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Real-World Performance, Adherence Dynamics, and Exposure Gaps of Household Air Pollution Interventions in Low- and Middle-Income Countries: A Systematic Review

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Systematic Review

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Abstract

Household air pollution (HAP) interventions may perform differently under real-world household conditions than under laboratory or controlled testing because of adherence, fuel stacking, maintenance, household practices, and differences in measurement conditions. This systematic review synthesizes real-world field performance, adherence dynamics, and post-implementation exposure gaps of cookstove, filtration, and fuel-switching interventions across low- and middle-income country (LMIC) households, while mapping the underlying technical, behavioral, and measurement mechanisms. PubMed, Scopus, Web of Science, African Journals Online, and LILACS were searched for studies published between 1 January 2021 and 31 December 2025 that presented laboratory and field or intervention and control performance data. Seventeen eligible publications (primary intervention reports and linked secondary analyses) arising from six parent evidence groups in eight LMICs were identified; the majority of evidence originated from the HAPIN, GRAPHS, and CHAP cohorts. Reported mechanisms included fuel stacking, decline in adherence after withdrawal of free fuel or behavioral support, and household fuel-loading and cooking practices that differed from standardized laboratory protocols. Controlled-condition performance is not directly transferable to household use. Field validation of adherence and continuous monitoring of health-relevant pollutants are required before widespread implementation.

1. Introduction

Household air pollution (HAP) from the use of solid fuels for cooking, heating and lighting remains a major environmental driver of disease burden, particularly in low- and middle-income countries (LMICs) [1]. Combustion of biomass and other solid fuels generates particulate matter, carbon monoxide (CO) and additional pollutants that concentrate within and around the home [2]. Women and young children typically experience the highest exposures because of prolonged time spent in cooking areas and involvement in fuel handling and food preparation [3]. Documented health effects include acute lower respiratory infections and pneumonia in children, chronic respiratory and cardiovascular disease in adults, and adverse pregnancy and birth outcomes [4]. Growing evidence also links chronic HAP exposure to cognitive and developmental outcomes across the life course [5, 6].

A range of household-level interventions has been designed and deployed in LMICs to reduce this burden. These include improved and clean-burning cookstoves, fuel-switching programmes (most commonly to liquefied petroleum gas, LPG), ventilation improvements, and, less frequently, portable or fixed air-filtration devices [7]. Laboratory and standardized testing protocols—emission measurements under controlled fuel, stove and operating conditions, and controlled cooking or water-boiling tests—are routinely used to characterize technical performance [8, 9]. However, the conditions under which interventions are evaluated in the laboratory systematically differ from those encountered in ordinary household settings. Laboratory protocols control fuel properties, cooking tasks, stove operation and the measurement environment, whereas household cooking is shaped by fuel type and quality, cooking

methods, stove maintenance, cultural preferences, weather, room layout, ventilation and socio-economic constraints [10].

Several mechanisms can produce divergence between controlled-condition and field performance. Fuel stacking—continued concurrent use of traditional fuels—can offset the exposure benefit of exclusive adoption of a cleaner technology. Adherence may decline over time because of fuel cost or availability, cooking preference, equipment failure, or withdrawal of behavioural or logistical support [11]. Stove use patterns and fuel-loading practices frequently differ from those assumed in standard tests, and room configuration and ventilation further modulate the relationship between stove emissions and measured indoor concentrations [12]. A consistent observation across the household-energy and public-health literature is that laboratory or standardized performance does not automatically translate into equivalent household-level performance [13]. Individual studies and field trials have examined this question with heterogeneous pollutants, intervention packages, comparators, follow-up durations and adherence metrics, making direct comparison difficult [14, 15].

This systematic review addresses three specific gaps: (1) transparent juxtaposition of laboratory/controlled and field numerical benchmarks without pooling non-comparable metrics; (2) restriction to a 2021–2025 LMIC household evidence window; and (3) explicit mapping of behavioural, technical and measurement mechanisms together with identification of under-represented regions and intervention types.

Research questions

RQ1: What laboratory-to-field performance differences are reported for HAP interventions in LMIC households, and which can be contrasted numerically?

RQ2: What behavioural, technical and measurement mechanisms underlie this gap?

RQ3: What is the 2021–2025 geographic and intervention coverage, and which areas remain under-represented?

2. Materials and Methods

This review was conducted and is reported in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 statement. Ethics approval was not required because the study is a systematic review of previously published literature and did not involve human participants or primary data collection.

2.1 Eligibility criteria

A PECOS (Population, Exposure/Intervention, Comparator, Outcome, Study design) framework guided eligibility decisions (Table 1). Complementary decision rules were applied for inclusion and exclusion.

Table 1
PECOS framework used to define eligibility

PECOS domain	Inclusion criteria	Exclusion criteria
Population	Households in countries classified by the World Bank as low-, lower-middle- or upper-middle-income at the time of study conduct; exposure measured in the home.	High-income-country studies regardless of subgroup socioeconomic status; non-residential settings unless household exposure was explicitly measured.
Exposure / intervention	Improved or clean-burning cookstoves; household fuel switching to LPG, biogas, ethanol or electricity; household ventilation modification; household air filtration/purification.	Ambient, outdoor or industrial interventions without a household combustion source; studies of naturally occurring practices with no introduced intervention; tobacco-smoke-only interventions.
Comparator	Laboratory/controlled performance versus field performance of the same intervention; intervention versus control/traditional practice; or within-cohort performance before versus after withdrawal of behavioural or financial support.	Cross-sectional association studies without an intervention comparator, including national survey analyses without an intervention arm.
Outcome	Extractable quantitative pollutant concentrations (e.g., PM2.5, PM10, CO, black carbon); objective clinical/physiological outcomes linked to the same cohort; quantitative adherence/fidelity measures.	Self-reported or perceived health outcomes without an objective exposure or clinical measure.
Study design / period	Randomized trials, controlled pre/post field studies, crossover trials, and paired laboratory-versus-field studies published 1 January 2021–31 December 2025.	Cross-sectional surveys; case-control studies without an intervention arm; ecological or exposure-modelling studies without an intervention; qualitative-only studies; non-combustion risk-assessment studies; reviews; publications outside the date window.

2.2 Information sources and search strategy

PubMed/MEDLINE, Scopus, Web of Science, African Journals Online and LILACS were searched for records published from 1 January 2021 to 31 December 2025 (English-language studies only). Search concepts covered household air pollution interventions, laboratory versus field or real-world performance, pollutant and exposure outcomes, and LMIC household settings. Database-specific search strings are provided in Supplementary Table S1.

2.3 Study selection

Titles and abstracts were screened against the inclusion criteria; potentially eligible records underwent full-text examination. When multiple publications reported on the same trial cohort (e.g., HAPIN,

GRAPHS, CHAP), each publication was retained if it contributed a distinct outcome, while the underlying population was counted once for geographic distribution. One reviewer independently screened titles, abstracts and full texts. A second check was performed for eligibility and data consistency; discrepancies were resolved by discussion. Reasons for full-text exclusion were recorded and are summarized in the PRISMA 2020 flow diagram (Fig. 1).

2.4 Data extraction and synthesis

Data were extracted on study design, country, intervention package, laboratory or controlled benchmarks (where available), field pollutant concentrations or personal exposures, adherence or fidelity metrics, and any reported clinical or physiological outcomes. Because pollutants, sampling locations, averaging periods, comparators and follow-up durations varied substantially, quantitative meta-analysis was not performed. Results are presented as a semi-quantitative synthesis that preserves the original metrics and highlights patterns and mechanisms rather than a single pooled effect size.

3. Results

3.1 Study selection

The systematic search yielded 1,842 records. After removal of 416 duplicates, 1,426 records remained for title and abstract screening. Of these, 1,289 were excluded as clearly irrelevant. The remaining 137 articles underwent full-text evaluation. One hundred and twenty articles were excluded for the following reasons: publication date outside the 2021–2025 window (n = 48); conducted in high-income countries (n = 29); no intervention introduced (cross-sectional or qualitative only) (n = 21); non-household settings (n = 9); outcomes limited to self-reported health or qualitative data only (n = 8); and other reasons (duplicate cohort report without distinct outcomes, wrong study design, or insufficient extractable data) (n = 5). Seventeen publications met all eligibility criteria and were included. These publications arose from six independent parent evidence groups (HAPIN, GRAPHS, CHAP and three single-country studies) conducted in eight LMICs. The selection process is summarized in Fig. 1.

3.2 Characteristics of included publications

Table 2 summarizes the 17 eligible publications. Rows should not be interpreted as 17 independent intervention studies; multiple publications are linked to the same parent cohorts, particularly HAPIN, GRAPHS and CHAP. Cohort linkage is therefore central to interpretation of the evidence base.

Table 2
Eligible publications (2021–2025, LMIC households only)

Parent cohort / evidence group	No. of publications	Countries represented	Intervention(s)	Main outcomes assessed
HAPIN Cohort	5	Guatemala, India, Peru, Rwanda	LPG fuel-switching intervention	PM2.5, CO, personal exposure, adherence, selected health outcomes
CHAP Cohort	3	Peru	LPG stove + free fuel + behavioural support	PM2.5, exposure, stove use/adherence, clinical outcomes
GRAPHS Cohort	3	Ghana	Improved biomass cookstove and LPG	PM2.5, CO, exposure, adherence, health outcomes
Single studies	6	Various LMIC settings (India, Ethiopia, Rwanda, Cameroon/Ghana/Kenya, others)	Cookstoves, fuel switching, filtration and/or ventilation	Exposure, concentration, emissions, adherence and related outcomes
Total	**17**	**8 countries**	**Multiple intervention categories**	**Heterogeneous**

3.3 Geographic and intervention distribution

Six parent evidence groups were represented by the 17 publications: five from the HAPIN group, three from the CHAP group, three from the GRAPHS group, and six independent studies. Cohort (N = 6) rather than publication was used as the primary unit for geographic and intervention synthesis to avoid over-representation of countries and interventions from which multiple papers originated. HAPIN primarily evaluated LPG fuel switching; CHAP evaluated LPG with free fuel and behavioural support in Peru; GRAPHS evaluated improved biomass cookstoves and LPG in Ghana. The remaining single studies examined a variety of cookstove, fuel-switching, filtration and ventilation interventions in other LMIC settings.

3.4 Summary of controlled and field performance (semi-quantitative)

No single quantitative estimate of a laboratory-to-field performance gap was calculated because most publications did not provide directly paired laboratory and field values on the same scale, and pollutants, outcome definitions, comparators and follow-up periods differed. The semi-quantitative pattern was

nonetheless informative (Table 3). HAPIN reported a median post-randomization reduction in personal PM2.5 of approximately 66% relative to control under intensive LPG support [19]. GRAPHS reported approximately 32% lower PM2.5 and 47% lower CO in the LPG arm relative to control, with no significant reduction for improved biomass stoves [23]. Gupta et al. reported field reductions of 89–94% for PM2.5 and 35–57% for CO after introduction of an improved cookstove, although absolute concentrations remained above health-based guideline values [29]. Cuesta-Mosquera et al. reported approximately 77% lower indoor PM2.5 with an improved stove versus traditional three-stone fire [16]. In contrast, Islam et al. found that in-home LPG emissions exceeded laboratory measurements and that several improved biomass stoves showed no clear field reduction relative to traditional stoves [17]. Adane et al. likewise observed that pollutant concentrations remained elevated above health-based guidelines after an improved-biomass intervention [18].

Table 3
Semi-quantitative summary of field-performance results

Evidence source	Intervention / contrast	Extractable field result	Interpretation for this review
HAPIN (Johnson et al., 2022)	LPG + fuel + behavioural support vs control	Median post-randomization PM2.5 ~ 66% lower vs control	Strong field reduction under intensive support; not itself a numerical laboratory–field gap
GRAPHS (Chillrud et al., 2021)	LPG and improved biomass vs control	LPG: PM2.5 ~ 32% lower, CO ~ 47% lower; improved biomass: no significant reduction	Intervention-specific heterogeneity in field effectiveness
Islam et al. (2021)	Biomass and LPG stoves	In-home LPG emissions higher than laboratory; improved biomass showed no unambiguous reduction vs traditional stove	Most direct evidence that laboratory measurements may overstate in-home performance under some conditions
CHAP (Fandiño-Del-Rio / Checkley)	LPG + free fuel + behavioural messaging	Field concentrations lower than control; high exclusive LPG use; clinical outcomes not significantly improved in one report	Supports separation of exposure performance from clinical benefit
Gupta et al. (2021/2023)	NEERDHUR improved cookstove + IEC	PM2.5 reduction 89–94%; CO reduction 35–57%; concentrations still above health-based limits	Large relative field reduction can coexist with residual absolute exposure
Cuesta-Mosquera et al. (2025)	Save80 improved stove vs traditional three-stone fire	Indoor PM2.5 reduction ~ 77%	Substantial field reduction in one setting; argues against describing attenuation as universal
Adane et al. (2021)	Improved biomass stove	Measured pollutants remained above health-based guideline values	Demonstrates residual exposure but not a numerical laboratory–field gap

3.5 Mechanisms associated with controlled-versus-field differences

3.5.1 Technical and behavioural mechanisms

Islam et al. identified fuel re-loading and cooking-pattern effects that were not captured by standardized laboratory protocols and that produced substantially higher in-home emissions for the same fuel [17]. Traditional stove use and fuel stacking were recurring themes. HAPIN adherence sub-studies indicated generally high fidelity with minimal stacking during the period of active fuel delivery, although a later fidelity analysis flagged that 26% of participants ran out of LPG at some point, most often because of COVID-19-related supply disruption [24, 25]. The CHAP trial in Peru provided the clearest quantitative demonstration of adherence decay: LPG use fell from near-exclusive during the funded intervention period to 85.4% of monitored days and 63.2% of cooking minutes once free fuel and behavioural support were withdrawn [22].

3.5.2 Measurement and outcome-related mechanisms

A distinct measurement-related mechanism emerged from the CHAP cohort. Despite 98% exclusive LPG use and personal PM2.5 exposures below the WHO interim target—conditions close to ideal intervention delivery—Checkley and colleagues reported no significant difference in blood pressure, lung function or respiratory symptoms compared with control [20]. This dissociation between a successfully closed exposure gap and a persistent health-outcome gap suggests that part of the overall “efficacy gap” documented in the literature may reflect the time course, dose threshold or biological pathway of health recovery following exposure reduction, rather than a failure of the intervention to reduce exposure.

3.6 Risk of bias assessment

Risk of bias was assessed with the Cochrane Risk of Bias 2 (RoB 2) tool for randomized controlled trials and the ROBINS-I tool for non-randomized intervention studies. Domain-level judgements are summarized in Table 4 and Fig. 2. Randomized intervention publications were generally rated as low risk or some concerns. The principal concerns related to deviations from intended intervention (adherence) and missing outcome data rather than to randomization itself. Secondary analyses of HAPIN, GRAPHS and CHAP were evaluated with reference to their parent randomized designs and were not treated as independent studies. Secondary exposure–response analyses that did not estimate intervention effects were not assigned an intervention-effect risk-of-bias judgement.

Table 4
Risk of bias assessment for included publications

Publication	Design	Overall judgement
Johnson et al. [19] (HAPIN)	RCT	Low
Quinn et al. [24] (HAPIN fidelity)	RCT	Low
Williams et al. [25] (HAPIN fidelity)	RCT	Low
Chillrud et al. [23] (GRAPHS)	Cluster RCT	Low
Agyapong et al. [26] (GRAPHS secondary)	Secondary RCT analysis	Some concerns
Kinney et al. [27] (GRAPHS exposure–pneumonia)	Exposure–response analysis	Some concerns
Fandiño-Del-Rio et al. [20] (CHAP)	RCT + crossover	Some concerns
Simkovich et al. [21] (CHAP)	RCT	Some concerns
Williams et al. [22] (CHAP sustained use)	Post-intervention follow-up	Some concerns
Adane et al. [18]	Cluster RCT	Some concerns
Cuesta-Mosquera et al. [16]	RCT	Some concerns
Islam et al. [17]	Observational field study	Serious
Parvizi et al. [28]	Cross-sectional measurement study	Serious
Gupta et al. [29]	Pre/post field study	Serious
Ndikubwimana et al. [30] (HAPIN BMI)	Baseline cross-sectional secondary analysis	N/A for intervention effect
Balakrishnan et al. [31] (HAPIN birthweight)	Secondary RCT analysis	Some concerns

4. Discussion

This systematic review demonstrates that the real-world effectiveness of household air pollution interventions is highly variable and is not necessarily comparable to performance under controlled conditions. The 17 publications arose from only six parent evidence groups in eight LMICs, with the majority of evidence coming from the HAPIN, GRAPHS and CHAP trials. Quantitative pooling was not feasible because direct laboratory-to-field numerical comparisons were rare and pollutants, sampling techniques, treatment characteristics and follow-up periods differed. Nonetheless, regular patterns emerged with respect to fuel type, adherence, household practices and exposure measurement.

In general, larger field reductions in exposure were observed with LPG interventions than with improved biomass cookstoves. HAPIN reported an approximate 66% reduction in post-randomization personal PM2.5 exposures in the LPG arm relative to controls under intensive support [19], and CHAP studies documented substantial reductions in PM2.5 at high levels of LPG use [20–22]. GRAPHS showed significant decreases for LPG but less consistent change for improved biomass stoves [23]. These differences should not be read as an indictment of improved biomass technologies in general: Gupta et al. documented large relative reductions in PM2.5 and CO, and Cuesta-Mosquera et al. reported an approximate 77% reduction in indoor PM2.5 [16, 29]. Field effectiveness therefore varied according to the specific technology and setting rather than in a uniform direction.

Islam et al. noted that in-home emissions were higher than laboratory emissions and that clear exposure reductions were absent for some improved biomass stoves [17]. The quantity of fuel loaded, intensity of cooking, air-exchange rates, stove-use patterns and fuel characteristics can differ markedly from the conditions under which devices are tested. Laboratory-based testing and field assessments should therefore be regarded as complementary: laboratory testing characterizes technical potential, while field testing characterizes performance under real conditions.

Observed effectiveness was strongly conditioned by adherence. Periods of active LPG provision and behavioural support produced high intervention fidelity; interruptions in fuel availability and withdrawal of free fuel and support were associated with measurable declines in exclusive use, most clearly quantified in the CHAP follow-up data [22]. Assignment to an intervention arm does not equate to sustained household exposure reduction. Sustained use is shaped by fuel availability, cost, user preference, equipment reliability and the presence of support systems.

There was no consistent evidence of clinical improvement accompanying lower pollutant exposures. Even when personal PM2.5 exposures fell substantially and exclusive LPG use approached 100%, as in CHAP, clinical outcomes were not uniformly improved [20]. Exposure reduction is a necessary intermediate endpoint; clinical benefit may require longer follow-up, different exposure thresholds, or consideration of additional biological pathways and baseline risk profiles.

5. Limitations

Several limitations constrain inference. The evidence base does not comprise 17 independent studies; many publications derive from the same parent cohorts (HAPIN, GRAPHS, CHAP). This clustering creates a false impression of the number of independent intervention settings and over-represents a small number of large multi-country trials. Direct laboratory-versus-field numerical comparisons were uncommon, while pollutants, sampling locations, averaging periods, comparators, adherence measures and clinical outcomes varied substantially. A single pooled estimate would therefore risk combining non-equivalent quantities. Geographic coverage was narrow relative to the LMIC world: fewer than ten countries contributed eligible publications, some of which belonged to the same multi-country trial.

Consequently, recent evidence meeting the review criteria is absent for large parts of South and Southeast Asia, the Middle East and North Africa, and much of sub-Saharan Africa.

6. Conclusion

In the LMIC context examined here, controlled-condition performance is an inadequate proxy for household-level performance. Field exposure reductions ranged from null or partial reductions in some biomass-improvement assessments to substantial reductions in certain LPG and improved-stove assessments. The number of direct laboratory-to-field comparisons was too small to support a single pooled estimate. The available evidence therefore supports cautious interpretation of laboratory certification, routine field validation, and explicit monitoring of adherence, fuel stacking and health-relevant pollutants. Conclusions about the magnitude or universality of a laboratory-to-field gap should be regarded as tentative given the limited number of cohorts and countries represented and the methodological diversity of the evidence.

Declarations

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Conflict of interest

The author declares no competing interests.

Authors' contributions

Asra Noor: Conceptualization; Methodology; Investigation; Data curation; Formal analysis; Writing – original draft; Writing – review & editing.

Data availability statement

All data analyzed in this systematic review were obtained from publicly available published sources cited within the manuscript.

Ethics approval

Ethics approval was not required because this study is a systematic review of previously published and publicly available literature and did not involve human participants or the collection of primary data.

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Figures

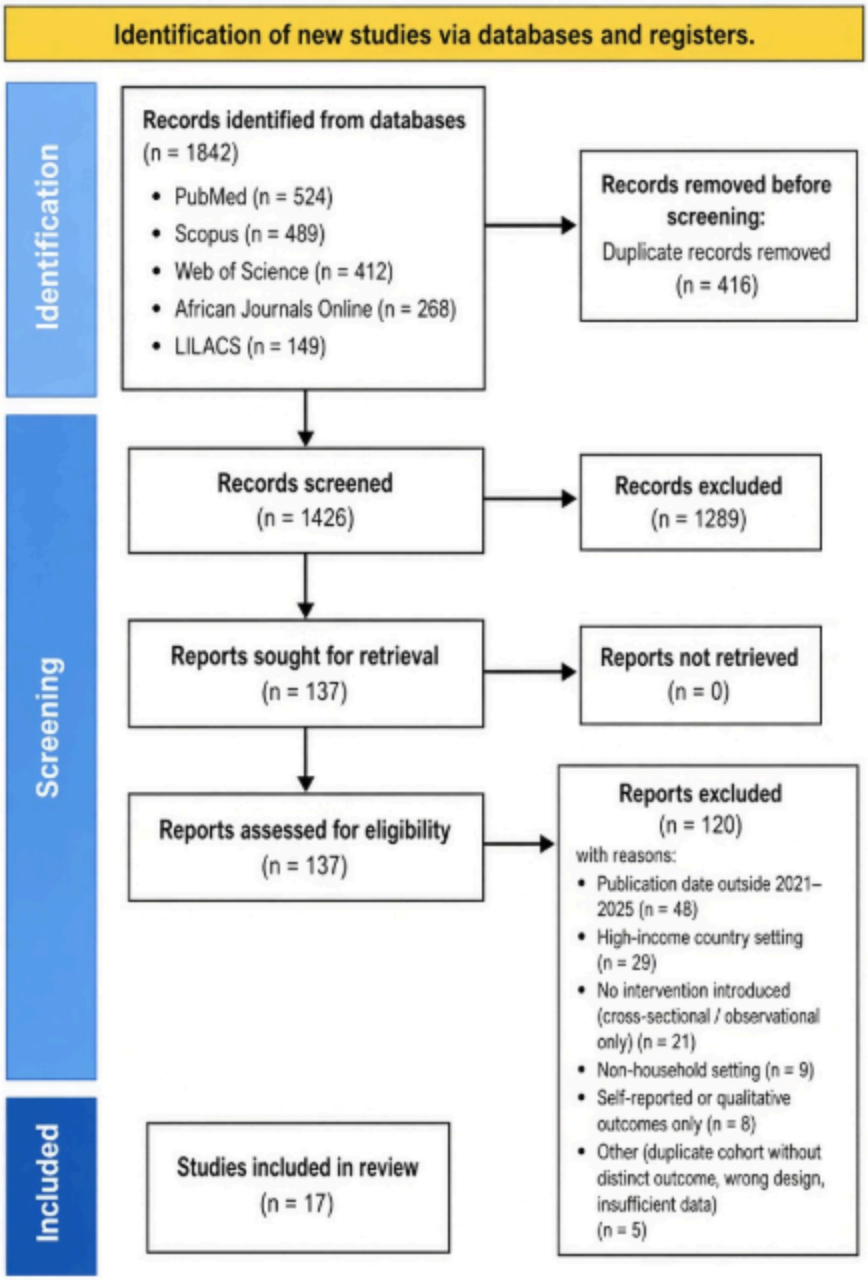

Figure 1

PRISMA 2020 flow diagram of study selection. From 1,842 records identified, 17 publications arising from six parent evidence groups met eligibility criteria.

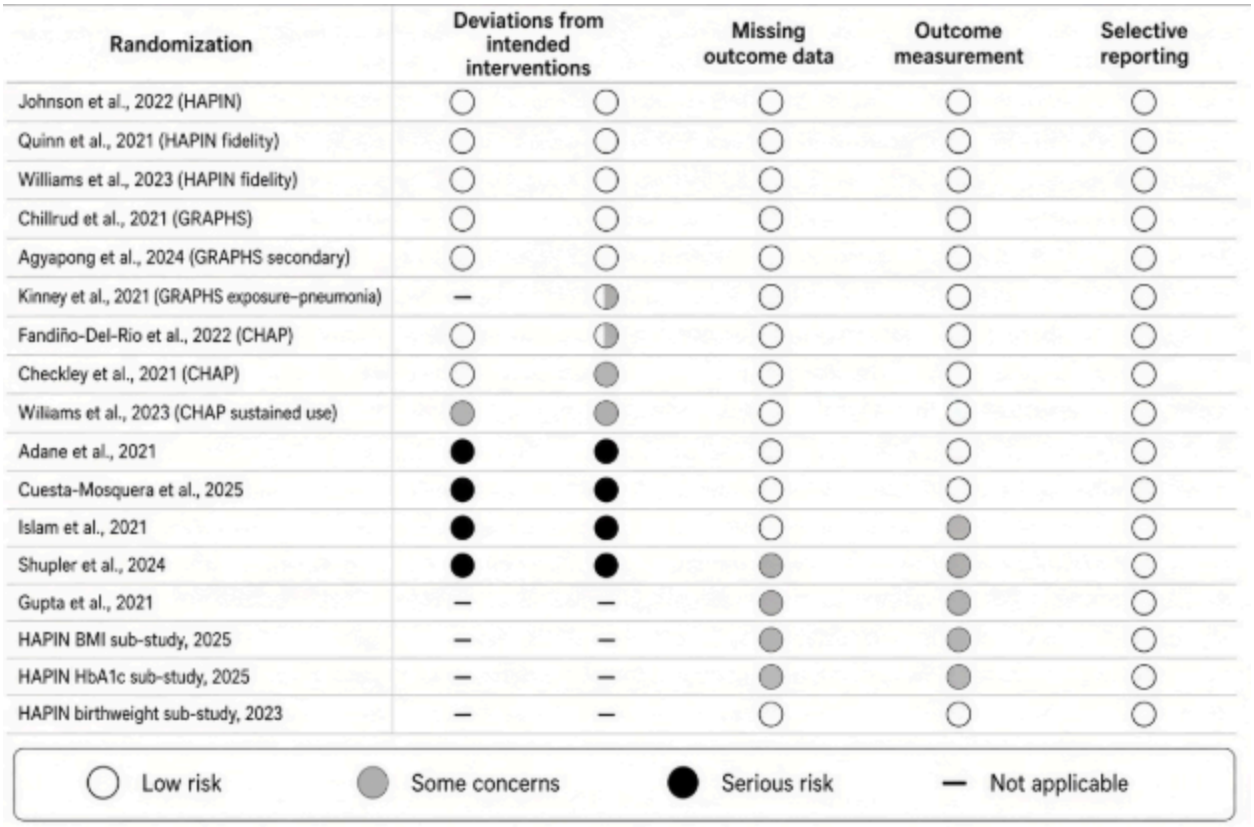

Figure 2

Risk-of-bias summary for the 17 included publications. Linked HAPIN, GRAPHS and CHAP papers are not independent cohorts; judgements reflect the design of the parent trial where applicable.