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Effectiveness of Interventions to Reduce Household Air Pollution and/or Improve Health in Homes using Solid Fuel in Low-and-Middle Income Countries: a Systematic Review and Meta-analysis

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Abstract

Background: Cookstove intervention programs have been increasing over the past two (2) decades in Low and Middle Income Countries (LMICs) across the globe. However, there remains uncertainty regarding the effects of these interventions on household air pollution concentrations, personal exposure concentrations and health outcomes.

Objectives: The primary objective was to determine if household air pollution (HAP) interventions were associated with improved indoor air quality (IAQ) in households in LMICs. Given the potential impact of HAP interventions on health, a secondary objective was to evaluate the effectiveness of HAP interventions to improve health in populations receiving these interventions.

Data sources: OVID Medline, Ovid Embase, SCOPUS and PubMED were searched from their inception until December 2015 with no restrictions on study design. The WHO Global database of household air pollution measurements and Members' archives were also reviewed together with the reference lists of identified reviews and relevant articles.

Study eligibility criteria, participants and intervention:

We considered randomized controlled trials, or non-randomized control trials, or before-and-after studies; original studies; studies conducted in a LMIC (based on the United Nations Human Development Report released in March 2013 (World Bank, 2013); interventions that were explicitly aimed at improving IAQ and/or health from solid fuel use; studies published in a peer-reviewed journal or student theses or reports; studies that reported on outcomes which was indicative of IAQ or/and health. There was no restriction on the type of comparator (e.g. household receiving *plancha* vs. household using traditional cookstove) used in the intervention study.

Study appraisal and synthesis methods: Five review authors independently used pre-designed data collection forms to extract information from the original studies and assessed risk of bias using the Effective Public Health Practice Project (EPHPP). We computed standardized weighted mean difference (SMD) using random-effects models. Heterogeneity was computed using the Q and I2-statistics. We examined the influence of various characteristics on the study-specific effect estimates by stratifying the analysis by population type, study design, intervention type, and duration of exposure monitoring. The trim and fill method was used to assess the potential impact of missing studies.

Results: Fifty-five studies met our *a priori* inclusion criteria and were included in the systematic review. Fifteen studies provided 43 effect estimates for our meta-analysis. The largest improvement in HAP was observed for average particulate matter (PM) (SMD=1.57) concentrations in household kitchens (1.03), followed by daily personal average concentrations of PM (1.18), and carbon monoxide (CO) concentrations in kitchens. With respect to personal PM, significant improvement was observed in studies of children (1.26) and studies monitoring PM for ≥ 24 hrs (1.32). This observation was also noted in terms of studies of kitchen concentrations of CO. A significant improvement was also observed for kitchen levels of PM in both adult populations (1.56) and in RCT/cohort designs (1.59) involving replacing cookstoves without chimneys. Our findings on health outcomes were inconclusive.

Limitations, conclusions and implications of key findings: We observed high statistical between study variability in the study-specific estimate. Thus, care should be taken in concluding that HAP interventions - as currently designed and implemented - support reductions in the average kitchen and personal levels of PM and CO. Further, there is limited evidence that current stand-alone HAP interventions yield any health benefits. Post-intervention levels of pollutants were generally still greatly in excess of the relevant WHO guideline and thus a need to promote cleaner fuels in LMICs to reduce HAP levels below the WHO guidelines.

Systematic review registration number: The review has been registered with PROSPERO (registration number CRD42014009768)

Keywords Developing country, HAP, health improvement, intervention, meta-analysis, systematic review

1. Introduction

Nearly one-third of the world's population use solid fuels such as wood, animal dung, and crop residues as their primary source of domestic energy use (e.g. Bonjour et al., 2013; Balakrishnan et al., 2013; Chafe et al., 2014). Cooking and heating with solid fuel on open fires or traditional stoves emits a complex mixture of organic compounds and gases, which include carbon monoxide (CO), oxides of nitrogen (NOx) and sulphur (SOx), aldehydes, polycyclic aromatic hydrocarbons (PAHs), volatile organic compounds (VOCs), chlorinated dioxins, fine particulate matter (PM), and free radicals (Albalak, 2001; Mishra, 2003). Health problems associated with household air pollution (HAP) from solid fuel/biomass fuel use includes, but is not limited to, respiratory tract infection (Mishra, 2003) exacerbation of inflammatory lung conditions (Gordon et al., 2015), cardiac events (Bruce et al., 2015), asthma (Bruce et al., 2015; Gordon et al., 2015), chronic obstructive pulmonary disease (COPD) (Assad et al., 2015; Bruce et al., 2015; Gordon et al., 2015), low birth weight (Amegah et al., 2014) and tuberculosis (Kurmi et al., 2014).

Cookstove intervention programs have been implemented and studied extensively in Low and Middle Income Countries (LMICs). However, there remains significant uncertainty regarding the effectiveness of these interventions. Rehfuess et al. (2014) and Thomas et al. (2015) recently reported reviews on this subject. Rehfuess et al. (2014) conducted a systematic review and meta-analysis covering the period between 1998 and July 2012. The authors identified 38 studies published in LMICs and ICs and noted reduction in average daily concentrations of the two most commonly measured pollutants: PM and CO. Thomas et al. (2015) conducted a systematic review of studies published up to April 2014. These authors captured almost the same studies previously reviewed by Rehfuess et al. (2014) but the findings from these two reviews were contradictory. The household air pollution field is changing rapidly and new evidence has accumulated since the last review (Thomas et al. 2015). In such a rapidly evolving field there is the need to confirm or refute previous findings. Also timely evaluation of methods and results of studies can help inform public health policy and future studies. It is from these perspectives that we are conducting this systematic review to determine if HAP interventions are associated with improved IAQ in households in LMICs. A secondary objective is to evaluate the effectiveness of HAP interventions to improve health in populations living in LMICs.

2. Methods

2.1Search strategy

This systematic review was carried out according to established methods (NICE, 2012; IRIS, 2012) and reported according to recommendations from the Preferred Reporting Items for Systematic Reviews and Meta-Analyses statement (PRISMA) (2014). A review protocol is reported elsewhere (Quansah et al., 2015).

We performed a systematic literature search of OVID Medline, Ovid Embase, SCOPUS and PubMED databases (Supplementary, search strategy) from their inception until October 2013 and updated our search in December 2015 (Fig.1). Furthermore, the reference lists of identified articles and that of a recent review (Thomas et al., 2015) were searched. Three authors (RQ, SS, and CO) carried out the initial screening of titles and abstracts from the searches. Full papers of potentially relevant publications were located and independently appraised by five reviewers (RQ, CO, SS, FA and IL) to select those satisfying the inclusion criteria.

Study selection

Population of interest

Studies had to be carried out in populations located within LMICs based on the United Nations Human Development Report released in March 2013) (World Bank, 2013). There were no other restrictions on population type.

Type of Intervention

We considered any type of household intervention that was explicitly aimed at improving indoor air quality and/or health by changing or reducing emissions from solid fuel use within the home. Such interventions include for example, changes in stove or heating apparatus, changes in ventilation arrangements and changes in behavior geared towards reducing emission and exposure to cooking smoke. This allowed us to examine the influence of intervention type on study-specific estimates. Interventions targeting for example, deforestation, fire wood use, particle size distribution and cooking time were excluded because they did not address our research questions.

Type of comparisons

Different types of comparators have been used in intervention studies. We aimed to provide a comprehensive evaluation of the evidence and did not impose any restrictions on the type of comparator used in the intervention studies (for example, convenience comparison group, randomized control group, no intervention control, and usual practice control). Studies with and without comparators were included in the review.

Types of outcomes

We assessed both health and exposure outcomes. The primary outcomes were measures of indoor air quality (IAQ), e.g. airborne concentrations of carbon monoxide or fine particulate matter or soot or smoke. We also included biomarkers of exposure to air pollutants in the form of metabolites of poly-aromatic hydrocarbons. Secondary outcome measures were common health indicators and included (but again not be limited to) acute lower respiratory infection, sensory irritation (for example, itchy/watery/sore eyes), cough and high blood pressure (Quansah et al., 2015). Studies that only reported on fuel use, cooking time, climate, and non-IAQ/health related outcomes were excluded.

Type of study

We included randomized controlled trials (RCT or quasi-RCT), or non-randomized control trials (i.e. cohort, case-controlled and cross-sectional studies), or before-and-after studies. We excluded all controlled experimental studies (i.e. both laboratory and field) because they did not qualify as interventions. We further excluded studies conducted in developed countries because they did not answer our research questions.

Types of publications

In order to provide a comprehensive review of the literature we considered both articles in peer-reviewed journals and student theses. Our search included publications in the following languages: English, Spanish, and Chinese.

2.2. Data extraction and risk of bias assessment

Relevant characteristics of eligible studies were extracted and recorded independently by five authors (i.e. RQ, CO, SS, FA and IL). Discrepancies were resolved through discussion. TABLE 1 displays the main characteristics of the eligible studies. Risk of bias was assessed with the Effective Public Health Practice Project Quality Assessment Tool (EPHPP) (1998). The results of the risk of bias assessment tool for each individual study (**Supplemental Table 1**) and the data extraction forms (**Supplemental Table 2**) are available in the supplementary materials.

2.3. Statistical analysis

We anticipated substantial between study variability and we computed standardized weighted mean difference (SMD) for each of our outcomes: personal levels of particulate matter (P-PM) and carbon monoxide (PCO) and kitchen levels of particulate matter (MPM) and carbon monoxide (MCO) using a random effects model. The studies presented mean differences and corresponding exact p-values, or mean difference and their 95% confidence interval, or mean and standard deviation. The mean difference and their corresponding standard error were computed in excel using standard methods (Borenstein et al., 2009; Follmann et al., 1992; Higgins et al., 2010). Heterogeneity was computed using the Q ($p < 0.1$ considered significant), and I^2-statistics (I^2-statistic > 50% indicates high, 25–50% moderate, and < 25% low heterogeneity). We examined the influence of various characteristics on the study-specific effect estimates by stratifying the analysis by: a) population type (children vs. female adult vs. both children and female adult); b) study design (cross-sectional vs. pre-post design vs. RCT); c) intervention type (*plancha* vs. *justa* vs. *patsari* vs. other); d) duration of exposure monitoring (≤24 hours vs. >24 hours). Publication bias was assessed using the Egger test of asymmetry (Egger et al., 1998). The trim and fill method was used to assess the potential impact of missing studies. Statistical analysis was performed using STATA software version 11 (StataCorp, College Station, TX, USA).

3. Results

3.1. Literature Search

Our systematic search of the literature is shown in Figure 1. Fifty-five studies met our *a priori* inclusion criteria and were included in the systematic review. Fifteen studies provided 43 effect estimates for our meta-analysis (Supplementary Table 3). Of the 55 studies, 46 were identified from the searched databases, three were identified from reference lists of relevant studies, with a further six retrieved from a recent review (Thomas et al., 2015). Sixty-eight studies were excluded for reasons given in Supplementary Table 4.

3.2. Study Characteristics

Characteristics of the 55 eligible studies by study design are presented in Tables 1a and 1b. The interventions identified were carried out in three continents: South America (Guatemala (n=12); Honduras (n=2); Nicaragua (n=1); Peru (n=6); and Mexico (n=7)); Asia (Bangladesh (n=1);

China (n=8); India (n=4); Nepal (n=1); Pakistan (n=1); and Africa (Senegal (n=4); Ghana (n=1); Nigeria (n=1); Kenya (n=4); South Africa (n=1); Malawi (n=1); and Rwanda (n=1)). Sixteen of the intervention studies were cross-sectional designs, nineteen were before-and-after designs, eleven were randomized control trials (RCTs), and eight cohort designs. In two studies, two complementary study designs were applied. That is, between-group comparisons based on randomized stove assignment, and before-and-after comparisons within control subjects who used open fires during the trial and received chimney stoves after the trial. The interventions were carried out among female adults population or among children or both population groups. Most of the studies applied a single intervention and these included improved cookstoves, mostly wood burning stoves such as *patsari* cookstove, *plancha* cookstove, improved *justa* stove, OPTIMA cookstove, eco-cookstove, *sukhad* cookstove, ONIL stove, gyapa cookstove and “smoke free stove”. There was one study carried out on the use of biogas digesters, three on solar ovens and one on a switch to ethanol fuel. Other interventions assessed in the studies were: installation of chimneys (n=1); health education campaign (n=1); and behavioural interventions such as education and counselling on cooking outdoors, opening windows/doors and reducing the amount of time the child spends in the kitchen (n=1). The funding model for the intervention was often poorly described. Some studies indicated that the improved cookstoves were offered for free but most studies failed to report the delivery mechanism and financing of the intervention.

Several outcomes were reported in the intervention studies and we classified them into personal exposure outcomes and micro-environment exposure outcomes (Table 1a); and health outcomes (Table 1b). Personal exposure outcomes were outcomes measured at the individual level using for example, personal monitors attached to individuals clothing, measurement of metabolites in urine and so on. Micro-environment exposure outcomes refer to particulate matter (PM) and/or carbon monoxide (CO) measured from a fixed point in the home, most commonly in the kitchen. Health outcomes reported in the identified studies were generally sparse and heterogeneous.

3.3. Personal Exposure Outcomes

Twenty-eight studies reported on personal indicators of indoor air quality (IAQ) and are described below (Table 1a).

3.3.1 Studies on Personal Particulate Matter

Of the 11 studies that reported on daily average personal particulate matter (P-PM), five did not provide sufficient data for our quantitative analysis and were therefore analyzed qualitatively. Cynthia et al. (2008) studied the impact of improved wood burning stove (Patsari) in reducing personal exposure to $PM_{2.5}$ and CO in 60 homes in rural Michoacan in Mexico. The daily average personal 24-hr $PM_{2.5}$ was 0.29 mg/m^3 for women using a traditional open fire. Installation of the *Patsari* cookstove resulted in a 35% reduction in the median 24-hr personal $PM_{2.5}$. The corresponding reduction in 48-hr personal CO exposure was 77%. Li et al. (2011) investigated whether replacement of open pit stoves by improved stoves equipped with a chimney reduced exposure to PAHs, $PM_{2.5}$ and CO exposure in rural Peru. Two stove types were evaluated (A, n=30; B, n=27). Installation of improved cookstoves reduced personal exposures by 47-74% and urinary hydroxylate PAH metabolites (OH-PAHs) by 19-52%. Mukhopadhyay et al. (2012) assessed two brands of commercial advanced cookstoves (i.e. Philips and Oorja) with small blowers to improve combustion. These advanced cookstoves produced reductions in personal $PM_{2.5}$ and CO.

In total, seven effect estimates were provided by five studies for our quantitative analysis of P-PM (Supplementary Table 1). Of this, Naeher et al. (2000) provided data on both the populations of children and their mothers. Fitzgerald et al. (2012) used two different improved cookstoves, referred to in the forest plot as ICS1 and ICS2. The overall summary SMD was 1.18 (95% CI: 1.05, 1.32) (Fig 1). High between-study variability was observed (I^2-index=89.7%, P=0.000, Q-statistics (n=7) =58.17). In the stratified analysis, moderate to large improvements in average daily personal PM was observed (Fig. 2 and Table 1). With the exception of studies on *plancha* cookstoves and those studies monitoring personal PM levels for less than 24-hr, heterogeneity persisted (Table 2). The Egger test of small study effects showed no evidence of publication bias (p=0.123). However, adjustment for publication bias by the trim and fill method imputed three studies and the overall summary SMD was reduced marginally (1.08; 95% CI: 0.95, 1.22) and heterogeneity persisted (91.66 (10), p=0.00, 99.2%) (Table 2).

3.3.2. Studies on Personal Carbon monoxide

Twenty-one intervention studies reported daily average personal carbon monoxide levels (PCO). Clark et al. (2013) examined the impact of a cleaner-burning cookstove intervention among non-smoking female cooks and measured indoor $PM_{2.5}$, CO and PCO concentrations. Large mean reduction concentrations were observed for all exposure metrics following installation of a subsidized eco-stove. Diaz et al. (2007) observed a median reduction in exhaled breath CO in the intervention group compared to the control group following the installation of improved *plancha* stoves. Rollin et al. (2004) conducted a feasibility study to assess the impact of reduction of IAQ on acute lower respiratory infection in infants. When mean concentrations of CO were compared between electrified and un-electrified dwellings, there was strong evidence (p=0.0004) that the mean concentrations of log (CO) in the kitchen was higher in the electrified areas (1.25 vs. 0.69) and strong evidence (p<0.0001) that the mean concentration of log (CO) on the child was higher in electrified areas (0.83 s. 0.34). Beltramo et al. (2013) did not observe any evidence that solar ovens reduced exposure to carbon monoxide.

Altogether seven studies provided 10 effect estimates for our quantitative analysis of PCO (Supplemental Material, Table S1). The overall summary SMD was 0.81 (95% CI: 0.63, 1.05) and substantial heterogeneity was noted (I^2=99.8%, p=0.00, Q-statistics (11) =5089.79). Slight to moderate improvement in IAQ related to PCO was observed across study level characteristics (Fig. 3 and Table 2) and substantial heterogeneity persisted. Egger small study effect (p=0.415) and the trim and fill did not show any evidence of publication bias (Table 2).

3.2. Micro-environment Exposure Outcomes

A total of 26 studies reported micro-environment indicators of HAP from solid fuel use and are described below (Table 1a).

3.2.1. Studies on Micro-environment Particulate Matter

With respect to particulate matter (PM), 10 studies provided 13 effect estimates for our quantitative analysis. Masera et al. (2007) evaluated the impact of improved *patsari* cookstoves in the Purepecha region of Michoacin state in Mexico. Average concentrations of CO and $PM_{2.5}$ were measured both before and after the introduction of the improved cookstove at 1- minute intervals for 48 hrs. $PM_{2.5}$ and CO were reduced by 67% and 66% respectively. In the study by Chowdury et al. (2013), 24-hr $PM_{2.5}$ and CO concentrations in the kitchen ranged between 0.15-0.71 ppm for $PM_{2.5}$ and 3.0-11 ppm for CO when using the traditional cookstove; and between 0.08-0.18 ppm for $PM_{2.5}$ and 0.7-5.5 ppm for CO when using improved cookstoves. In three Andean communities within the Santiago de Chuco province of Peru, two different models of improved cookstoves (i.e. stove 1 and stove 2) were installed in 64 homes. In the community receiving stove 1, baseline 48-hr personal exposure and kitchen concentrations of $PM_{2.5}$ were 116.4 and 207.3 μg/m^3, respectively; and 48-hr hour personal and kitchen CO levels were 1.2 and 3.6 ppm respectively. After introducing the new stove to this community, personal exposure and kitchen concentrations of $PM_{2.5}$ reduced to 68.4 and 84.7 μg/m^3 respectively; and that of personal and kitchen CO levels to 0.4 and 0.8 ppm respectively, representing reductions of 41.3%, 59.2%, 69.6% and 77.7%. In the two communities receiving stove 2, corresponding levels were 126.3 μg/m^3, 173.4 μg/m^3, 0.9 ppm , and 2.6 ppm before the installation of the stoves, and they reduced to 58.3, 51.1 μg/m^3 and 0.6, 1.0 ppm. Overall, homes receiving stove 2 saw reductions of 53.8, 70.5, 25.8 and 63.6%.

In the meta-analysis of 13 effect estimates from 10 studies (Supplementary Table 3), the overall summary SMD was 1.57 (1.22, 2.01). High statistical heterogeneity was observed (I^2=98.2%, p=0.00, Q-statistics (13) =661.63). A slight to large improvement in average kitchen levels of PM (MPM) was noted across study level characteristics and with the exception of studies looking at the exposure of children substantial between-study variability persisted (Table 2). A test of publication bias showed no evidence of small study effects (p=0.184). Again this was not confirmed by the trim and fill method which showed a decline in the summary SMD (1.16; 0.85, 1.53) (Table 2).

3.2.2. Micro-environment Carbon Monoxide

In the study by Chengappaa et al. (2007) in the Bundelkund region of India, CO was measured for a 48-hr period in 60 rural kitchens before and after installation of a *sukhad* improved cookstove. One year after the intervention, CO concentrations were reduced by 70% (p<0.001) and 44% (p<0.01) respectively. Khushk et al. (2005) reported levels of 15.4 ppm for smoke-free stoves compared to 28.5 ppm for traditional cookstoves. A 3-stage risk reduction program was applied by Torres-Dorsal et al (2007). These steps included (i) removal of indoor soot adhered to roofs and internal walls (ii) paving dirty floors and (iii) introduction of a new wood stove with a metal chimney. Blood caroxyhaemoglobin (% COHb) and urinary 1-OHP levels were measured before and after the intervention. In the 20 participants the levels of COHb reduced by an average of 2.5% one month after the intervention. A similar observation was noted for 1-OHP levels.

In all, eleven studies provided 13 effect estimates for our quantitative analysis of kitchen levels of CO. The overall summary SMD was 1.21 (0.89, 1.66; I^2=99.5%, p=0.00, Q-statistics (13) =2578.71) (Fig 4). A slight to large improvement in indoor air quality (IAQ) related to average kitchen levels of CO (MCO) was noted across study level characteristics and, except for studies scoring weak on the Effective Public Health Practice Project Quality Assessment Tool

(EPHPP), substantial heterogeneity persisted. There was no evidence of the small study effect (p=0.154) and this was confirmed by the trim and fill method (1.03; 0.76, 1.41) (Table 2).

3.3. Health Outcomes

A total of twenty-nine studies reported health outcomes. Of these, 10 studies reported on respiratory health problems alone, 10 studies on non-respiratory health problems, and 8 studies on both respiratory and non-respiratory health problems (Table 1b). Due to the sparse nature of individual health outcomes, it was not possible to conduct a meta-analysis. These studies are discussed below.

3.3.1. Respiratory Health Problems

Different definitions of asthma were applied in the studies and this included asthma based on lung function measurements and self-reported symptoms of asthma such as wheezing, cough, phlegm production, difficulty breathing, runny or stuffy nose and chest tightness. Beltramo and Levine (2013) compared respiratory symptoms in 465 women who purchased solar ovens and 325 control women. The authors did not observe any evidence that the use of solar ovens reduced the incidence of cough and/or sore throat. They concluded that their study was a policy success because it halted a nationwide proposal to roll-out solar ovens. Women who reported using *patsari* cookstoves most of the time compared to those using open fire experienced significantly lower levels of cough and wheezing (Romieu et al., 2009). Significant reductions in several respiratory symptoms such as dry cough, chest tightness, difficulty breathing and runny nose were observed in mothers and children in homes that used improved cookstoves compared to those that used traditional cookstoves in Guatamela (Albalak et al., 2001).These findings were confirmed by Ludwinski et al. (2011) who reported a 48.6% and a 63.3% reduction in respiratory symptoms in mothers and children respectively, and in Romieu et al. (2009) and Dohoo et al. (2012). However, no significant improvement in measures of lung function was observed in users of *plancha* (Smith-Sivertsen et al., 2009), *justa* (Clark et al., 2009) and *Gram vikas* (Hanna et al., 2012) cookstoves. In a parallel randomized controlled trial in Guatemala, Smith et al. (2011) investigated whether an intervention to lower indoor wood smoke emissions would reduce pneumonia in children. Pneumonia was defined as physician-diagnosed pneumonia, without use of a chest radiograph or fieldworker-assessed pneumonia (all and severe) and seven other conditions of physician-diagnosed pneumonia. Significant reductions in the intervention group for three severe outcomes: fieldworker-assessed, physician-diagnosed, and RSV-negative pneumonia were noted. In the exposure-response analysis, a 50% exposure reduction was significantly associated with a reduction in physician-diagnosed pneumonia (RR 0·82; 0·70, 0·98). Hosgood et al. (2002) evaluated lung cancer mortality reduction after changing from a traditional smoky stove to an improved cookstove in China. A significant reduction in lung cancer mortality was observed in women and men who changed to improved cookstoves compared to those who did not change. Reductions in lung cancer incidence (Lan et al. 2002) and pneumonia mortality (Shen et al. 2009) were also observed in similar populations following a switch to an improved cookstove .

3.3.2. Non-respiratory Health Problems

Household air pollution (HAP) intervention studies on non-respiratory symptoms have been inconclusive. Whereas Jary et al. (2014) did not observe any significant improvement in headache and back pain following the use of wood burning clay improved cookstove for 7 days, Burwen and Levine (2012), Diaz et al. (2008) and Alam et al. (2006) noted marginal to significant improvements in these indicators. A small number of studies have observed improvements in blood pressure (Hanna et al., 2002; McCracken et al., 2007) and low birth weight (Thompson et al., 2011) following the use of improved cookstoves.

4. Discussion

This systematic review and meta-analysis of HAP interventions conducted in Low and Middle Income Countries (LMICs) aims to address the question, whether HAP interventions to improve indoor air quality (IAQ) and/or health in homes using solid fuel for cooking and heating are effective. Fifteen of the 55 studies were eligible for quantitative analysis. The largest reduction in HAP was particulate matter (PM) levels in the kitchen, followed by daily personal average levels of PM, levels of carbon monoxide (CO) in the kitchen and daily personal average levels of CO. Slight to large improvement related to study level characteristics in average kitchen levels of PM and CO as well as average daily levels of PM and CO. The findings from the qualitative analysis corroborate that of the quantitative analysis. Findings on health outcomes were inconclusive. We also observed high statistical between study variability in the study-specific estimates and this persisted in most cases in the stratified analysis. Thus, caution is warranted in concluding that HAP interventions - as currently designed and implemented – support reductions in the average kitchen and personal levels of PM and CO.

4.1. Validity issues

Our study has a number of strengths. We searched several databases and used secondary references that were cited in the original articles and a recent review. Five reviewers independently assessed the articles based on *a priori* eligibility criteria. We also followed the methods of the National Institute of Healthcare Excellence (NICE) and the National Academy of Science review of the EPA Integrated Risk Information System process; and reported the findings according to recommendations by the Preferred Reporting Items for Systematic Reviews and Meta-analysis statement. We also evaluated the possibility of publication bias using Egger's test of asymmetry and the trim and fill method.

We acknowledge a number of limitations in our study. We applied the Effective Public Health Practice Project Quality Assessment Tool (EPHPP) to assess the risk of bias, but due to a lack of data we were unable to explore the influence of each of the six domains on our overall summary SMD. Nevertheless, we applied a single global rating score to assess the influence of risk of bias on overall summary SMD and the majority of the studies were rated as weak on this scale. How well a study fairs on the scale is dependent on the amount of information available in the article for evaluation. Thus, a well conducted study may score poorly on the scale because the author(s) failed to provide adequate information when writing up their manuscript. As a result, interpretation on how well a study does on the EPHPP should be carried out with caution. We also observed high statistical between study variability in the study-specific estimates and this persisted in most cases in the stratified analysis. Thus, caution may be warranted in concluding that HAP interventions as currently designed and implemented support reductions in the average kitchen and personal levels of PM and CO.

Furthermore, of the studies meeting our *a priori* inclusion criteria, the majority came from cross-sectional studies in which it was not possible to judge the temporal relation between HAP intervention and our outcomes of interest. However, the generally consistent results from the different study designs and study level characteristics support the hypothesis that HAP interventions reduce average kitchen levels of PM/CO and daily average personal levels of PM/CO. A variety of exposure outcomes and interventions were reported in the original studies. With respect to the outcomes we carefully segregated them into average daily PM/CO personal levels and levels of PM/CO in the kitchen and this allowed us to study the impact of HAP intervention on each outcome. Due to practical, ethical and budgetary constraints the studies have typically been small in size with a very small proportion of them being RCT design. The monitoring period tended to be short and the duration of measurement was inconsistent across the studies making comparison difficult. We also carefully categorized the monitoring period into 2 levels (i.e. $<$24hrs vs $\geq$24hrs) to understand how daily exposure variability impacts on the overall SMD. Most of the studies also had qualitative components and these did not contribute to the evaluation of the impact of HAP intervention on our outcome of interest. The studies generally differed on baseline indoor PM/CO and in most cases post-intervention measurements were above the WHO guideline.

4.2. Comparison with previous studies

Two previous reviews: a WHO report (Rehfuess et al., 2014) and a systematic review by Thomas et al. (2015) were available on this subject. In the first study, Rehfuess et al. (2014) conducted a systematic review and meta-analysis to answer the question whether improved cookstoves in everyday use, compared to traditional cookstoves are effective in reducing average concentrations of, or exposure to, particulate matter and carbon monoxide among households in. The authors identified 38 studies and reported average kitchen levels of PM and CO reducing by 38 to 82%. Reductions of average personal levels of PM and CO ranging between 47 to 76% were also observed. In the second study, Thomas et al. (2015) conducted a qualitative review of epidemiologic evidence that improved cookstove interventions reduced household air pollution and improved health. They searched 10 databases and identified almost the same studies included in Rehfuess et al. (2014) but failed to reach any conclusion. .

We identified **55** studies, and across these household air pollution (HAP) interventions resulted in improvement in daily average personal and average kitchen levels of particulate matter by 24% and 18% respectively. A much smaller (3%) improvement in average kitchen levels of carbon monoxide was observed.

This observation was also observed across different study designs, population types and monitoring duration. Our findings are consistent with the WHO report (Rehfuess et al., 2014), although ours is more comprehensive as we include 17 additional studies. We observed that the performance of the *Plancha* and the *Justa* on average daily personal levels of PM was broadly similar. However, both the *Justa* and the *Patsari* outperformed the *Plancha* in reducing average kitchen levels of PM/CO. The reason for this later observation is not clear, but the former observation corroborates the finding of a WHO report (Ruhfuess et al., 2014) which suggests a substantial improvement of personal PM levels with stoves with chimneys. In spite of the observed improvement in average PM and CO levels, post-intervention concentrations of PM/CO are much higher than the WHO guidelines for these air pollutants.

Our findings have important public health implications for populations living in Low and middle-income countries (LMICs) given the tremendous health burden of household air pollution (HAP) (Amegah and Jaakkola, 2015) and the fact that the total number of users of solid/biomass fuels in these countries have not declined (Bonjour et al., 2013). Our findings further suggest that current stand-alone HAP interventions yield little if any health benefit. Thus, there is the need to re-examine the ways in which interventions are designed and implemented in homes in LMICs. Multi-faceted HAP interventions could offer an opportunity to reduce exposures to HAP that could have marked public health impact in LMICs. Cleaner fuels such as liquid petroleum gas, ethanol, solar and electrification may reduce indoor emission levels substantially. However, to date only five qualitative studies (1 on LPG, 2 on ethanol, 1 on electrification and 1 on solar) have evaluated the impact of cleaner fuel on HAP or health. An ongoing HAP randomized trial in Ghana may shed light on the impact of cooking with cleaner fuels on health/IAQ (Jack et al., 2015).

Our findings on health outcomes were inconclusive, supporting the findings of a previous systematic review (Thomas et al., 2015) and recent large intervention studies (Bensch and Peters, 2012; Hanna et al., 2012). The exposure-response (E-R) curve for most health effects is poorly understood but data for cardio-pulmonary and cardiovascular effects from outdoor air pollution, second-hand tobacco smoke and smoking studies tend to suggest that the curve, at least for PM, is steep and may plateau at moderate PM doses (Pope, 2009). Such an E-R curve would then suggest that minimal or no health improvements may accrue from the moderate HAP improvements seen by some of the studies reported in this review especially when the improvements achieved are within the upper, plateau part of the curve. Behavioral change interventions have the potential to reduce average concentrations of particulate matter and carbon monoxide by 20-98% in laboratory settings and by 31-94% in field setting (Barnes, 2014). Behavioral strategies may include cooking outdoors, reducing time spent in the cooking area, keeping the kitchen door/widows open while cooking, avoiding leaning over the fire while cooking, avoiding carrying children while cooking and keeping children away from the cooking area. Opportunities to educate communities on reducing household air pollution exposure include durbars, festival celebrations, religious meetings and child welfare outreach clinics. Community health workers are the fulcrum of the health system in many developing countries and represent important change agents (Leon et al., 2015). Adoption and sustainability are big issues for most HAP interventions. There is a need for qualitative research on the barriers and facilitators for adoption and continued use. There is also a clear need for a standard method to evaluate HAP interventions. A Standard Operating Procedure for stove evaluation programs that included sections on HAP assessment, health assessment and intervention adoption/use assessment is required for the HAP research community.

5. Conclusions

Our study suggests improvement in average PM/CO concentrations at the personal and micro-environment level occur following HAP interventions. Despite this, post-intervention levels are generally still far above the WHO guidelines for PM and CO, and perhaps because of these continued high exposures, the study finds little evidence of improvements in health outcomes. There is a need to develop effective interventions in LMICs that are capable of reducing HAP levels below the WHO guidelines, particularly in many communities in the developing world where adoption of improved cookstoves continues to prove challenging. There is also a need for a

Standard Operating Procedure for stove evaluation programs that include sections on HAP assessment, health assessment and intervention adoption/use assessment for the HAP research community.

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