Field Performance and Adoption of the Culturally Compatible PAVAK Improved Cookstove in Rural India

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Abstract Nearly 448 million Indians continue to rely on solid biomass fuels for cooking, a practice that poses severe risks to both health and climate. Stove stacking remains widespread in rural households, highlighting the need for supplementary cleaner cooking solutions to minimize environmental and health burden during the cleaner energy transition. To address these gaps, CSIR-NEERI, in association with Glenmark Foundation, developed PAVAK, a culturally compatible improved cookstove. Its design resembles traditional chulhas, preserving cooking practices and improving acceptance. The present study evaluates the real-world performance of PAVAK in tribal villages. Preliminary results show that PAVAK reduced $PM_{2.5}$ emission factors by 45% and CO emission factors by upto 57% compared to traditional stoves, with estimated annual wood savings of ~600 kg per stove. A pilot scale survey indicated that nearly 90% of the PAVAK households perceived no change in taste as compared to traditional cooking. These findings suggest that PAVAK offers a viable, low-cost intervention to mitigate household air pollution and deforestation while respecting local cooking traditions. Scaling such culturally compatible solutions can serve as a critical intermediate strategy to protect public health and the climate during India's transition to cleaner energy.

Keywords Improved cookstove · Household air pollution · solid fuel combustion · energy transition · climate change · cooking energy.

1. Introduction

Nearly 2.3 billion people worldwide rely on solid biomass fuels for cooking, with India accounting for approximately 448 million users according to the National Family Health Survey-5 (IIPS, 2020). Traditional cookstoves, typically constructed from mud or concrete, emit high concentrations of particulate matter ($PM_{2.5}$), carbon monoxide (CO), and black carbon during incomplete combustion. These emissions contribute significantly to household air pollution (HAP), which is responsible for an estimated 600,000 premature deaths annually in India, disproportionately affecting women and children who spend extended periods near cooking fires (Pandey et al., 2020). Beyond health impacts, biomass combustion releases short-lived climate pollutants that contribute to regional warming (Bilsback et al., 2019)

Recognizing these challenges, the Government of India launched the Pradhan Mantri Ujjwala Yojana (PMUY) in 2016, aiming to provide liquefied petroleum gas (LPG) connections to Below Poverty Line (BPL) households. As of December 2024, PMUY has achieved over 126.8 million LPG connections nationwide. However, empirical evidence reveals persistent stove-stacking, where a significant number of rural households continue using traditional biomass stoves alongside LPG (Khanwilkar et al., 2021; Mani et al., 2021). Multiple factors drive this behaviour:

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high refill costs, supply chain inefficiencies create availability gaps in remote areas; free or low-cost firewood collection remains economically attractive, and cultural preferences for traditional cooking methods, particularly for specific dishes, sustain biomass use. These realities highlight that while LPG infrastructure expansion continues, complementary clean cooking solutions are essential to accelerate India's energy transition and achieve health and climate co-benefits.

Improved cookstoves (ICS) represent a proven intermediate technology pathway, designed to enhance combustion efficiency and reduce harmful emissions while maintaining compatibility with biomass fuels. However, conventional metal-based ICS face significant adoption barriers in rural Indian contexts. Metal stoves typically cost ₹1,500-4,000 per unit, representing a substantial investment for resource-constrained households. Field studies reveal persistently low adoption rates for metal-based ICS in rural settings, with challenges in sustained use due to practical and cultural incompatibilities.

Recognizing these implementation gaps, CSIR-NEERI, in collaboration with Glenmark Foundation, developed PAVAK, a concrete-based, culturally compatible improved cookstove. PAVAK is a result of an extensive optimization study via the Response Surface Methodology (RSM) approach (Gupta et al., 2026). PAVAK's design philosophy centres on three pillars: cultural compatibility, local fabrication capability, and affordability. Constructed entirely from locally available concrete, PAVAK resembles the operational characteristics of traditional chulhas that have served rural households for generations. The stove can be fabricated at the community level by trained masons using materials sourced within villages, eliminating supply chain dependencies. Household-level repairs require only basic skills, enabling sustained functionality. Most critically, PAVAK costs 3 to 5 times less expensive than metal ICS, making it financially accessible for large-scale dissemination.

The performance of PAVAK has been validated in the laboratory, with emissions and efficiency satisfying the BIS 13152:2013 cookstove testing protocol. However, real-world performance often diverges from controlled testing due to variations in fuel properties, cooking practices, and environmental conditions. Field-based evaluation using standardized protocols is therefore essential to assess actual emission reductions and user experiences. The present study evaluates PAVAK's real-world performance in tribal villages of Khandwa district (Madhya Pradesh) and Nandurbar district (Maharashtra) and estimates health and climate benefits of PAVAK compared to traditional chulhas

2. Methods

Field assessments were conducted in rural tribal villages across two regions: Khandwa district in Madhya Pradesh and Nandurbar district in Maharashtra. These sites are characterized by a high prevalence of biomass cookstove use (>90% of households), minimal LPG adoption despite PMUY availability, and tribal populations with strong traditional cooking practices.

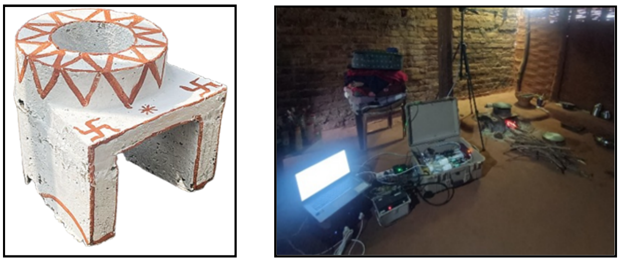

Fig. 1 PAVAK improved concrete cookstove and the sampling setup for source emissions monitoring

A six-armed stainless-steel probe with sampling ports radially centred in equal areas was used to capture a representative sample of naturally diluted emissions approximately 1−1.5 m above the cookstove. From the probe, emissions were sampled through a conductive sampling tubing via a 2.5 μm cut-point cyclone (BGI, USA). The Laboratory Emissions Monitoring System (LEMS) 3006 (Make: Aprovecho) provided real-time measures of CO and CO_2. Additionally, parallel sampling trains consist of a bare quartz filter in one train and a PTFE filter coupled with a downstream quartz filter to account for gas-phase absorption artefacts (Wathore et al., 2023).

Background air was sampled for 10 −15 min before and/or after each cooking session. Wood fuel was set aside before the start of cooking, and the moisture content and weight of the wood were recorded. The wood moisture content was measured using an electronic moisture meter (Flir MR60). The weights of the wood before and after cooking were used to determine the amount of wood consumed.

PTFE filters were pre-conditioned in desiccation boxes for 24 hours prior to weighing. Pre- and post-weighing was done on an ultra-microbalance. Quartz filters were pre-baked at 550 °C for 24 hours and stored in petri dishes lined with aluminium foil before and after sampling. 10% dynamic field blanks were considered to correct for background levels.

Fuel-based emission factors (EFs) in grams of pollutant per kilogram of wood (g/kg) were derived using the carbon balance method as outlined in the ISO 19869:2019 cookstove field testing protocol (ISO, 2019). EC/OC analysis of filters was done using an EC-OC Analyser (Make: DRI) with the IMPROVE-A protocol.

3. Key Findings and Insights

Table 1 summarizes the emission factors for $PM_{2.5}$, CO, Elemental Carbon (EC), and Organic Carbon (OC). In Khandwa district, PAVAK achieved a significant 46% reduction in $PM_{2.5}$ EF compared to traditional stoves (6.56 vs 12.16 g/kg wood). Nandurbar district showed similar trends with a 39% $PM_{2.5}$ EF reduction (5.12 vs 8.43 g/kg).

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Location (Sample size)	Pollutant EF (g/kg)	Traditional average	Pavak average	Percent Reduction
Khandwa (Trad = 6 Pavak = 12)	PM2.5	12.16	6.56	46 % *
	CO	55.09	46.89	15%
	EC	4.75	2.47	34 % *
	OC	5.51	3	61 % *
Nandurbar (Trad = 3; Pavak = 3)	PM2.5	8.43	5.12	39%
	CO	45.25	19.26	57 % *
	EC	2.27	1.49	46%
	OC	2.76	1.07	48%

Carbon monoxide (CO) emission factors differed markedly between the two locations. Khandwa showed a 15% reduction (46.89 vs 55.09 g/kg), whereas Nandurbar achieved a statistically significant 57% reduction (19.26 vs 45.25 g/kg).

Substantial reductions were also observed in both carbon fractions. In Khandwa, EC decreased significantly by 34% (2.47 vs 4.75 g/kg), and OC decreased by 61% (3.00 vs 5.51 g/kg). Nandurbar exhibited comparable patterns with a 46% EC reduction (1.49 vs 2.27 g/kg) and a 48% OC reduction (1.07 vs 2.76 g/kg).

Finally, a pilot-scale user perception survey of nearly 300 households in Khandwa indicated high user acceptability. Nearly 90% of households reported no change in the taste of their food, while the majority of users perceived both less smoke emission and reduced wood consumption.

4. Discussion and Implications

Despite regional variations in baseline emissions, likely reflecting differences in wood species, moisture content, or cooking practices, PAVAK consistently demonstrated emission reductions across both tribal communities. This suggests robust performance across diverse operational conditions.

The significant disparity in CO reductions between the two districts reflects distinct local cooking practices. In Khandwa, traditional flatbread (roti/bhakri) preparation involves extracting embers from the stove and baking the flatbread directly on top of them. This creates additional smouldering combustion that generates high CO emissions outside the primary combustion chamber. Because this practice persists with both traditional and PAVAK stoves, the CO reduction potential in Khandwa is inherently limited. Conversely, households in Nandurbar use pans (tawa) for roti preparation, allowing the stove to achieve a much higher 57% reduction in CO emissions.

The substantial reductions in EC and OC are critical, as these two fractions constitute the majority of particulate matter mass and represent distinct combustion pathways with different health and climate implications. Black carbon from residential biomass combustion contributes heavily to regional atmospheric warming and glacial melting, making the 34–46% EC reductions particularly valuable for climate mitigation. Furthermore, OC comprises semi-volatile compounds and condensed hydrocarbons formed during incomplete combustion, including toxic polycyclic aromatic hydrocarbons (PAHs). PAVAK's substantial OC reductions (48–61%) indicate a more complete combustion of volatile species, achieved through improved mixing with secondary air. This not only drives a substantial decrease in critical $PM_{2.5}$ emissions, which mainly contribute to respiratory health impacts, but also significantly reduces the overall toxicity of the household air pollution.

Coupled with the high user acceptability regarding food taste and observed fuel savings, these findings imply that PAVAK is a highly viable intervention for sustained adoption and long-term emission mitigation in rural households.

5. Policy/ Practice Relevance

This work establishes an evidence-based roadmap for scaling affordable, durable, and climate-smart cookstove solutions as a vital complementary strategy to the Pradhan Mantri Ujjwala Yojana (PMUY) and other renewable energy initiatives. By addressing the persistence of solid fuel use, PAVAK provides a practical intermediate solution for rural households during India's clean energy transition. The demonstrated emission reductions and fuel savings will directly inform policy frameworks and CSR programs aimed at mitigating household air pollution. Furthermore, the verified performance data provide essential inputs for developing robust carbon finance mechanisms under India's emerging carbon market framework. Specifically, the outcomes will support the formulation of carbon credit methodologies, such as the Comprehensive Lowered Emission Assessment and Reporting (CLEAR) Methodology, by establishing accurate baselines for health and climate co-benefits.

6. Conclusion

Our findings confirm that the low-cost, concrete-based PAVAK cookstove achieves substantial reductions in pollutant emission factors across different tribal regions. These real-world performance improvements are consistent with previous Indian studies on improved cookstoves (Grieshop et al., 2017; Islam et al., 2021; Wathore et al., 2023) and highlight the significant potential for mitigating health and climate risks associated with traditional cooking practices.

Ongoing activities are focused on strengthening this evidence base through expanded emission testing in Nandurbar to increase statistical confidence, alongside a 10,000-household user perception survey to assess adoption drivers, sustained use patterns, and operational challenges. Future work will quantify health benefits by measuring micro-environmental concentrations of $PM_{2.5}$ and CO in kitchens to estimate reduced personal exposure and project avoided respiratory disease burden. Simultaneously, climate benefits will be calculated by converting measured emission factors into CO_2-equivalents using appropriate global warming potentials for CO_2, CO, Elemental Carbon (EC), and Organic Carbon (OC). This comprehensive approach will further validate the role of improved cookstoves in reducing black carbon radiative forcing and advancing sustainable energy goals.

Acknowledgements

This work was supported by Glenmark Foundation under Project CNP-2872. We sincerely thank the NGO Spandan Samaj Sewa Samiti, its co-founders Mr. Prakash and Mrs. Seema Prakash, as well as the YUVA Mitra staff members Mr. Nilesh Kulkarni, Mr. Atul Surwase, and Mr. Ankush Suryawanshi, along with the entire NGO team, for their valuable field support. We deeply thank the rural communities in the villages in Khandwa and Nandurbar for allowing us to conduct testing and surveys in their homes.

Reference

1. Alam, A., Tawale, N., Patel, A., Dibley, M., Jadhao, S., Raynes-Greenow, C., 2016. Household Air Pollution Intervention Implications: Findings from Qualitative Studies and a Field Trial of Clean Cookstoves in Two Rural Villages in India. Int. J. Environ. Res. Public. Health 13, 893. https://doi.org/10.3390/ijerph13090893
2. Bilsback, K.R., Dahlke, J., Fedak, K.M., Good, N., Hecobian, A., Herckes, P., L'Orange, C., Mehaffy, J., Sullivan, A., Tryner, J., Van Zyl, L., Walker, E.S., Zhou, Y., Pierce, J.R., Wilson, A., Peel, J.L., Volckens, J., 2019. A Laboratory Assessment of 120 Air Pollutant Emissions from Biomass and Fossil Fuel Cookstoves. Environ. Sci. Technol. 53, 7114–7125. https://doi.org/10.1021/acs.est.8b07019
3. Grieshop, A.P., Jain, G., Sethuraman, K., Marshall, J.D., 2017. Emission factors of health- and climate-relevant pollutants measured in home during a carbon-finance-approved cookstove intervention in rural India. GeoHealth 1, 222–236. https://doi.org/10.1002/2017GH000066
4. Gupta, A., Wathore, R., Hedaoo, R., Bherwani, H., Dhoble, A.S., Labhasetwar, N., 2026. Multiparameter design optimisation of a mud-based natural draft biomass cookstove using response surface methodology and desirability function. Sci. Rep. 16, 668. https://doi.org/10.1038/s41598-025-29684-x
5. IIPS, 2020. National Family Health Survey (NFHS-5) [WWW Document]. URL http://rchiips.org/nfhs/ (accessed 5.28.23).
6. Islam, M.M., Wathore, R., Zerriffi, H., Marshall, J.D., Bailis, R., Grieshop, A.P., 2021. In-use emissions from biomass and LPG stoves measured during a large, multi-year cookstove intervention study in rural India. Sci. Total Environ. 758, 143698. https://doi.org/10.1016/j.scitotenv.2020.143698
7. ISO, 2019. ISO 19869:2019 Clean cookstoves and clean cooking solutions — Field testing methods for cookstoves [WWW Document]. ISO. URL https://www.iso.org/standard/66521.html (accessed 6.26.23).
8. Khanwilkar, S., Gould, C.F., DeFries, R., Habib, B., Urpelainen, J., 2021. Firewood, forests, and fringe populations: Exploring the inequitable

socioeconomic dimensions of Liquified Petroleum Gas (LPG) adoption in India. Energy Res. Soc. Sci. 75, 102012.

9. Mani, S., Agrawal, S., Jain, A., Ganesan, K., 2021. State of Clean Cooking Energy Access in India. CEEW.

10. Mani, S., Jain, A., Tripathi, S., Gould, C.F., 2020. The drivers of sustained use of liquified petroleum gas in India. Nat. Energy 5, 450–457. https://doi.org/10.1038/s41560-020-0596-7

11. Pandey, A., Brauer, M., Cropper, M.L., Balakrishnan, K., Mathur, P., Dey, Sagnik, Turkgulu, B., Kumar, G.A., Khare, M., Beig, G., Gupta, T., Krishnankutty, R.P., Causey, K., Cohen, A.J., Bhargava, S., Aggarwal, A.N., Agrawal, A., Awasthi, S., Bennitt, F., Bhagwat, S., Bhanumati, P., Burkart, K., Chakma, J.K., Chiles, T.C., Chowdhury, S., Christopher, D.J., Dey, Subhojit, Fisher, S., Fraumeni, B., Fuller, R., Ghoshal, A.G., Golechha, M.J., Gupta, P.C., Gupta, Rachita, Gupta, Rajeev, Gupta, S., Guttikunda, S., Hanrahan, D., Harikrishnan, S., Jeemon, P., Joshi, T.K., Kant, R., Kant, S., Kaur, T., Koul, P.A., Kumar, Praveen, Kumar, R., Larson, S.L., Lodha, R., Madhipatla, K.K., Mahesh, P.A., Malhotra, R., Managi, S., Martin, K., Mathai, M., Mathew, J.L., Mehrotra, R., Mohan, B.V.M., Mohan, V., Mukhopadhyay, S., Mutreja, P., Naik, N., Nair, S., Pandian, J.D., Pant, P., Perianayagam, A., Prabhakaran, D., Prabhakaran, P., Rath, G.K., Ravi, S., Roy, A., Sabde, Y.D., Salvi, S., Sambandam, S., Sharma, B., Sharma, M., Sharma, S., Sharma, R.S., Shrivastava, A., Singh, S., Singh, V., Smith, R., Stanaway, J.D., Taghian, G., Tandon, N., Thakur, J.S., Thomas, N.J., Toteja, G.S., Varghese, C.M., Venkataraman, C., Venugopal, K.N., Walker, K.D., Watson, A.Y., Wozniak, S., Xavier, D., Yadama, G.N., Yadav, G., Shukla, D.K., Bekedam, H.J., Reddy, K.S., Guleria, R., Vos, T., Lim, S.S., Dandona, R., Kumar, S., Kumar, Pushpam, Landrigan, P.J., Dandona, L., 2020. Health and economic impact of air pollution in the states of India: the Global Burden of Disease Study 2019. Lancet Planet. Health 0. https://doi.org/10.1016/S2542-5196(20)30298-9

12. Rosenthal, J., Balakrishnan, K., Bruce, N., Chambers, D., Graham, J., Jack, D., Kline, L., Masera, O., Mehta, S., Mercado, I.R., Neta, G., Pattanayak, S., Puzzolo, E., Petach, H., Punturieri, A., Rubinstein, A., Sage, M., Sturke, R., Shankar, A., Sherr, K., Smith, K., Yadama, G., 2017. Implementation Science to Accelerate Clean Cooking for Public Health. Environ. Health Perspect. 125. https://doi.org/10.1289/EHP1018

13. Wathore, R., Hedaoo, R., Ahmad, A., Gupta, A., Dhoble, A.S., Labhasetwar, N., 2023. Field based performance evaluation of optimized improved biomass mud cookstoves in rural India. Renew. Energy 119567. https://doi.org/10.1016/j.renene.2023.119567

14. Wathore, R., Mortimer, K., Grieshop, A.P., 2017. In-Use Emissions and Estimated Impacts of Traditional, Natural- and Forced-Draft Cookstoves in Rural Malawi. Environ. Sci. Technol. 51, 1929–1938. https://doi.org/10.1021/acs.est.6b05557