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Review article

Health effects of household air pollution related to biomass cook stoves in resource limited countries and its mitigation by improved cookstoves

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ABSTRACT

Background: Household air pollution (HAP) related to cooking is associated with significant global morbidity and mortality. An estimated three billion people worldwide are exposed to cooking related HAP caused by solid fuel combustion. This exposure is highest for the vulnerable population of women and children resulting in significant cumulative health effects.

Methods: A literature review was conducted for health effects of household air pollution related to biomass cookstoves in resource limited countries and to evaluate the effect of improved cookstoves on these health effects. We searched PubMed, Embase and Cochrane Library. We conducted searches in January 2018 with a repeat in February 2020. We included only studies conducted in resource limited countries, published in English, irrespective of publication year and studies that examined the health effects of HAP and/or studied the effects of improved cookstove (IC). Two authors independently screened journal article titles, abstracts and full-text articles to identify those that included the following search term: biomass cookstoves and health risks. We also assessed the limitations of IC with barriers to their uptake.

Results: Health effects associated with HAP mostly include increased blood pressure (BP), dyspnea, childhood pneumonia, lung cancer, low birthweight and cardiovascular diseases. Being a global problem with divergent environmental factors including wide variety of fuel used, housing condition, foods prepared, climatic condition and social factors; most solutions though efficient seems inadequate. Improved cookstove (IC) mitigates emissions and improves short term health, though few randomized long-term studies could substantiate its longstanding continuance and health benefits.

Conclusion: There is ample data about the health effects of HAP, with some benefit with IC intervention for elevated blood pressure, dyspnea symptoms, mutagenicity and cardiovascular diseases. IC does not have any benefit in pregnancy outcomes or children health.

Background: Approximately three billion people worldwide are exposed to HAP from cooking with solid fuels like wood, charcoal, coal, dung, and crop residues(Bonjour et al., 2013). Two-thirds in South Asian and African countries cook with solid fuels and almost all of the 2.6 million estimated premature deaths attributed to HAP exposure occur in low- and middle-income countries thus making HAP an important reversible environmental risk factor for diseases in resource limited countries(Arku et al., 2018). A study on global atmospheric impacts of residential fuel burning found emissions like fine particulate matter with aerodynamic diameter < 2.5 µm ($PM_{2.5}$), organic compounds and black carbon are dominated by transport in North America, by open burning in Africa and by residential solid fuels in Asia(Bond et al., 2004). Household air pollution related to cooking is henceforth termed HAP. Fuelwood extraction for cooking also contributes to forest degradation and deforestation(Menghwani et al., 2019). HAP is caused by inefficient burning of solid biomass fuels has multiple direct adverse impacts on human health, especially amongst young children and their mothers. Possible related acute health effects include respiratory and eye irritation, cough, headache, acute lower respiratory infection and severe pneumonia in children. While longer term exposure has shown to be associated with adverse birth outcome including stillbirths, low birth weight, and preterm births; and increased prevalence of several chronic diseases including chronic obstructive pulmonary disease (COPD), diabetes, hypertension, cardiovascular disease, stroke, lung cancer and other types of neoplasia(Gibbs-Flournoy et al., 2018). According to the 2013 Global Burden of Disease Study (GBD) assessment, between 3 and 5 percent of the GBD in terms of disability-adjusted life years (DALYs) is attributed to HAP, about one-third in children less

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than age five years of age and the rest in the adult population. HAP is ranked among the top risk factors examined in the GBD assessments and is the single most significant environmental health risk factor globally (Smith and Pillarisetti, 2017). At a country level with resource limitations, among all risk factors contributing to ill health in India, exposure to HAP from cooking ranks second for mortality. HAP causes approximately 925,000 premature deaths yearly and 25 million lost DALYs per year (Collaborators, 2015). Experimental non-human studies show acute exposure to HAP emissions results in robust proinflammatory cytokine production, neutrophilic inflammation, airway resistance and hyperresponsiveness. These effects were significantly higher in mice exposed to particulate matter (PM) from cow dung. Contrarily, eosinophilic inflammation, PM-specific antibody responses and alveolar destruction were highest for sub-exposure to wood PM. These effects is possibly mediated by Toll Like receptor and Interleukin-1R pathways (Sussan et al., 2014). Further studies show traditional cookstove exposed mice developed acute lung injury, possibly because of the inhaled high concentrations of hazardous air toxicants (e.g., 1,3-butadiene, toluene, benzene, acrolein) in association with the higher amount and percent organic carbon content of the particulate mass. Similarly, mice exposed to HAP with traditional cookstove vs. improved cookstove showed decrease emitted particulate mass concentrations by 60–80% with corresponding decrease in particles visible within murine alveolar macrophages with improved cookstoves(Gibbs-Flournoy et al., 2018).

It is still uncertain if an improved biomass based cookstove with or without ventilations is a health intervention or another kitchen appliance. Evidence of benefit and user perception is heterogenous(Cundale et al., 2017). Figs. 1 and 2 shows traditional and improved cookstoves. Even though, estimates show an overall declined in the use of biomass fuel over the coming years, reliance on biomass fuel as a major source of energy will remain substantial in the foreseeable future because of issues with affordability(Dutta et al., 2007; Mundial, 1996). Most of the region affected by HAP are undergoing epidemiologic transition and economic development leading to the rapid uptake of modern cookstoves, hence the global efforts to deliver clean cookstoves is progressing rapidly. The significance of this action is based on calculating the avoidable burden of HAP, defined as "the reduction in the future burden of disease if the current or future exposure to a risk factor is reduced to a counterfactual distribution." A considerable share of these households globally are also adopting gas or electric stove (cleaner fuels). South Asia (3.6% of total DALY) and Sub-Saharan Africa (3.9% of total DALY) have more scope for HAP intervention as per this framework to decrease the HAP associated avoidable burden(Kuhn et al., 2016). Thus, there is still scope for HAP improvement in these regions in spite of the ongoing social, economic and health transitions that constantly alters the disease and risk factor landscape for HAP(Kuhn et al., 2016).

Fig. 1. Newer improved cookstoves (Courtesy Environmental Protection Agency).

Fig. 2. Traditional cookstove (Courtesy CQuestCapital).

Rationale for literature review: The World Health Organization (WHO) had set an annual average target exposure level of 10 μg/m^3 for PM $_{2.5}$. However, the PM $_{2.5}$ exposure related to solid fuel use for cooking may be as high as 200–300μg/m^3(Arku et al., 2018). HAP is mostly caused by poor efficiency of energy conversion to heat (incomplete combustion) in most of the solid-fuel stoves, with almost 6%–20% of the fuel-carbon is converted to toxic substances(Mortimer et al., 2012). A study to understand the impact of HAP on health characterized the HAP emissions including PM $_{2.5}$ and carbon monoxide (CO) associated with biomass cookstove. According to the 21 h continuous data gathering, the average stove-influenced concentrations for PM $_{2.5}$ was 3469 (3350–3588) μg/m^3 and 21.8 (21.1–22.6) parts per million (ppm) for CO(Chen et al., 2016). While another rural study on households using traditional cookstove, showed the 48-h average concentrations to be 1250 μg/m3 for PM $_{2.5}$and 10.8 ppm for CO(Dutta et al., 2007). Similarly, the concentration of particulate matter less than 10 μm in size due to biomass fuel usage could reach even up to 30,000 μg/m^3 in rural homes during the peak period of cooking(Sussan et al., 2014). Significant ultra-fine particle exposure in children results from cooking, contributing to almost 64% of the daily exposure from firewood combustion in houses using traditional mud cookstoves (Wangchuk et al., 2015). A significant amount of this exposure occurs in the vulnerable population prone to health problems including women and small children. Research had shown interventions decreasing emissions without necessarily attaining WHO target results in 20%–50% decrease in risk of several health-related outcomes(Bruce et al., 2015). The most common emissions causing health problems are PM $_{2.5,}$ CO and polyaromatic hydrocarbons (PAH). These emissions can be modified by ventilation and fuel type(Leavey et al., 2017). IC were developed to improve fuel efficiency and ventilation during cooking. Improved cookstoves have decreased personal exposure to PM $_{2.5,}$ CO and PAH(Quansah et al., 2017). Launched in September 2010, the Global Alliance for Clean Cookstoves is a public-private initiative by United Nations Foundation to achieve the goal of 100 million homes adopting clean cooking technology by 2020(Mortimer et al., 2012). Research suggests acquisition of stoves does not necessarily ensure sustained long-term use. Despite continual efforts, recurrent attempts have failed to develop conceptual models of household energy use behavior thus impeding the transition to cleaner cooking fuels/stove. Consequently, it is estimated that over 700 million people in South Asia could still rely on solid fuels by 2030(Menghwani et al., 2019). Challenges to adoption of cleaner fuels and IC include cost feasibility, stove sustainability, fuel access and cultural acceptance(Wolf et al., 2017). Confounding to these issues further other attributes like baseline type of stove ownership in a community, female literacy rate, decision making options of women in household, access to biomass (wood, dung, crop residues) and uses of biomass (heating, cooking) plays a key role in adoption of improved cookstove/fuel(Menghwani et al., 2019). These factors obscures the clear benefits of IC in HAP. Nevertheless, making progress though the energy ladder towards cleaner fuels and improved cookstoves would result in improved health(Ojo et al., 2015). The objectives of the review are:

- Brief review of burden of HAP related to solid fuel cookstove and major pollutants released by solid fuel cookstoves
- Health effects of HAP associated with solid fuel cookstoves
- Role of improved cookstove on HAP, disadvantages; and barriers to their uptake

1. Methods

For the literature review, In January 2018, we electronically searched the PubMed database for the term cookstove, with no date restrictions using a detailed search strategy and no language restrictions. Studies without English translation were excluded. Cookstove is not available as a MeSH term. We included cohort, case-control, cross-sectional studies, conference abstracts, editorials and reviews. We excluded case reports and studies related to ambient air pollution. All data cited confirmed to Helsinki Declaration on human experiments. Study titles and abstracts were screened, and 23 articles met the objectives of the review. Full text of these articles was downloaded and reviewed further (Appendix A: Articles included from 2018 search).

We repeated the literature search in February 2020 to update the search results, with no restrictions on article publication date.

Search Strategy: With guidance from a medical librarian, we conducted a systematic search on February 19, 2020, with no restrictions on article publication date. We searched PubMed/Medline, Embase and Cochrane Library. The search strategy included the following terms and medical subject headings: Biomass Cookstoves and Health Risks.

Study inclusion and exclusion criteria: We limited our search strategy to only studies published in English. We included (1) randomized controlled trials (RCTs), cohort studies, case-control studies, observational studies and studies with pre–post design; (2) studies conducted in resource limited countries; (3) studies that addressed the relationship between biomass cookstove use and human health effects and/or (4) studies with improved cookstove intervention. We excluded studies presenting study protocols and studies for which full text articles were not available.

Article selection, data extraction and analysis: Two independent reviewers reviewed and selected eligible articles based on the selection criteria outlined above. Articles were deemed relevant for inclusion by initially scanning the titles and abstracts. If the criteria were not easily identifiable from the titles and abstract, the article was included, and a full article review was then conducted to confirm eligibility. The second round of screening comprised a more in-depth evaluation of each article. We downloaded the full-text articles and reviewed them for eligibility. Eligible studies were examined for study location, effect of HAP on health and/or improved cookstove intervention. We resolved discrepancies by discussion.

Study quality assessment: Two authors individually assessed the risk of bias of each study that met the inclusion criteria. The “Quality Assessment Tool for Quantitative Studies” developed by the Effective Public Health Practice Project (EPHPP) was utilized for assessing study quality and for doing knowledge synthesis. The study components graded for quality includes (1) presence of selection bias, (2) study design, (3) confounders, (4) blinding (if applicable), (5) data collection method and (6) withdrawals or drop-outs. Discrepancies were resolved by discussion. We extracted all data using a Google form designed based on eligibility criteria. Please refer to Appendix B and C for details of study quality assessment. Fig. 3 shows the Consort flow diagram.

Results and Discussion: Most studies were observational studies and the outcome measured were objective than subjective. Very few studies were randomized. 31 studies were of moderate quality in study design though 45.5% studies had a global score of strong quality in the study quality assessment.

1.1. Major pollutants released by solid fuel cookstoves

A brief summary of the major HAP emissions and factors affecting HAP is provided in Table 1. $PM_{2.5}$, CO and PAH being major pollutants associated with HAP have significant health effects.

2. Health effects of the pollutants released by solid fuel cookstoves and effect of improved cookstove

2.1. Blood pressure

Health effect: A study by Baumgarter et al. found an average increase in SBP of 4.1 mm Hg (95% CI 1.5–6.6) for each unit log of $PM_{2.5}$ among women over 50 years with little effect on SBP in women aged 25–50 years(Baumgartner et al., 2011). Studies have been replicated in pregnant women where higher BP were seen with higher exposure to HAP though the conclusions from the study are uncertain because BP among pregnant women tends to vary by falling initially and rising in third trimester(Alexander et al., 2017). For the long-term effect of HAP, a recent large study from China found a similar increase of 1.33 mm Hg (0.04–3.56) for SBP using an estimated prior three-year average of $PM_{2.5}$ level and the odds ratio for hypertension was 1.14 for each 10 μg/m^3 increase of ambient $PM_{2.5}$(Lin et al., 2017). In the study by Arku et al., in random effects meta-analysis of the country specific estimates, the pooled effects across all countries showed that primary cooking with solid fuels was associated with 0.58 mm Hg higher SBP compared to clean fuels. In the same study, rural women cooking with solid fuels had 16% higher odds of having hypertension compared to those using electricity or gas; though the odds were not different in urban women. Being a country level analysis, proxy indicators for HAP exposure were used and may not take into account a number of factors that might affect both actual HAP exposure and measured BP, including information on cooking time, kitchen type, stove technology, ventilation, sodium intake or other dietary influences, physical activity and ambient temperature; which have been shown to be linked to the prevalence of hypertension(Arku et al., 2018).

Ambulatory BP monitoring has been found to be feasible in cookstove studies(A. Quinn et al., 2015). As an extension, SToVES study enrolled 48 young, healthy participants to receive six 2-h controlled treatments of pollution from five different cookstoves and a filtered air control. Pulse wave velocity (PWV), central augmentation index (AIx), and central pulse pressure (CPP) measurement were taken after each treatment at 0, 3, and 24 h. PWV and CPP were marginally higher 24 h after all cookstove treatments compared to control. The study data may be skewed since the study was not done in resource limited country and the exposure was not chronic. The clinic significance of this finding is uncertain though CPP, PWV and AIx are proxy markers for elevated blood pressure and worse cardiovascular outcomes(Walker et al., 2020). In the same study, at 24 h after exposure, mean systolic pressure was 2–3 mm Hg higher for all treatments compared with control except for the rocket elbow stove. HAP may be detrimental to cardiovascular health and high blood pressure, even at low $PM_{2.5}$ levels(Fedak et al., 2019). Blood pressure also seems to be more closely associated with black carbon levels than PM levels and is affected by the exposure to motor vehicle emissions(Baumgartner et al., 2014).

Mitigation by IC: In an intervention study by McCraken et al., the IC group had an average 3.7 mm Hg lower SBP and 3 mm Hg lower diastolic blood pressure (DBP) in the intervention group as compared to controls(McCracken et al., 2007). Other similar intervention studies for IC had shown benefit in the form of lower blood pressure (BP) in non-pregnant women of age group over 40 years(Baumgartner et al., 2011; Clark et al., 2013) (Young et al., 2019). Similarly, meta-analysis had shown switching to clean cooking fuels reduced the odds of having hypertension by about 16% among rural women. Systematic review has

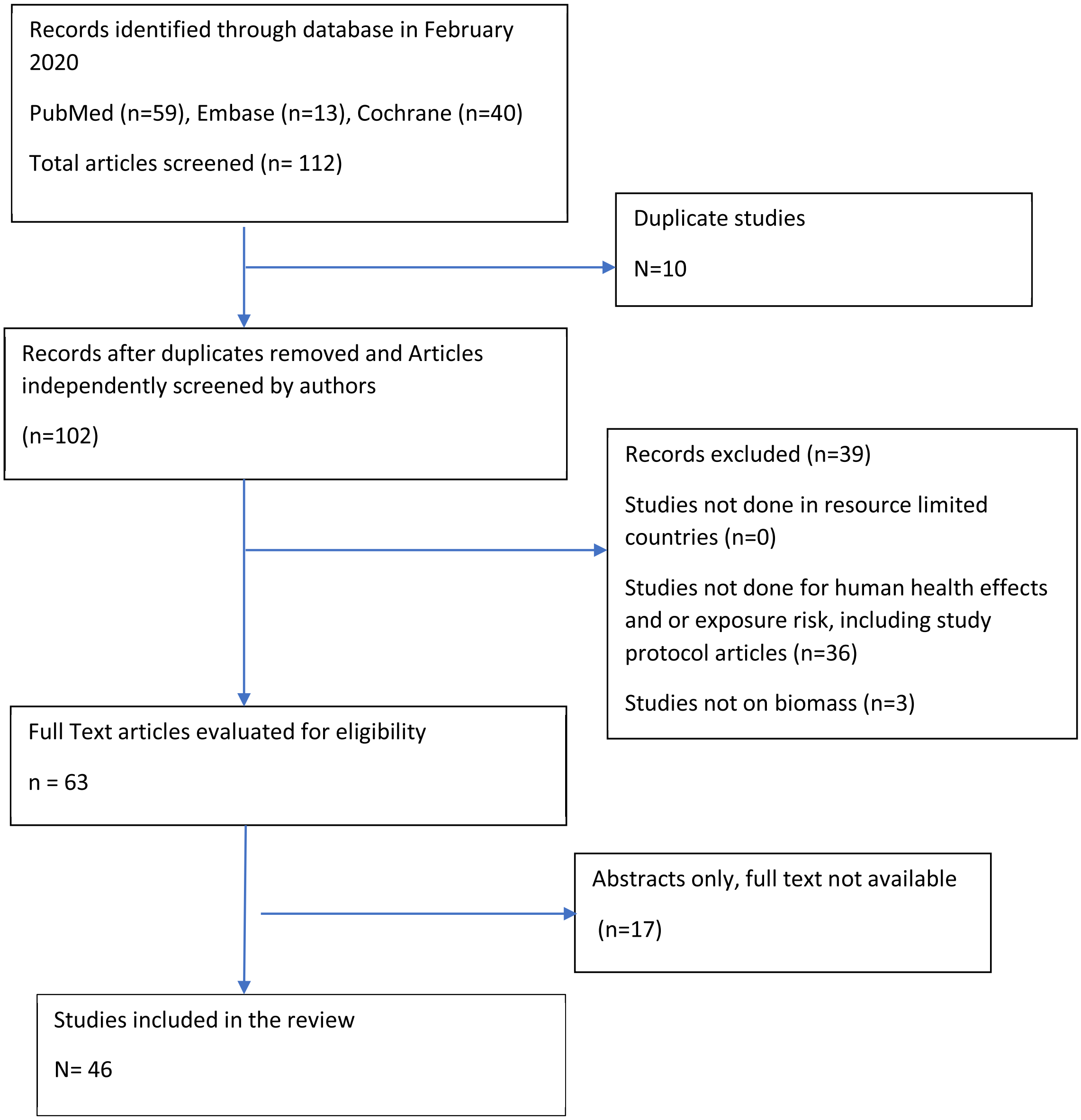

Fig. 3. Consort diagram.

summarized that IC significantly improves both systolic and diastolic BP among women(Onakomaiya et al., 2019). This could result in a considerable downward shift in the population distribution of raised BP in low- and middle-income countries and its related morbidity and mortality(Arku et al., 2018). On the other hand, there are important potential bias in household air pollution studies resulting from the possibility that those receiving improved stoves are themselves prone to better or worse health outcomes. Health relevant factors like age, income and kitchen ventilation could affect estimates of IC in a non-randomized study(Mueller et al., 2011).

Conclusion: IC is beneficial in decreasing HAP effect on blood pressure mostly in women above 40 years.

2.2. Respiratory (dyspnea, Cough)

Health Effects: In a self-reported health survey conducted amongst bakery workers in Ethiopia, 13 out of 35 participated stated they had to 'stop for breathing when walking at own pace on level ground'. Of those who answered 'yes', 57% worked in bakeries using biomass as compared to 24% working in bakeries using electric cookstoves. These symptoms correlated with $PM_{2.5}$ and CO levels(Downward et al., 2018; Pope et al., 2015). The health survey was not accompanied by physical examination and being a pilot study, the study results needed further confirmation in future epidemiological studies(Downward et al., 2018). A similar health survey from India conducted in households utilizing open fire cookstoves and burning solid fuels found almost one third of adults and half of the children in the survey experienced symptoms of respiratory illness in the past 30 days(Duflo et al., 2008). A study on effects of acute HAP associated with biomass fuel on pulmonary deficits found exposure to HAP is associated with acutely elevated $PM_{2.5}$ concentrations leading to a decrease in pulmonary function including forced expiratory volume in 1 s (FEV1), forced vital capacity (FVC) and ratio of (FEV1)/FVC(Medgyesi et al., 2017). FEV1/FVC is used for diagnosis for chronic obstructive pulmonary disease. Respiratory symptoms develop more often in women and children because they spend more time near the cookstove. In a study to assess HAP from Sri Lanka, the prevalence ratio (PR) of respiratory conditions including cough, phlegm, wheeze, or asthma was significantly elevated for cooks cooking without chimney and also non-significantly elevated if they cooked in a separate but poorly ventilated building. Similar findings were noted in children for symptoms of wheeze or asthma(Phillips et al., 2016).

Mitigation by IC: Studies have shown in women using biomass fuels

Table 1
Household air pollution related to cook stoves and its health effects.

		Health Effects
Emission Factors	PM $_{2.5}$ •Toxicity, mutagenicity •Oxidative potential •Source and composition apportionment •Ambient level to be considered •Difficult to measure	•Elevated SBP and DBP •Lower birth weight •Decreased pulmonary function, forced expiratory volume in 1 s (FEV1), forced vital capacity (FVC) and ratio of (FEV1)/FVC. •Increased Cough, Phlegm, Wheeze, Asthma
	CO •Easier to measure •Correlation with PM $_{2.5}$ varies with setting	•Increased respiratory and cardio-vascular morbidity and mortality •Negative birth outcomes •Developmental and central nervous system effects •Increased SBP
	PAH •Formed by pyrolysis •Difficult to measure •Mutagenic and Teratogenic •Correlation with PM varies with setting •Larger PAH and formed intermediate PAHs more toxigenic •Redox and oxidative potential to cause inflammation	•Lung cancer •Bladder cancer •Cataract •Liver damage •Neural tube defects
Cookstove Factors	Ventilation •Natural or cookstove related •Confounder •Could switch indoor pollution to outdoor	•Focus for public health education •Decreases PM $_{2.5}$ and CO related health effects
	Fuel •Fuelwood and densified briquettes with lower emission •Fuel type affect cooking time •Accessibility and cost major factors •Drier fuels have lower emission though may have higher PAH release	•Changing to cleaner fuels like LPG, biogas and electricity improves emission related health outcomes

with self-reported symptoms of more phlegm production improved when women switched to IC(Clark et al., 2009; Phillips et al., 2016). These symptomatic improvement corelated with measured kitchen and personal PM $_{2.5}$ levels(Walker et al., 2019). These improvement in symptoms by women have also been noted in multiple self-reported studies (Jagger et al., 2019; Thakur et al., 2018) wherein women preferred the ICS over the traditional three-stone fire for perceived reduction in smoke and improved health(Loo et al., 2016).

Conclusion: There is better health-related quality of life among women using improved cookstoves.

2.3. Childhood pneumonia

Health effect: The Randomized Exposure Study of Pollution Indoors and Respiratory Effects (RESPIRE) trial randomized pregnant women or infants of 534 households in Guatemala to an IC vs. traditional stove and assessed its impact on the incidence of pneumonia in children younger than 19 months. In intention-to-treat analyses of the study, the IC 'Plancha' showed a non-significant reduction in the incidence of physician-diagnosed pneumonia. When further analysis was done to consider other factors, there was a statistically significant reduction in physician diagnosed severe pneumonia. Additionally, there was a 50% reduction in personal child exposure to CO, although the levels were still above WHO recommended limits(Smith et al., 2011). Evidence had shown exposure to HAP could cause significant morbidity and mortality secondary to acute lower respiratory infections in children(Smith et al., 2000). In a prospective study, of 1586 children (19%) had ≥ 1 episode of acute lower respiratory infection (ALRI) and multivariable analysis indicated that the odds of ALRI was significantly high at 2.1 (95% CI: 1.4–3.3) for > 3 h of exposure to solid fuel cookstoves compared with no exposure ($p < 0.01$) (Arlington et al., 2019). Similar studies done in different populations have shown diverse results(Rana et al., 2019; Rey-Ares et al., 2016). Average prenatal CO exposure is significantly associated with reduced time to peak tidal expiratory flow to expiratory time, increased respiratory rate and increased minute ventilation during first year of life. These altered infant lung function could be a risk for pneumonia in the first year of life(A. G. Lee et al., 2019). Additionally, HAP is associated with infant microbial nasal bacterial carriage that may also increase susceptibility to childhood pneumonia (Carrion et al., 2018).

Mitigation by IC: The current data about the health benefit of HAP reduction with IC in childhood pneumonia is equivocal(Soto-Martinez, 2019). Possible causes may be biomass burning in one home can be a source of indoor air pollution in multiple homes. Other causes may be even lower levels of HAP seen with IC causing health effects in children. Hence without a whole community intervention, the health benefits may not be evident(Weaver et al., 2019). A community-level open cluster randomized controlled trial to compare the effects of a cleaner burning biomass-fueled cookstove intervention to continuation of open fire cooking on pneumonia in children did not reduce the risk of pneumonia in children(Mortimer et al., 2017). Similar IC studies, Systematic review and meta-analysis did not demonstrable child health impact for pneumonia or ALRI(Clark et al., 2009; Foote et al., 2013). Though IC use has been associated with 28% lower odds of child mortality (OR = 0.72; CI = 0.61–0.86) compared to nonusers of improved cookstoves that may be a spurious association with other related confounding social factors(Pandey and Lin, 2013).

Conclusion: IC is not beneficial to improve childhood pneumonia. Though in most of these studies the diagnosis of pneumonia in child was self-reported or self-reported with confirmation with health records that may be a limitation of this inference. Further research studies are needed with community level intervention for IC or switching to less expensive cleaner fuels (e.g. kerosene, biogas) to evaluate their effect on child health.

2.4. Mutagenicity

Health effect: Biomass cookstove emissions had mutagenicity that was positively corelated with PM $_{2.5}$ emissions. There is inconsistent relationship between mutagenicity and PAH emissions possibly because PAHs comprise minor fractions of toxic organics contributing to the total mutagenicity(Mutlu et al., 2016; G. Shen, 2017). Oxygenated PAHs have mutagenicity almost nine times higher than the corresponding estimate for 16 priority parent PAHs(Mutlu et al., 2016).

Mutagenicity being a complicated test is not performed in most studies, though it should be recommended to evaluate the various components of emissions and be a proxy marker for long term effect of possibly causing cancer(Reid et al., 2012). Human health effects from long-term exposure to PAHs include lung and bladder cancer. For HAP causing lung cancer, strong evidence came from a retrospective cohort study of farmers exposed to smoky coal throughout their lifetime with a sample size of 21,232. The study reported the lung cancer risk was reduced after transition to IC with a chimney(Lan et al., 2002). Another case control study from Taiwan showed increased prevalence of adenocarcinoma of the lung in people using coal or anthracite as cooking fuel (C.-H. Lee et al., 2001). Globally, incremental lifetime risk assessment for lung cancer due to ambient PAHs exposure is about 3.1×10^{-5}, the most important sources being biomass and fossil fuel combustions in residential and commercial sector. Contrary to common belief, the risk contribution from residential sector at 40% exceeded commercial sector which was 14%, thus highlighting the importance of improving HAP(H. Shen et al., 2014).

Mitigation by IC: Lower mutagenic emissions were observed for high efficiency stoves such as a forced-draft one(Mutlu et al., 2016; G. Shen, 2017). Study evaluating carcinogenic risk with exposure to PM $_{2.5}$ bound polycyclic aromatic hydrocarbons in rural settings found personal concentration of PAHs compounds was significantly high for traditional cookstove as compared to IC. Further PAHs concentrations were converted to benzo [a]pyrene equivalent for calculating cancer and non-cancer effects using toxicity equivalency factors. This toxicity levels causing lifetime carcinogenic risk were higher for traditional cookstove as compared to IC(D. Sharma and Jain, 2020).

Conclusion: HAP could cause cancer with a strong association for lung cancer seen in cohort and case control studies. Studies are lacking about the cancer mitigation by IC.

2.5. Birthweight

Health effect: Most of the premature deaths attributed to HAP exposure occur in low- and middle-income countries(Arku et al., 2018). In a study by Wylie et al. in Tanzania, the linear regression using the log of PM $_{2.5}$ showed a decrease in birth weight of 270 g for each increase in one-unit log PM $_{2.5}$ and the results were similar when the data was restricted to full term births(Wylie et al., 2017). Another meta-analysis of 17 studies on ambient air and birth weight showed that for every 10 mcg/m^3 PM $_{2.5}$ increase there is a decrease of 15.9 gm in birthweight. The PM $_{2.5}$ levels were averaged over the entire gestation(Sun et al., 2016). One of the factors related to low birth weight may be elevated BP seen on exposure to HAP(Alexander et al., 2017). On the other hand, low birth weight is only one of the adverse outcomes of pregnancy associated with HAP. Systematic review on HAP also inferred household use of solid fuels adversely affected pregnancy outcomes. Solid biomass fuel use could lead to an 86.43 g reduction in birth weight and a 35% increased risk for low birth weight. There was some evidence of increased risk of stillbirth, preterm birth, intra-uterine growth retardation and miscarriage related to solid fuel at home. In this meta-analysis two studies were very high quality, three high quality, twelve satisfactory and two were low quality. Test for publication bias was positive and could have affected the estimates of risk. When publication bias was accounted for, the estimates still showed the correlation for adverse effects(Amegah et al., 2014). It is unclear if the trend of increased blood pressure seen in pregnant women using biomass cookstoves is associated with hypertensive complications of pregnancy(A. K. Quinn et al., 2016).

Mitigation by IC: Systematic review and meta-analysis conclusion suggest that IC intervention has no health benefit for low birth weight (one study; 174 babies; OR = 0.74 (95% CI 0.33 to 1.66)) or other birth related outcomes including miscarriages, stillbirths and infant mortality (one study; 1176 babies; risk ratio (RR) change = 15% (95% CI -13 to 43).(Thakur et al., 2018).

Conclusion: Cleaner fuels as compared to IC may be needed to improve pregnancy related outcomes.

2.6. Cardiovascular (CV) effects

Health effect: PM $_{2.5}$ effect on CV and cerebrovascular disease may be caused by the HAP associated elevation of blood pressure. To date, however there is limited evidence of an effect of HAP on cardiovascular disease. Possible cause may be the long latency period of cardiovascular disease (CVD). Randomized population-based studies have shown a decrease in all-cause mortality of about 1.82% for every mm of Hg reduction in SBP. Hence statistical prediction of changing from cook stoves to LGP gas stoves assumed an average decrease in SBP of 5.5 mm resulting in 10% reduction in mortality. Most of these data is from PM $_{2.5}$ of women and hence the prediction cannot be generalized to whole population(Steenland et al., 2018). CRP levels, a biomarker for CVD risk was elevated in women with HAP exposure though the increase was not statistically significant and high level of between person variability was seen in the study(Young et al., 2020). Another prevalence study suggested associative effect between metabolic syndrome and exposure to household air pollution which is another known risk factor for CVD. This effect was stronger in women $\geq$40 years of age(Rajkumar et al., 2019). Thus reducing HAP should be considered with other interventions for decreasing blood pressure like low salt diet, exercise and medications for decreasing the burden of non-communicable diseases like hypertension and CVD in resource limited countries(Abtahi et al., 2017). With little direct evidence of association between HAP and cardiovascular diseases, further research on coherence, biological plausibility and gradient is needed to address the association. In spite of these problems, several observational studies have reported positive associations between biomass use and CVD diagnoses and/or CVD mortality(Mitter et al., 2016). A study on DALY found ischemic heart disease contributed directly to 43.4% of all the DALYs, while hemorrhagic stroke accounted for 9.7% and ischemic stroke 7.8% of the DALYs in Iran. It shows that almost > 50% of DALYs attributable to HAP is related to CVD and hence needs immediate attention and intervention(M.-S. Lee et al., 2012).

In a nationwide prospective cohort study recruiting participants from 5 rural areas across China; a total of 271,217 adults without a self-reported history of physician-diagnosed cardiovascular disease were enrolled at baseline, with a random subset of 10,892 participants being surveyed again after a mean interval of 2.7 years. HAP from cooking was associated with greater risk of cardiovascular mortality, a hazard ratio of 1.20 [95% CI, 1.02–1.41] and increased all-cause mortality. While, use of ventilated cookstoves was associated with non-statistically significant lower risk of cardiovascular mortality and statistically significant lower HR, 0.89 [95% CI, 0.80–0.99]) and all-cause mortality (ARD, 87 [95% CI, 20–153]; HR, 0.91 [95% CI, 0.85–0.96])(Yu et al., 2018). Similarly, hypothetical models including strategy of combined fabric, ventilation, fuel switching, and behavioral changes for India showed substantial benefits incurring from substantial benefits for ALRI in children, chronic obstructive pulmonary disease, and ischemic heart disease(Wilkinson et al., 2009).

Conclusion: HAP is a CVD risk factor that could be mitigated by IC.

2.7. Miscellaneous

Health effects: IC also had shown to decrease many health effects like symptoms of dry cough, chest tightness, difficulty breathing, eye irritation and runny nose in mothers and children in homes using IC as compared to traditional cookstoves(Aung et al., 2018; Dohoo et al., 2012). Chronic obstructive pulmonary disease (COPD) associated with HAP exhibits bronchial anthracofibrosis and differs from COPD from tobacco smoke. This form of HAP shows disproportionately greater bronchial involvement, impact on quality of life, oxygen desaturation and pulmonary hypertensive changes with lesser emphysematous changes. Decrease exposure to HAP may decrease the risk for this type of COPD and attenuate the longitudinal decline in lung function though further well-designed longitudinal studies are needed(Assad et al., 2015). A Nepalese study had shown positive associations of biomass cookstoves with nuclear opacity and change in nuclear color leading to cataract(Pokhrel et al., 2013). Toxicological studies in animal models and epidemiological studies in smokers indicate a potential association between HAP and cataracts. Pooled estimate from systematic review suggest effect on HAP is significant only in women with an OR of 2.47 (1.61, 3.73)(Smith and Pillarisetti, 2017). On the other hand another Nepalese study did not find correlation between HAP and latent tuberculosis(Albers et al., 2019).

HAP could also increase carboxyhemoglobin level in children above the recommended limit with adverse neurodevelopmental and cognitive effects(Havens et al., 2018).

In another large prospective cohort study, solid fuel use for cooking increased the risks for major respiratory disease (including ALRI and COPD) related admissions and death, and switching to clean fuels or use of ventilated cookstoves lowered the risk(Chan et al., 2019). Though not a direct health effect, school attendance as a proxy marker for HAP effect did not improve with IC(Kelly et al., 2018). IC also decreased black carbon in airway macrophages that was a indicator for inhaled HAP dose as compared to traditional cookstove(Whitehouse et al., 2017). Endothelial dysfunctions measured as a marker for CVD risk did not change with IC implementation though the study included predominantly male participants(Miele et al., 2017).

3. New cookstove

3.1. Role in HAP vs. Cleaner fuels

IC has improved thermal efficiency and decreased HAP(M. Sharma and Dasappa, 2017). The IC would decrease release of black carbon (BC) which has 680 times more global warming potential as compared to carbon dioxide(MacCarty et al., 2008). Estimation of BC and organic carbon have received more attention because BC contributes to global warming due to its strong absorbing nature and organic carbon on the other hand causes global cooling since it is composed of aerosol particles. In South East Asia, BC is found to be largely responsible for the change in monsoon pattern(Rehman et al., 2011). IC also decreases the release of PAHs, though this emission is affected by the type of fuel used. PAH emissions were the least for IC with pellets type fuel. Consequently, adoption of pellets may be beneficial. But being a commercial fuel, its availability affects its adoption as fuel in developing countries(Leavey et al., 2017). Some studies have shown no, or undetected mutagenicity related from emissions from cookstoves using kerosene or propane for burning(Mutlu et al., 2016; G. Shen, 2017). The IC used more fuel and time to cook or boil same amount of fluid though the emission related to cooking was less. The LPG stove had the lowest time to boil(Ojo et al., 2015). Some new gasifier stoves that have energy efficiency almost equal to LPG require electric fan to modulate the air supply for combustion and may not be feasible in many areas with limited or no electricity(M. Sharma and Dasappa, 2017). LPG though the cleanest fuel, still is more expensive than biomass in most parts of the world, making price an issue in adaptation. Countries like India and Peru have implemented a nationwide subsidization of LPG which could have substantial impact on the uptake of LPG for cooking(Steenland et al., 2018). Extended cost-effective analysis from these intervention show maximum benefit for investment in averting death and DALY though LPG subsidization(Pillarisetti et al., 2017). In a recent study, of the 87.3% participants using IC as primary cooking method, almost 69% had stove stacking, and used LPG or traditional stove as secondary cooking option. One of reasons given for not using LPG for all cooking was cost and change in taste of traditional food. There was a good sustainability for IC since most participants had IC since 2009. Hence implementing multiple cleaner stoves and fuels like LPG simultaneously may improve the sustainability of IC(Wolf et al., 2017). Similar pattern in IC studies could cause between study variabilities and spurious study-specific estimate, unless close monitoring is implemented (Chartier et al., 2017; Pillarisetti et al., 2014; Quansah et al., 2017; Thomas et al., 2016).

3.2. Disadvantages

Long term randomized control trials for IC are difficult to implement. Most trials are short-term and cannot easily evaluate long-term effects of HAP on chronic disease like lung cancer, stroke, and heart disease(Steenland et al., 2018). Sometimes there are additional sources of HAP e.g. using traditional stoves for heating water, smoldering and stove which dampens the IC benefit to decrease emissions and its related health effects(Ruiz-Mercado and Masera, 2015). The process of developing IC requires laboratory and field condition testing. Then these IC are provided to needed communities in an organized way to increase its uptake and sustainability. This process is too complex in real world setting and is unable to meet the overall goal(M. Sharma and Dasappa, 2017). There are very few studies on the cost benefit of IC in disability adjusted life years (DALY) and cost savings in health-related expenditure, daily wages lost, and school days lost with households using IC. Traditional cookstoves and the fuel used for cooking varies a lot depending upon the region, agricultural residues available, seasonal variation affecting access to fuel, fuel cost and availability of other fuels. It is difficult to predict a model about how much and how long the IC would be used. Time to cook, fuel procurement and usage, taste of food cooked in IC and size of vessel used for cooking have been additional factors stated to affect usage of IC in some households. Hence, it is important to understand the local factors in a given region before implementing IC(M. Sharma and Dasappa, 2017). IC could shift HAP to environmental/outdoor pollution(Downward et al., 2016).

3.3. Barriers

Studies have found stove design, knowledge and awareness about IC, household characteristics, market development, financial support and favorable policies as important factors that enable better adoption of IC(G. Shen et al., 2015). Cost, education, fuelwood cost, credit access in the form of microfinance and household size were positively associated with adoption of IC(Lewis and Pattanayak, 2012). Decreased community awareness about the benefits of IC like decrease in the time, money and labor required for acquiring fuel. Other benefits include decrease in health hazards and emissions that is good for family health. This awareness is required to increase the consumers decision-making power innately to overcome the cost and logistic factors related to IC. To supplement the effort to disseminate newer IC, companies producing IC could offer free trials, time payments and return options. There is inadequate comparative data regarding international standard cookstoves that are well tested before deployment vs. locally manufactured stoves that may not have been well tested but may be more user friendly, though not sustainable. Countries should have basic requirements for IC before they are marketed, for good sustainable use and to overcome social norms about IC. Safety, social network and peer attitude in the initial phase of uptake plays an important role in understanding of stove attributes and performance. In one study though health related awareness with IC was understood by a community, it did not increase the purchase rate of IC. In most families, women are the primary cooks, however, they have little decision-making power about procuring items for household. Cost seems to be a key factor and hence IC implementation programs should be complemented with good government program for subsidized fuel supply, options of replaceability if the efficiency of the IC decreases and good servicing facility at least during the initial phases of IC adoption(Shankar et al., 2014). In a study about IC adoption, encountering problems with IC functioning was negatively associated (OR 0.62, 0.41–0.93); while knowledge of somebody being able to build or repair an IC was positively associated with daily IC use(Wolf et al., 2017).

4. Limitations

The review included all forms of studies and did not take into consideration the duration of follow up in these studies. Very few studies were randomized. We did not evaluate the psychosocial and thermal environmental effects of HAP or its mitigation by IC. We did not exclude studies that evaluated HAP in the context of cooking and other activities (heating). Smoking as a confounder in these studies was not analyzed. We also included reviews, though the quality of these reviews were not evaluated. We included studies involving mathematical modeling to study the health effects of HAP that possibly could have incorrect estimates.

5. Conclusion

Household air pollution is an important global health problem with significant morbidity and mortality. Global Alliance for Clean Cookstoves is an initiative by the United Nations to improve the lives of people dependent on biomass fuel. Recently, several newer cookstoves are being developed with good thermal and emission performances. There is current, substantial and comprehensive evidence about the health effects of household air pollution with some evidence about the efficacy and cost-benefit of IC. Most IC studies show modest benefit. Hence initiatives and policies are needed to implement strategies for dissemination and adoption of cleaner fuels and IC in households that are currently using traditional cookstoves. A strategy with amalgamated intervention including IC and cleaner fuels, may be needed to reduce HAP to levels that are likely to resolve and not mitigate the health effects of HAP.

Declaration of competing interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envres.2020.109574.

CRediT statements

Rebecca Pratiti: Conceptualization, Methodology, Formal analysis, Writing original draft.David Vadala: Methodology, Formal analysis.Zirka Kalynych: Writing review editing.Parul Sud: Writing review editing, Supervision.

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