Spatio-Temporal Modeling of $PM_{2.5}$ Deposition for ARI Prevention in Enclosed Kitchens Using Python with Morris-Sobol and LHS

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Abstract *: Cooking emissions in enclosed kitchens require effective exposure controls relevant to acute respiratory infection (ARI) prevention. This study modeled the spatio-temporal transport and surface deposition of cooking-generated $PM_{2.5}$ and compared interventions for reducing breathing-zone exposure. A Python-based computational framework coupled three-dimensional, size-resolved particle transport with a prescribed airflow field. Four 30-min scenarios, including 12 min of cooking, were evaluated: closed baseline, local exhaust, portable air cleaner, and combined control. Cumulative breathing-zone exposure was the primary outcome. Morris screening, Sobol analysis, and Latin hypercube sampling (LHS) were conducted using a separate reduced model. The spatial simulation showed heterogeneous concentrations and persistent post-cooking exposure. Cumulative exposure decreased from 28,694.3 $\mu g \cdot min\ m^{-3}$ at baseline to 7,082.5, 17,043.3, and 6,045.8 $\mu g \cdot min\ m^{-3}$ with local exhaust, air cleaning, and combined control, representing reductions of 75.3%, 40.6%, and 78.9%, respectively. Source-capture efficiency was the dominant parameter and explained 52.1% of reduced-model variance through its first-order Sobol index. LHS reproduced the intervention ranking of the spatial simulation. Source-directed extraction, supplemented by filtration and continued post-cooking operation, therefore offers a promising strategy for reducing $PM_{2.5}$ exposure in enclosed kitchens and supporting ARI prevention.*

Keywords : *Acute Respiratory Infection, Particulate Matter, Enclosed Kitchens, Breathing-Zone, Spatial-Temporal*

Abstrak : Emisi memasak di dapur tertutup memerlukan pengendalian paparan yang relevan dengan pencegahan infeksi saluran pernapasan akut (ISPA). Penelitian ini memodelkan transpor spasial-temporal dan deposisi permukaan $PM_{2.5}$ serta membandingkan intervensi untuk mengurangi paparan pada zona pernapasan. Kerangka komputasi berbasis Python menggabungkan transpor partikel tiga dimensi berdasarkan ukuran dengan medan aliran udara yang ditetapkan. Empat skenario berdurasi 30 menit, termasuk 12 menit memasak, dievaluasi: kondisi dasar tertutup, ventilasi pembuangan lokal, pembersih udara portabel, dan pengendalian gabungan. Paparan kumulatif pada zona pernapasan menjadi luaran utama. Penapisan Morris, analisis Sobol, dan Latin hypercube sampling (LHS) dilakukan menggunakan model tereduksi terpisah. Simulasi menunjukkan konsentrasi heterogen dan

paparan yang bertahan setelah memasak. Paparan kumulatif menurun dari 28,694.3 μg·menit·m^{-3} menjadi 7,082.5, 17,043.3, dan 6,045.8 μg·menit·m^{-3}, masing-masing setara dengan penurunan 75.3%, 40.6%, dan 78.9%. Efisiensi penangkapan emisi pada sumber merupakan parameter dominan dan menjelaskan 52.1% varians luaran model tereduksi melalui indeks Sobol orde pertama. LHS menghasilkan urutan efektivitas intervensi yang sama dengan simulasi spasial. Penghisapan emisi pada sumber, disertai filtrasi dan pengoperasian berkelanjutan setelah memasak, merupakan strategi menjanjikan untuk mengurangi paparan $PM_{2.5}$ di dapur tertutup dan mendukung pencegahan ISPA.

Kata Kunci : Infeksi saluran pernapasan akut, Materi partikulat, Dapur tertutup, Zona pernapasan, Spasial-temporal

INTRODUCTION

Cooking-related fine particulate matter ($PM_{2.5}$) is a preventable component of household air pollution with consequences that extend beyond momentary deterioration of indoor air quality. Its health significance is supported by evidence linking particulate pollution and household environmental conditions with acute respiratory infection (ARI), although the magnitude of risk varies across populations, exposure definitions, and clinical outcomes (Adhikary et al., 2024; McCollum et al., 2024; World Health Organization, 2021). Indonesian studies similarly show that ARI among children is shaped by interacting household, environmental, nutritional, and socioeconomic conditions rather than by a single pollutant source (Purnama et al., 2024; Santri et al., 2023). Studies involving women responsible for cooking and residents of densely occupied settlements further associate fuel choice, kitchen characteristics, ventilation, and indoor pollution with respiratory symptoms, while perceived health risks influence whether protective practices are understood and adopted (Shine et al., 2023; Wafula et al., 2023; Zewdie et al., 2023). Longitudinal and intervention evidence, however, does not consistently translate lower $PM_{2.5}$ exposure into fewer respiratory events, confirming that a simulation should estimate exposure reduction rather than predict ARI incidence directly (McCollum et al., 2024; Shackelford et al., 2025).

The exposure produced by cooking cannot be represented adequately by a single room-average concentration. Experimental and numerical investigations demonstrate that emission, transport, decay, and surface deposition change throughout cooking and post-cooking periods and are strongly affected by particle size, buoyant flow, source position, and ventilation mode (Ding et al., 2023; Jones et al., 2024; Zeng et al., 2025). Fresh-air supply, stove location, cooking process, and measurement height can produce markedly different concentration and deposition patterns within the same kitchen (Xin et al., 2024; Yuan et al., 2023; Zheng et al., 2022). Cooking particles may also migrate into adjacent spaces, persist after the heat source is switched off, or accumulate in the breathing zone despite acceptable room-level averages (Deng et al., 2022; Liu et al., 2022; Tang & Pfrang, 2023). Emission intensity is itself variable because it depends on food, oil, temperature, cooking method, kitchen volume, fuel, and duration; this variability has been observed across controlled frying experiments, multicity measurements, and rural Indonesian households (Amin et al., 2025; Chiang et al., 2022; Kumar et al., 2022). Surface deposition must therefore be treated as one term in the particle mass balance, alongside airborne storage, filtration, and exhaust, rather than as a direct surrogate for respiratory dose.

Available controls can reduce cooking-related $PM_{2.5}$, but their effectiveness depends on how they are configured and operated. Portable air cleaners and sensor-supported interventions can reduce indoor particle concentrations, while source capture generally performs better when the hood is activated promptly and coordinated with other removal mechanisms (Pantelic et al., 2023, 2024; Sankhyan et al., 2022). Natural ventilation, household mitigation practices, and routine use of kitchen ventilation can also accelerate removal, but their performance changes with opening

configuration, outdoor conditions, user behavior, and the perceived effectiveness of the installed device (Jaffe et al., 2025; Su et al., 2026; Sun & Singer, 2023). Behavioral and community-based interventions further show that owning a device does not ensure sustained use and that technically effective measures may be constrained by noise, maintenance, placement, energy use, or household routines (Holm et al., 2024; McIntyre et al., 2024). For a kitchen that must remain enclosed, the practical question is therefore not whether ventilation is beneficial in general, but which combination of local exhaust, make-up air, filtration, activation time, and post-cooking operation reduces exposure without relying on an open door as the main control.

When these findings are considered together, a narrower research gap becomes apparent. Existing studies have established that cooking emissions are transient and spatially heterogeneous, and several have compared specific ventilation or filtration arrangements (Jones et al., 2024; Pantelic et al., 2024; Zeng et al., 2025). What remains insufficiently resolved for an enclosed kitchen is whether the strategy selected from room-average concentration is also the strategy that minimizes time-integrated exposure at the occupant's breathing zone, and whether that ranking remains stable when emission rate, particle properties, airflow, deposition, control timing, and occupant presence vary. This issue matters because equipment availability, actual use, and exposure reduction do not necessarily move together (Holm et al., 2024; McIntyre et al., 2024; Sun & Singer, 2023). It also prevents the engineering output from being interpreted too confidently as a health outcome, since ARI is influenced by multiple environmental and host determinants and cannot be inferred from surface deposition or a short concentration peak alone (Adhikary et al., 2024; Shackelford et al., 2025).

This study aims to evaluate how transient transport and surface deposition of cooking-generated $PM_{2.5}$ shape occupant exposure in an enclosed two-burner kitchen and to identify control strategies that remain effective under uncertain emission and operating conditions. A three-dimensional transient model implemented in Python will integrate size-dependent particle transport and surface deposition using a prescribed airflow field, together with a mass balance that distinguishes airborne, deposited, filtered, and exhausted fractions. Health relevance will be represented through time-integrated concentration at specified breathing-zone locations or trajectories, while ARI will remain the interpretive health context rather than a simulated diagnosis. The analysis will test whether make-up-air configuration changes exposure at the same exhaust rate, whether rankings based on room-average concentration and occupant exposure differ, whether parameter interactions materially affect the prediction, and whether the nominally best control remains preferable across the uncertainty range. Morris screening will identify influential inputs, Sobol indices will separate main and interaction effects, and Latin hypercube sampling (LHS) will propagate uncertainty and examine ranking stability. The contribution is therefore an exposure-oriented and uncertainty-aware basis for selecting and operating $PM_{2.5}$ controls when the kitchen must remain enclosed, supported by a reproducible Python workflow and bounded by the modeled geometry, occupant scenario, and operating range.

METHODS

This study employs a quantitative computational approach using transient three-dimensional computational fluid dynamics (CFD) to investigate airflow, heat transfer, $PM_{2.5}$ transport, surface deposition, and breathing-zone exposure during cooking activities. The computational setting represents an enclosed two-burner kitchen measuring 4.0 × 3.0 × 3.0 m (36.0 m^3), with a closed door and an upper ventilation opening, under conditions informed by secondary experimental data. The study is simulation-based and does not involve human participants; therefore, its population of interest comprises plausible cooking and ventilation conditions, with individual cooking episodes serving as the units of analysis. Each simulation represents a 12-minute cooking period followed by a defined post-cooking observation period, using a two-minute emission ramp and a subsequent emission rate of 3.2 mg/min. The computational geometry incorporates the stove, cooking emission sources, ventilation opening, and a fixed breathing-zone evaluation point at coordinates (2.00, 1.70, 1.50) m. A three-dimensional finite-volume model implemented in Python is used to simulate transient airflow, thermal behaviour, particle transport, and deposition. Initial conditions include an

air temperature of 28.4 °C, floor temperature of 18.6 °C, ceiling temperature of 28.0 °C, and cooking-surface temperature of 180 °C or an equivalent verified heat-flux condition. Model inputs are derived from secondary experimental measurements, published technical specifications, and explicitly documented assumptions. The simulation procedure comprises computational domain construction, mesh generation, initialisation and airflow stabilisation, transient cooking-emission modelling, post-cooking particle tracking, and comparison of baseline and intervention scenarios. Interventions include local exhaust ventilation, portable air cleaning, and their combined application, with source-operation scenarios evaluated separately under fixed-total-emission and increased-load conditions.

Data collection involves extracting and organising secondary experimental measurements, emission characteristics, ventilation parameters, thermal properties, and particle-deposition information using a structured input database and computational simulation outputs as research instruments. The primary outcome is time-integrated $PM_{2.5}$ concentration at the breathing-zone evaluation point, while secondary outcomes include peak concentration, time to peak, room-average concentration, particle decay, surface loading, and airborne, deposited, exhausted, and filtered mass fractions. Surface deposition is interpreted as particle removal and storage within the kitchen, rather than respiratory deposition, while acute respiratory infection (ARI) provides health-related context without supporting direct disease-risk estimation. Model outputs are analysed through descriptive comparisons, Morris screening, Sobol variance-based sensitivity analysis, and Latin Hypercube Sampling (LHS) uncertainty propagation. Morris screening initially uses 20 trajectories, increasing to 40 to assess ranking stability, whereas Sobol analysis uses base sample sizes of 256 and 512 to evaluate first-order and total-order parameter contributions. LHS employs 256, 512, and 1,024 paired samples to examine uncertainty distributions and the robustness of intervention performance under matched input conditions. Control effectiveness is evaluated through paired exposure reductions, parameter influence through sensitivity indices, and differences between exposure-based and room-average intervention rankings through Kendall rank correlation and ranking-reversal frequency. Input distributions are specified from available evidence or identified as assumptions, with sampling uncertainty and convergence assessed before interpreting results. The findings are limited to simulated pollutant concentrations, exposure indicators, and particle fate under the modelled conditions, without estimating individual ARI probabilities.

RESULTS AND DISCUSSION

Spatio-Temporal Distribution of $PM_{2.5}$

The closed-baseline simulation produced a spatially non-uniform $PM_{2.5}$ field, with the highest marker density concentrated above and around the two-burner source and a progressively more dispersed distribution toward the upper and lateral parts of the enclosure. The top and side projections also show that a fraction of the transported particle mass crossed the prescribed outflow boundary. At the breathing-zone point, P (2.0, 1.7, 1.5 m), the representative near-peak concentration was 1,675.05 μg m^{-3}. The 0.5, 1.0, and 2.5 μm size classes contributed 470.4, 447.8, and 756.8 μg m^{-3}, respectively; thus, the 2.5 μm class accounted for approximately 45.2% of the concentration at that point.

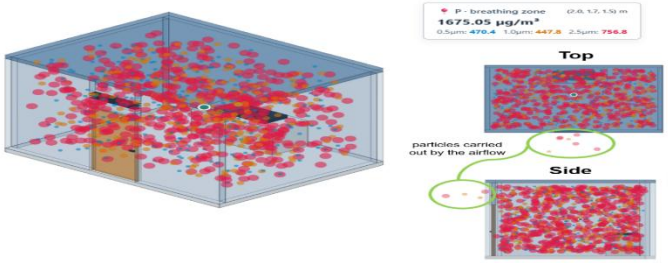


Figure 3. Spatial distribution of size-resolved $PM_{2.5}$ in the closed-baseline kitchen, including three-dimensional, top, and side views. Point P denotes the breathing-zone location at (2.0, 1.7, 1.5 m).

The non-uniform field confirms that a room-average value alone would not adequately represent the concentration encountered by a cook. Concentration at a fixed breathing-zone location is controlled not only by the total emitted mass but also by the interaction between the source plume, prescribed recirculation, removal boundaries, and the position of the occupant relative to the burners. This behavior is consistent with experimental and computational evidence showing strong vertical and horizontal gradients during cooking and sensitivity to source position, ventilation configuration, and measurement height. The spatial result therefore supports the use of breathing-zone exposure as the primary occupant-oriented indicator rather than treating surface deposition or a room mean as a direct surrogate for inhalation.

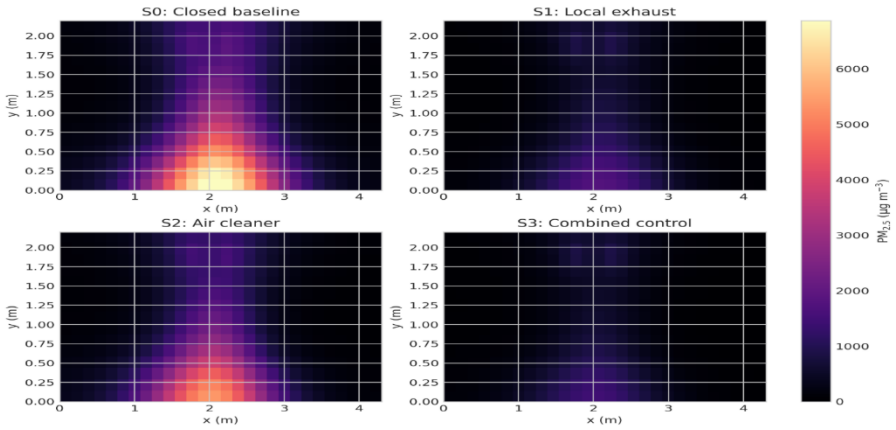


Figure 4. Spatial distribution of $PM_{2.5}$ concentration under the closed baseline (S3), local exhaust (S1), air-cleaner (S2), and combined-control (S3) scenarios.

Breathing-Zone Dynamics and Control Performance

Breathing-zone concentrations increased throughout the 12-min cooking period in all scenarios and reached their maxima when cooking ended. The closed baseline (S0) produced the highest peak concentration, 1,773.1 µg m^{-3}, followed by the air-cleaner scenario (S2) at 1,358.3 µg m^{-3}. Local exhaust (S1) and combined control (S3) limited the peaks to 602.3 and 538.4 µg m^{-3}, corresponding to peak reductions of approximately 66.0% and 69.6% relative to S0. The simultaneous peak time across the scenarios indicates that the source schedule governed the timing of maximum exposure, whereas the controls primarily altered its magnitude and post-cooking removal.

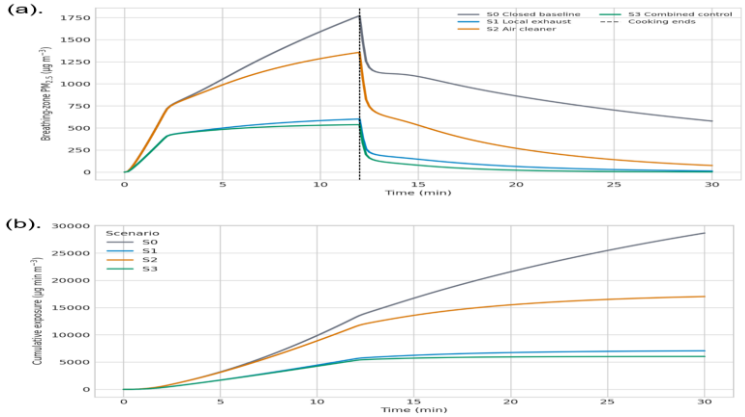


Figure 5. Breathing-zone $PM_{2.5}$ under S0–S3: (a) concentration over 30 min and (b) cumulative exposure. The dashed line marks the end of cooking at 12 min.

The cumulative curves provide a clearer measure of total exposure burden than the peak alone. Over 30 min, S0 generated 28,694.3 µg min m^{-3}, whereas S1, S2, and S3 generated 7,082.5,

17,043.3, and 6,045.8 μg min m^{-3}. These values represent modeled exposure reductions of 75.3%, 40.6%, and 78.9%, respectively. The ranking was therefore S3 < S1 < S2 < S0. Combined control produced the lowest cumulative exposure, but its additional deterministic reduction over local exhaust alone was 3.6 percentage points relative to the baseline. This relatively small increment indicates that source-directed removal was the principal mechanism under the specified operating conditions, while the portable air cleaner provided supplementary room-air treatment.

Post-cooking behavior further distinguished the scenarios. At 30 min, the predicted concentration remained 578.9 μg m^{-3} in S0, compared with 75.6 μg m^{-3} in S2, 13.6 μg m^{-3} in S1, and 2.1 μg m^{-3} in S3. Local exhaust and combined control therefore reduced both the concentration accumulated during cooking and the persistence of the residual plume. This finding agrees with studies showing that source capture is most effective when activated during emission and maintained long enough to remove the residual post-cooking burden, whereas filtration acts after contaminants have already entered the room air. For an enclosed kitchen, the result favors capture at or near the stove, with continued post-cooking operation and filtration used as an additional control rather than as a substitute for source capture.

Parameter Sensitivity

The preliminary Morris analysis identified source-capture efficiency as the most influential parameter for combined-control exposure, with a Morris μ^* of 1,423.7. It was followed by emission rate (735.4), hood flow (678.3), and portable-air-cleaner clean-air delivery rate (PAC CADR; 509.3). Deposition loss and passive air-change rate had much smaller effects, with μ^* values of 39.5 and 28.3. The comparatively large Morris σ values for source capture, emission rate, hood flow, and PAC CADR indicate that their effects were not fully constant across the sampled parameter space and may include nonlinear responses or interactions.

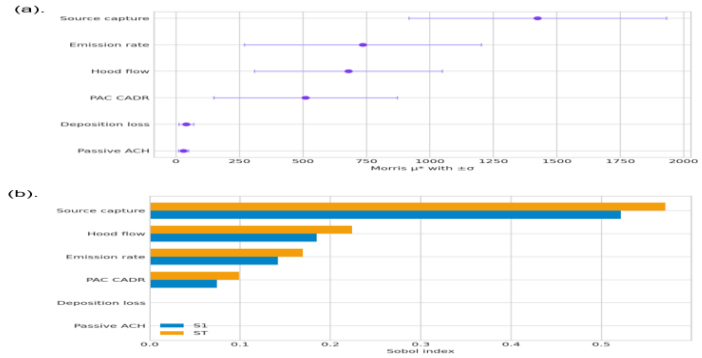


Figure 6. Global sensitivity of cumulative $PM_{2.5}$ exposure in the combined-control scenario: (a) Morris $\mu^* \pm \sigma$ and (b) Sobol S_1 and S_t indices.

The Sobol analysis supported the same hierarchy. Source capture explained 52.1% of the output variance through its first-order contribution and 57.1% when higher-order effects were included. Hood flow contributed 18.5% and 22.4%, emission rate 14.2% and 17.0%, and PAC CADR 7.4% and 9.9% through S_1 and S_t, respectively. The total-order minus first-order differences ranged from approximately 0.025 to 0.050 for these four parameters, indicating interactions, although their contribution was secondary to the main effects. Deposition loss and passive air change were negligible within the ranges assigned to this reduced model; this does not establish that they are universally unimportant outside those ranges or in a different geometry.

These findings provisionally support the hypothesis that the model inputs do not affect exposure equally. They also explain why S1 approached the performance of S3 in the deterministic spatial simulation: both source-capture efficiency and hood flow ranked above PAC CADR. However, the interaction hypothesis is only partially supported because the observed $S_t - S_1$ gaps were modest and have not yet been accompanied by finalized bootstrap convergence intervals. The sensitivity

results should therefore guide calibration priorities, particularly for capture efficiency, emission rate, and hood flow, rather than be treated as universal parameter weights.

Uncertainty and Robustness of the Control Ranking

LHS retained the same median ranking as the deterministic comparison: S3 produced the lowest exposure, followed by S1, S2, and S0. Median exposures from the reduced model were 30,741.2 μg min m^{-3} for S0, 1,885.0 μg min m^{-3} for S1, 5,809.9 μg min m^{-3} for S2, and 1,123.7 μg min m^{-3} for S3. The corresponding 5th–95th percentile ranges were 22,209.0–39,793.3, 793.0–4,202.0, 3,500.3–10,089.5, and 497.7–2,144.8 μg min m^{-3}.

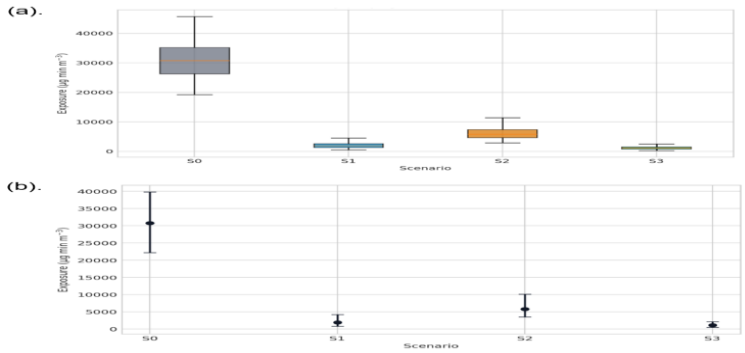


Figure 7. LHS uncertainty distributions of cumulative $PM_{2.5}$ exposure under S0–S3: (a) boxplots and (b) medians with 5th–95th percentile intervals.

The uncertainty ranges for S0 and S2 remained substantially above those of the source-capture scenarios, indicating that the advantage of local exhaust over no active control or filtration alone was maintained across the sampled input ranges. In contrast, the S1 and S3 ranges overlapped. The combined strategy had the lower median and upper percentile, but its superiority over local exhaust alone was less certain than its superiority over S0 or S2. This distinction is practically important: S3 was the nominally best strategy, whereas S1 represented a potentially efficient alternative when equipment cost, energy use, noise, or maintenance constrains simultaneous operation. Such operational factors can influence actual exposure reduction because installed controls are beneficial only when they are used consistently and correctly.

The spatial and reduced models should not be compared through their absolute exposure values. The spatial model resolves the prescribed three-dimensional transport field, whereas Morris, Sobol, and LHS were performed with a separate well-mixed reduced model to make repeated evaluations computationally feasible. Their agreement in scenario ranking is encouraging, but it is not a substitute for propagating uncertainty through the final validated spatial solver.

Respiratory-Health Interpretation and Preventive Implications

From a health-oriented perspective, the principal finding is the reduction in time-integrated $PM_{2.5}$ concentration at the cook's breathing zone. This indicator represents the pollutant burden encountered during the complete cooking and post-cooking period rather than at a single moment. The combined strategy minimized both the exposure accumulated while the source was active and the residual concentration after cooking. Local exhaust produced a comparable reduction, whereas the air cleaner alone provided a smaller but still meaningful improvement. These results establish a prevention hierarchy for enclosed kitchens: capture emissions close to the burners, provide an adequate make-up-air pathway, maintain exhaust operation during the post-cooking decay period, and use portable filtration as a complementary removal mechanism.

The reduction in breathing-zone exposure provides the direct connection between the engineering model and ARI prevention. Household $PM_{2.5}$ exposure has been investigated as an environmental determinant of pneumonia, respiratory symptoms, and other acute respiratory outcomes, particularly among susceptible household members. By reducing the magnitude and duration of $PM_{2.5}$ available for inhalation, the evaluated controls reduce a modifiable environmental burden associated with ARI risk. The marked persistence of $PM_{2.5}$ in S0 further shows that preventive

action should extend beyond the active cooking period because occupants entering or remaining in the kitchen may continue to receive substantial exposure during pollutant decay. Accordingly, source capture and continued post-cooking removal provide technically measurable interventions that can be incorporated into household health-promotion strategies for enclosed kitchens.

CONCLUSION

The simulation demonstrated that cooking-generated $PM_{2.5}$ formed a strongly time-dependent and spatially heterogeneous exposure field in the enclosed kitchen. All active controls reduced cumulative breathing-zone exposure relative to the closed baseline. The combined local-exhaust and air-cleaner strategy produced the lowest 30-min cumulative exposure, with a reduction of 78.9%, followed closely by local exhaust at 75.3%. The air cleaner alone reduced exposure by 40.6%. Local exhaust and combined control also accelerated post-cooking concentration decay, confirming that effective prevention requires both emission control during cooking and continued removal of the residual plume. Morris and Sobol analyses identified source-capture efficiency as the dominant parameter, followed by hood flow, emission rate, and PAC CADR. LHS propagation retained the ranking S3 < S1 < S2 < S0 across the evaluated uncertainty range. The consistency of this ranking demonstrates that source-directed extraction is the principal intervention, while portable filtration strengthens overall removal when operated as part of the combined strategy. By linking aerosol transport, breathing-zone exposure, control effectiveness, and uncertainty, the study provides an integrated engineering–health framework for addressing $PM_{2.5}$ as a modifiable environmental factor related to ARI risk in enclosed kitchens.

The findings support the combined use of local exhaust, adequate make-up air, continued post-cooking ventilation, and portable filtration as a practical exposure-prevention strategy. This framework can be developed further across different kitchen geometries, cooking activities, occupant movement patterns, and household operating conditions. Integration with real-time $PM_{2.5}$ sensing, adaptive control algorithms, and population-based respiratory-health data can expand the framework into a responsive prevention system capable of supporting ventilation design, household health promotion, and evidence-based strategies for reducing ARI-related environmental risk.

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REFERENCES

Adhikary, M., Mal, P., & Saikia, N. (2024). Exploring the link between particulate matter pollution and acute respiratory infection risk in children using generalized estimating equations analysis: a robust statistical approach. *Environmental Health: A Global Access Science Source*, *23*(1), 1–11. https://doi.org/10.1186/s12940-024-01049-3

Amin, M., Bachtiar, V. S., Hanami, Z. A., & Hustim, M. (2025). Characterization of Particulate Matter in Indoor Air from Cooking Activities in Rural Indonesian Households. *Atmosphere*, *16*(10), 1124. https://doi.org/10.3390/atmos16101124

Chiang, K.-M., Xiu, L., Peng, C.-Y., Lung, S.-C. C., Chen, Y.-C., & Pan, W.-H. (2022). Particulate matters, aldehydes, and polycyclic aromatic hydrocarbons produced from deep-frying emissions: comparisons of three cooking oils with distinct fatty acid profiles. *Npj Science of Food*, *6*(1), 28. https://doi.org/10.1038/s41538-022-00143-5

Deng, N., Fan, M., Hao, R., Zhang, A., & Li, Y. (2022). Field Measurements and Analysis on Temperature, Relative Humidity, Airflow Rate and Oil Fume Emission Concentration in a Typical Campus Canteen Kitchen in Tianjin, China. *Applied Sciences*, *12*(22), 11755. https://doi.org/10.3390/app122211755

Ding, M., Zhang, S., Wang, J., Ye, F., & Chen, Z. (2023). Study on Spatial and Temporal Distribution Characteristics of the Cooking Oil Fume Particulate and Carbon Dioxide Based on CFD and Experimental Analyses. *Atmosphere*, *14*(10), 1522. https://doi.org/10.3390/atmos14101522

Holm, S. M., Singer, B. C., Kang Dufour, M.-S., Delp, W., Nolan, J. E. S., Bueno de Mesquita, P. J., Ward, B., Williamson, Y., Le, O., Russell, M. L., Harley, K. G., & Balmes, J. R. (2024). Measured air quality impacts after teaching parents about cooking ventilation with a video: a pilot study. *Journal of Exposure Science and Environmental Epidemiology*, *35*(2), 223–232. https://doi.org/10.1038/s41370-024-00730-6

Jaffe, D., Nirschl, D., & Birman, S. (2025). Occurrence and Mitigation of $PM_{2.5}$, NO_2, CO and CO_2 in Homes Due to Cooking and Gas Stoves. *Atmosphere*, *16*(7), 882. https://doi.org/10.3390/atmos16070882

Jones, H., Kumar, A., O'Leary, C., Dillon, T., & Rolfo, S. (2024). Experimental and Computational Investigation of the Emission and Dispersion of Fine Particulate Matter ($PM_{2.5}$) During Domestic Cooking. *Atmosphere*, *15*(12), 1517. https://doi.org/10.3390/atmos15121517

Kumar, P., Hama, S., Abbass, R. A., Nogueira, T., Brand, V. S., Wu, H. W., Abulude, F. O., Adelodun, A. A., Anand, P., Andrade, M. de F., Apondo, W., Asfaw, A., Aziz, K. H., Cao, S. J., El-Gendy, A., Indu, G., Kehbila, A. G., Ketzel, M., Khare, M., … Shiva Nagendra, S. M. (2022). In-kitchen aerosol exposure in twelve cities across the globe. *Environment International*, *162*, 107155. https://doi.org/10.1016/j.envint.2022.107155

Liu, Q., Son, Y. J., Li, L., Wood, N., Senerat, A. M., & Pantelic, J. (2022). Healthy home interventions: Distribution of $PM_{2.5}$ emitted during cooking in residential settings. *Building and Environment*, *207*, 108448. https://doi.org/10.1016/j.buildenv.2021.108448

McCollum, E. D., McCracken, J. P., Kirby, M. A., Grajeda, L. M., Hossen, S., Moulton, L. H., Simkovich, S. M., Goodman-Palmer, D., Rosa, G., Mukeshimana, A., Balakrishnan, K., Thangavel, G., Garg, S. S., Castañaza, A., Thompson, L. M., Diaz-Artiga, A., Papageorghiou, A. T., Davila-Roman, V. G., Underhill, L. J., … Checkley, W. (2024). Liquefied Petroleum Gas or Biomass Cooking and Severe Infant Pneumonia. *New England Journal of Medicine*, *390*(1), 32–43. https://doi.org/10.1056/nejmoa2305681

McIntyre, A. M., Scammell, M. K., Kinney, P. L., Khosla, K., Benton, L., Bongiovanni, R., McCannon, J., & Milando, C. W. (2024). Portable Air Cleaner Usage and Particulate Matter Exposure Reduction in an Environmental Justice Community: A Pilot Study. *Environmental Health Insights*, *18*, 11786302241258588. https://doi.org/10.1177/11786302241258587

Pantelic, J., Son, Y. J., Staven, B., & Liu, Q. (2023). Cooking emission control with IoT sensors and connected air quality interventions for smart and healthy homes: Evaluation of effectiveness and energy consumption. *Energy and Buildings*, *286*, 112932. https://doi.org/10.1016/j.enbuild.2023.112932

Pantelic, J., Tang, M., Byun, K., Knobloch, Y., & Son, Y. J. (2024). Comparison of cooking emissions mitigation between automated and manually operated air quality interventions in one-bedroom apartments. *Scientific Reports*, *14*(1), 20630. https://doi.org/10.1038/s41598-024-69731-7

Purnama, T. B., Wagatsuma, K., Pane, M., & Saito, R. (2024). Effects of the Local Environment and Nutritional Status on the Incidence of Acute Respiratory Infections Among Children Under 5 Years Old in Indonesia. *Journal of Preventive Medicine and Public Health*, *57*(5), 461–470. https://doi.org/10.3961/jpmph.24.246

Sankhyan, S., Witteman, J. K., Coyan, S., Patel, S., & Vance, M. E. (2022). Assessment of $PM_{2.5}$ concentrations, transport, and mitigation in indoor environments using low-cost air quality monitors and a portable air cleaner. *Environmental Science: Atmospheres*, *2*(4), 647–658. https://doi.org/10.1039/d2ea00025c

Santri, I. N., Wardani, Y., Phiri, Y. V. A., Nyam, G., Putri, T. A., Isni, K., Suryani, D., & Sambo, G. (2023). Associations between indoor air pollutants and risk factors for acute respiratory infection symptoms in children under 5: An Analysis of Data From the Indonesia Demographic Health Survey. *Journal of Preventive Medicine and Public Health*, *56*(3), 255–263. https://doi.org/10.3961/jpmph.22.470

Shackelford, B. B., Steenland, K., Kirby, M. A., Balakrishnan, K., Chiang, M., Diaz-Artiga, A., McCracken, J. P., Thompson, L. M., Rosa, G., Waller, L. A., Jabbarzadeh, S., Wang, J.,

Pillarisetti, A., Johnson, M. A., Peel, J. L., Checkley, W., & Clasen, T. F. (2025). Gestational and postnatal exposures to fine particulate matter ($PM_{2.5}$) and their association with acute ear infections, diarrhea, respiratory symptoms, and mortality: A longitudinal study of infants in the multicountry Household Air Pollution Intervention. *Environmental Research*, *285*, 122258. https://doi.org/10.1016/j.envres.2025.122258

Shine, S., Tamirie, M., Kumie, A., Addissie, A., Athlin, S., Mekonnen, H., Girma, E., Molla, M., & Kaba, M. (2023). Pregnant women's perception on the health effects of household air pollution in Rural Butajira, Ethiopia: a phenomenological qualitative study. *BMC Public Health*, *23*(1), 1636. https://doi.org/10.1186/s12889-023-16578-8

Su, Y., Dai, Y., Shi, Z., Jiang, Y., Kong, L., & Pfrang, C. (2026). Natural Ventilation Reduces Cooking-Related $PM_{2.5}$ Peaks Indoors. *ACS ES&T Air*, *3*(2), 590–599. https://doi.org/10.1021/acsestair.5c00427

Sun, L., & Singer, B. C. (2023). Cooking methods and kitchen ventilation availability, usage, perceived performance and potential in Canadian homes. *Journal of Exposure Science & Environmental Epidemiology*, *33*(3), 439–447. https://doi.org/10.1038/s41370-023-00543-z

Tang, R., & Pfrang, C. (2023). Indoor particulate matter (PM) from cooking in UK students' studio flats and associated intervention strategies: evaluation of cooking methods, PM concentrations and personal exposures using low-cost sensors. *Environmental Science: Atmospheres*, *3*(3), 537–551. https://doi.org/10.1039/d2ea00171c

Wafula, S. T., Nalugya, A., Mendoza, H., Kansiime, W. K., Ssekamatte, T., Walekhwa, A. W., Mugambe, R. K., Walter, F., Ssempebwa, J. C., & Musoke, D. (2023). Indoor air pollutants and respiratory symptoms among residents of an informal urban settlement in Uganda: A cross-sectional study. *PLoS ONE*, *18*(8), e0290170. https://doi.org/10.1371/journal.pone.0290170

World Health Organization. (2021). *WHO global air quality guidelines: Particulate matter ($PM_{2.5}$ and PM_{10}), ozone, nitrogen dioxide, sulfur dioxide and carbon monoxide.* https://www.who.int/publications/i/item/9789240034228

Xin, J., Shi, X., Ye, F., Zhenlei, C., Yin, P., & Miao, B. (2024). Evaluation of the air quality and the thermal comfort in the kitchen fume environment under the fresh air supplement. *Results in Engineering*, *23*, 102681. https://doi.org/10.1016/j.rineng.2024.102681

Yuan, Y., Wang, Q., Zhang, S., Zhu, N., & Zhao, M. (2023). Distribution Characteristics of Cooking Oil Fume Particles in Residential Kitchens in Cold Regions. *Buildings*, *13*(5), 1227. https://doi.org/10.3390/buildings13051227

Zeng, J., Kagi, N., & Umishio, W. (2025). Transport and distribution of cooking-emitted particles in a residential environment. *Journal of Asian Architecture and Building Engineering*, 1–19. https://doi.org/10.1080/13467581.2025.2602300

Zewdie, A., Degefa, G. H., & Donacho, D. O. (2023). Health risk assessment of indoor air quality, sociodemographic and kitchen characteristics on respiratory health among women responsible for cooking in urban settings of Oromia region, Ethiopia: a community-based cross-sectional study. *BMJ Open*, *13*(6), e067678. https://doi.org/10.1136/bmjopen-2022-067678

Zheng, S., Shen, H., Shen, G., Chen, Y., Ma, J., Cheng, H., & Tao, S. (2022). Vertically-resolved indoor measurements of air pollution during Chinese cooking. *Environmental Science and Ecotechnology*, *12*, 100200. https://doi.org/10.1016/j.ese.2022.100200