible.

What (materials):

- Parental and owner/sardar awareness materials explaining risks of child labor and legal prohibitions
- Encourage owners and sardars to include in their contract templates a clause: "No workers under age 18 shall be employed"- This was acceptable and aligned with owners motivations to meaningfully address child labor at the onset
- Get commitment to include NID card verification protocol and photocopy collection forms from next season

What (procedures):

- Owners and managers will be sensitized about national child labor laws and their role in it
- Owners encouraged to include age verification clause in all sardar contracts before next season
- Sardars instructed to collect NID photocopies from all workers at recruitment for next season
- Sardars receive orientation on child labor laws and importance/awareness regarding child labour reduction (30-minute session)
- Awareness sessions/conversations with parents of children under 18 years at the kilns to encourage continuation of education and discourage involvement in income-generating activities.

Who provides: Field staff will sensitize sardars; owners enforce contract terms; managers verify documentation

Dose/intensity: One-time contract updates for the next season; at least one parental awareness conversation per family with children present

2.3 Data Collection

We developed the following quantitative data collection tools:

1. worker survey (baseline and endline)
2. individual worker-level personal exposure monitoring (endline)
3. kiln-level ambient exposure monitoring (endline)
4. kiln observation checklist
5. manager survey (endline)

Baseline survey (November-December 2025)
Prior to the start of the intervention, we will administer a comprehensive baseline survey across all study kilns. At each kiln, five adult workers will be randomly selected across the main job categories at brick kilns: firemen, molders, coal crusher, loaders, and unloaders, yielding a study population of approximately 1,255 workers. Eligible participants include adult kiln workers (aged 18 and above) who have been employed for at least two weeks during the production cycle across primary job categories (molding, loading, stacking, and firing). Exclusions apply to those unable

to provide informed consent or those in supervisory/non-production roles. The survey will capture detailed worker information, including demographics, employment status, and occupational exposures. Specific modules will measure access to PPE, payment practices, availability of rest and sanitation facilities, and self-reported health and well-being, including self-reported indicators of heat stress symptoms. A kiln observation form will be filled to capture baseline conditions of the kiln including living conditions and timely payment mechanisms used by managers. Baseline data was ultimately collected from a sample of 199 kilns (118 in treatment and 81 in control) and 1000 workers.

Ongoing monitoring (November 2025–April 2026)
Monitoring will occur throughout the kiln production season. Quantitative monitoring in intervention kilns will include regular audits of PPE availability and use, verification of wage payment records, inspections of sanitation and rest facilities, and short worker surveys on occupational safety, health, and well-being. Data from these monitoring activities will be used to adapt and refine the intervention in real time, ensuring responsiveness to local challenges.

Endline survey (projected April 2026 -May 2026)
Towards the end of the kiln season, we will collect an endline survey using instruments parallel to the baseline. This will allow for the measurement of uptake, changes in PPE availability and use, wage payment practices, access to rest and sanitation facilities, proportion of child labor, and worker health outcomes. Additional modules will capture worker satisfaction, well-being, and productivity indicators, as well as owner perceptions of costs and benefits associated with the intervention. A kiln observation and manager survey form will be filled to capture endline conditions of the kiln including living conditions and timely payment mechanisms used by managers.

At endline, trained field workers will also collect physiological markers associated with heat related exposure and illness, collected during one work-shift per worker. Specifically, these include core and skin body temperatures (using Calera research-grade sensors, see details on sensors below) and hydration status measured via urine specific gravity (USG). Temperature will be monitored continuously for three hours using validated wearable devices, and a single urine sample will be collected at the end of the shift to assess USG, color, and volume as indicators of hydration. We will track and aim to match the timing of data collection during work shifts across worker categories. The timing of data collection will be balanced across treatment and control kilns to ensure similar weather conditions. To complement these worker-level indicators, we will collect ambient temperature and humidity data using wearable and stationary sensors (e.g., HOBO loggers, Kestrel), as well as in in the firing zone. We will also collect ambient particulate matter (PM2.5) data using Purple Air at key locations around the kiln (e.g., on top of the kiln during firing) and complement this with remotely sensed data (on air temperature, relative humidity, wind speed, atmospheric pressure, and solar radiation) from the ERA5-Land Reanalysis Dataset Copernicus Climate Change Service (2019). These data will be used to characterize the environmental conditions brick kiln workers are exposed to and to construct relevant controls.

For data measured both through worker surveys, manager survey, and through enumerator observation, we will characterize the extent and direction of any discrepancies and discuss implications for interpreting worker-reported outcomes that lack enumerator validation.

Purposive qualitative assessment
To understand implementation experiences, barriers to adoption, and mechanisms of change, we will conduct in-depth interviews with stakeholders from purposively selected kilns representing varied implementation contexts. Selection will stratify kilns based on intervention adherence levels (high, moderate, low) as observed during monitoring visits, allowing us to identify facilitators and obstacles to successful implementation across different contexts. A team of trained qualitative researchers will conduct semi-structured interviews with approximately 10-15 firemen, 10-15 brick loaders. 10-15 workers from other job categories, up to 15 managers and 20 owners.

Qualitative objectives: These interviews will explore: (1) perceived usefulness and feasibility of each intervention component; (2) contextual factors that enabled or were barriers to implementation; (3) unintended consequences or spillover effects; (4) recommendations for adaptation in future scale-up; and (5) mechanisms through which the intervention may have affected (or failed to affect) worker health, safety, and economic outcomes.

2.3.1 Sensor Descriptions

Calera CORE: The Calera core body temperature sensor (greenteg AG, Rumlang, Switzerland) estimates core body temperature non-invasively using an AI-algorithm that incorporates heat flux and skin temperature measures by a chest strap-mounted sensor. Data was collected every 1 min, stored on device, and downloaded from the online Calera dashboard.

HOBO: HOBO MX2201 (Onset Computer Corporation, Bourne, Massachusetts) is a waterproof device that measures temperature. The sensor is factory-calibrated and has an accuracy of +-0.5C. Data was collected every 1 min and downloaded from the HOBO Connect app.

Kestrel 5400: The Kestrel 5400 Heat Stress Tracker (Nielsen-Kellerman, Boothwyn, Pennsylvania), is a handheld device that measures and records 15 different environmental measurements, including dry bulb temperature (accuracy ± 1.0C), relative humidity (accuracy ± 3%), wind speed (accuracy ± 3%), and Wet Bulb Globe Temperature (WBGT) (accuracy ± 0.5C). The device is factory-calibrated with a drift less than ± 0.25% per year after five years. Data was measured every 2 min, stored on-device, and downloaded via a physical connection.

Purple Air: The PurpleAir PA-II-SD (often called the Classic) (PurpleAir, Inc., Draper, Utah), has a Bosch BME280 sensor that records temperature, humidity, and pressure and a dual laser particle counters to measure particulate matter (PM1.0, PM2.5, and PM10) that is factory-calibrated by the laser counter manufacturer (Plantower). Since Plantower does not provide details on the calibration aerosol used, such as the density, or any correction factors employed in calculating PM1, PM2.5 or PM10. Given the high humidity and high PM.25 concentrations, we sought to avoid the overestimation of PM2.5 that is sometimes observed by applying the ALT-CF3 algorithm to calculate the PM2.5 concentration instead of using the values directly from the sensor (Wang et al., 2025); using this method precision was 5-6% and limits of detection were approximately 1 $\mu g/m^3$ (Wallace, 2022). Data was measured every 2 min.

3 Outcomes and Power Calculations

As described above, five adult workers were randomly selected across the main job categories at brick kilns: firemen, molders, coal crusher, loaders, and unloaders, yielding a study population of approximately 1,000 workers from the 199 enrolled kilns. The sample will be split by gender with an approximate ratio of 1-to-9, based on our previous survey experience (random sampling of workers resulted in a sample of 10% women). Where possible, intracluster correlation (ICC) for each of our primary outcomes is computed from previous survey results.

The cluster randomized study has one set of primary outcomes related to physiological heat stress, measured at the worker level and clustered at the kiln level. Specifically, we are collecting data on core and skin temperature and urine specific gravity (USG), following standard practice for assessing physiological heat strain (Ioannou et al., 2022) and recommendations from Calera, the Core sensor manufacturer. The outcomes are defined as follows:

1. **Core body temperature (T_{core})**: We will construct two outcomes indicating acute heat stress defined as the share of core body temperature measures that exceed 38°C (heat exhaustion) and the share of core body temperature measures that exceed 40°C (heat stroke) (Canadian Centre for Occupational Health and Safety, 2025; Gauer and Meyers, 2019). Core body temperature will be measured for a subset of 75% of workers at all treatment and control kilns due to limited supply of sensors, resulting in an estimate sample size of approximately 750 workers. Using pilot measurements taken during our baseline, our study is powered at 80%, using two-sided tests, to detect a change of 0.07 (or 7 percentage points) in the share of time workers experience core temperature that exceed 38°C, assuming a moderate ICC of 0.2 (standardized effect size of 0.26). Moreover, it is powered at 80%, using two-sided tests, to detect a change of 0.04 (or 4 percentage points) in the share of time workers experience core temperature that exceed 40°C, assuming a moderate ICC of 0.2 (standardized effect size of 0.26).

2. **Skin (surface) temperature (T_{sk})**: We will construct an outcome indicating more acute heat stress defined as the share of skin temperature measures that exceed $\geq$ 36°C. Skin temperature will be measured for a subset of 75% of workers at all treatment and control kilns due to limited supply of sensors, resulting in an estimate sample size of approximately 750 workers. Using pilot measurements taken during our baseline, our study is powered at 80%, using two-sided tests, to detect a change of 0.03 (or 3 percentage points) in the share of time workers experience skin temperature that exceed 36°C, assuming a moderate ICC of 0.2 (standardized effect size of 0.26).

3. **Urine specific gravity (USG)**: We will utilize 1) the continuous measure (measured via methods described above) and construct 2) two binary outcomes indicating more acute dehydration defined as USG ≥ 1.018 (elevated risk of dehydration) and USG > 1.030 (severe dehydration) (Montazer et al., 2013; Nainggolan et al., 2021). Wesseling et al. (2016) provide baseline estimates of USG among similarly at-risk workers (sugarcane workers and construction workers) of 1.0252 (sd = 0.0065). Our study is powered at 80%, using two-sided tests, to detect a change of 0.0016 in USG (standardized effect size of 0.24), assuming a moderate ICC of 0.2.

Secondary Outcomes:

1. **Worker-reported heat stress symptoms:** Heat stress symptoms will be captured through worker-reported experiences. Each worker is asked whether they had experienced each of 18 symptoms during the preceding 2 weeks. We then use principal components analysis to create heat stress symptom index.[2] Using a baseline microdata from preliminary observations of workers at the same study kilns, we compute an index of mean zero (sd = 1.86), and find a moderate intra-cluster correlation of 0.22. Our study is powered at 80% to detect a decline of 0.52 in the heat stress index (a standardize effect size of about 0.28). Sensitivity analysis will be conducted to explore effects on binary outcomes capturing whether each symptom was experienced during the preceding 2 weeks.

4 Empirical Strategy

To evaluate the causal impact of the integrated Zigzag2.0+ intervention, we will estimate intention-to-treat (ITT) specifications for the primary and secondary outcomes using ordinary least squares (OLS) regression of the following form

$$Y_{ik} = \beta_0 + \beta_1 T_k + \mathbf{X}'_{ik}\boldsymbol{\beta} + \delta_s + \epsilon_{ik} \tag{1}$$

where Y_{ik} is an outcome of interest for worker i at kiln k, T_k is a binary indicator for assignment to the treatment arm, $\mathbf{X}_{ik}$ is a vector of covariates[3] selected through post-double LASSO (Belloni et al., 2013), and δ_s are randomization strata fixed effects for stratum s. In addition to controls selected through post-double LASSO, specifications will control for worker age and sex, as well as kiln-level ambient measurements. Because baseline values of the primary physiological heat stress outcomes are not available (comprehensive physiological monitoring is conducted only at endline, which also coincides with the hottest months of the brick-firing season), our primary specification is a cross-sectional analysis of all endline workers. The coefficient β_1 captures the causal effect of assignment to the intervention on each outcome (relative to assignment to the control arm).

The covariate vector $\mathbf{X}_{ik}$ is selected using the post-double LASSO procedure, which runs LASSO separately for the outcome and treatment variables to identify covariates that predict either, then includes the union of selected covariates in the final specification to improve precision while guarding against overfitting. Because workers are nested within kilns, we will calculate heteroscedasticity-robust standard errors adjusted for clustering at the kiln-level for all specifications. For hypothesis testing, p-values will be calculated both based on the heteroscedasticity-robust standard errors from the regression and using randomization inference (RI) to honor the experimental design. We will conduct permutations by re-randomizing treatment assignment holding the number of treated and control units constant within each original stratum-wave cell. The final p-value will be derived from the distribution of the estimated coefficient β_1 across all feasible permutations.

Because workers in different jobs face different conditions at brick kilns, we will explore heterogeneity in the treatment effects by job category, and other characteristics such as prior kiln experience and

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[2] We will construct alternative versions of the index that use symptoms reported in the same day, previous day or previous week for sensitivity analysis.

[3] Potential covariates will be derived from the baseline survey and include worker demographics, type of work they perform at the kiln, outside work options, regular work during the non-brick season, migration to kilns, prior knowledge and experience on kilns, and self-reported health and well-being.

sex.

To account for multiple hypothesis testing across our primary physiological heat stress outcomes (core and skin temperature, and USG), we will report adjusted p-values following the procedure outlined by Anderson (2008) and using the Benjamini et al. (2006) sharpened two-stage procedure.

Because we do not anticipate perfect compliance with the intervention but it is of policy relevance to understand impacts among adopters, we will also estimate the local average treatment effect (LATE) using randomized assignment to the intervention arm as an instrument for adoption. Based on pilot experience, we will define kiln-level adoption using the kiln observation and the manager survey administered at endline. The checklist yields four domain scores: (i) PPE provision/availability and use, (ii) wage payment monitoring, (iii) sanitation and living conditions, and (iv) heat mitigation infrastructure and awareness. In each domain, items are scored and aggregated into a domain percentage score (points earned divided by points available). We then compute an overall adoption index as the (unweighted) average of the four domain percentage scores. A kiln is classified as an "adopter" if its overall adoption index is at least 50% at endline.[4] We will estimate the LATE using two-stage least squares (2SLS), in which the first stage regresses a binary indicator for adoption (A_k), as defined above, on a binary indicator assignment to the treatment arm and randomization strata. In the second stage, we regress our outcomes (Y_{ik}) on the instrumented adoption indicator ($\hat{A}_k$). In both stages, we will compute heteroskedasticity-robust standard errors adjusted for clustering at the kiln level.

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

$$A_k = \theta_0 + \theta_1 T_k + \mathbf{X}'_{ik}\boldsymbol{\theta} + \gamma_s + \epsilon_{ik} \tag{2}$$

$$Y_{ik} = \gamma_0 + \gamma_1 \hat{A}_k + \mathbf{X}'_{ik}\boldsymbol{\gamma} + \gamma_s + u_{ik} \tag{3}$$

where γ_1 represents the local average treatment effect (LATE) of adoption on compliers—those kilns induced to adopt by their assignment to treatment, and the remaining parameters are defined as in the OLS case.

While our primary analysis will be conducted at the worker level, we will conduct a complementary set of analyses at the kiln level. This approach allows us to distinguish between the intervention's impact on the presence of an outcome and its impact on the prevalence (i.e., the share of workers with a given outcome at a kiln). For kiln-level outcomes where baseline measurements are available, our preferred specification will include baseline values of the dependent variable to improve precision. The estimating equation will take the form:

$$Y_k = \beta_0 + \beta_1 T_k + \beta_2 Y_{k,t-1} + \mathbf{X}'_k\boldsymbol{\beta} + \delta_s + \epsilon_k \tag{4}$$

where Y_k represents the kiln-level outcome at endline, $Y_{k,t-1}$ is the baseline value, and other terms are defined as before but aggregated to the kiln level. For kiln-level physiological heat stress outcomes

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[4] For items measured both by enumerator observation and by manager self-report, we will use enumerator observation when available; manager report will be used when the corresponding observational measure is not collected and for sensitivity analysis. We will conduct sensitivity analysis around this adoption measure using alternative thresholds (greater or less than 50%).

(e.g., mean USG across workers at a kiln), which do not have corresponding baseline measurements, the specification will omit the $Y_{k,t-1}$ term.

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