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TOPICAL REVIEW

Health effects of liquid and gaseous fuels for household energy use: systematic evidence mapping

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Abstract

Exposure to household air pollution results in a substantial global health burden. The World Health Organization (WHO) Guidelines for Indoor Air Quality: Household Fuel Combustion stipulate emission rates for household energy devices should meet air quality guidelines and protect health. Liquefied petroleum gas (LPG), biogas, natural gas (NG), and alcohol fuels are considered clean for health due to their low emissions at the point of use. In light of the ongoing energy transition and increasing emphasis on these fuels, it is imperative to provide an updated synthesis of the impacts of these fuels on health. A systematic review was completed on the health effects of liquid and gaseous fuels for household energy use for cooking, heating, and lighting across high-, middle- and low-income countries. Comprehensive searches were undertaken in 12 international databases and selected studies were compiled into a new publicly available WHO Health Effects of Household Liquid & Gaseous Fuels Database, containing key study characteristics including pollutants and/or health outcomes measured. This database was then mapped to understand the breadth of evidence and potential gaps. From 48 130 search results, 587 studies were extracted for inclusion in the database on completion of the full-text review. Studies represented low-, middle- and high-income countries (HICs) over several decades - there has been a substantial increase in evidence from low- and middle-income countries (LMICs) published in the last decade, particularly in Asia. Most evidence focused on LPG for cooking in LMICs or NG used in HICs for cooking and heating. Women were the most studied demographic, with self-reported health outcomes and symptoms being the most common assessment method. Particulate matter and nitrogen oxides were the most monitored pollutants. A wide array of health symptoms and disease and injury outcomes were assessed, and most concerned respiratory health. This is the first time that evidence on the health effects of liquid fuels (such as alcohol fuels), with most studies concerning gaseous fuels. The WHO Health Effects of Household Liquid & Gaseous Fuels Database represents a valuable resource to enable the examination of the positive and negative health effects from these fuels.
1. Introduction

Around 2.4 billion people currently depend on polluting solid fuels (e.g. wood and coal) and kerosene for cooking, heating, and lighting, predominately in low- and middle-income countries (LMICs) (IEA et al 2022). The use of polluting fuels results in high levels of exposure to household air pollution (HAP), through generation of particulates and gasses from incomplete combustion (Naeher et al 2007, Apple et al 2010). The World Health Organization (WHO) estimates exposure to HAP causes millions of deaths per year (WHO 2021a), as air pollutants penetrate deep into the lungs and enter the blood stream, causing systemic respiratory and cardiovascular impacts (Yu et al 2018, Lee et al 2020).

The WHO guidelines for indoor air quality (GIAQ): household fuel combustion (WHO 2014) recommend fine particulate matter (PM$_{2.5}$) and carbon monoxide (CO) emission rate targets for household energy devices (e.g. stoves and space heaters) to achieve the WHO air quality annual PM$_{2.5}$ guideline levels, and the 24 h average CO levels (WHO 2021b). Based on these guidelines solar, electricity, liquefied petroleum gas (LPG), biogas, natural gas (NG), and alcohol fuels are recommended as clean household fuels/energy sources for health at the point of use due to their very low (or no) emissions of health damaging pollutants from fuel combustion. However, inefficient burning of gaseous fuels can result in higher emissions of various products of incomplete combustion—which can be the case in LMICs (Shen et al 2018). If biomass-burning devices can meet emission rate targets for PM$_{2.5}$ and CO they are also classified as ‘clean’, but in practice this is rarely the case (Pope et al 2021). The GIAQ discourage the use of kerosene and recommend against burning unprocessed coal in the home (WHO 2014).

Use of clean household fuels, such as electricity, NG and LPG, has been shown to realise significant health benefits (Baumgartner et al 2012, Pope et al 2021). Although there has been an increase in the number of households using clean fuels globally over the last two decades, improvements are being outpaced by population growth in many parts of the world, particularly in sub-Saharan Africa (Stoner et al 2021, IEA et al 2022). To expedite and maximise health gains, clean household fuels and technologies need to be rapidly scaled across LMICs (WHO 2014, Rosenthal 2018, Puzzolo et al 2019).

However, whilst efficient combustion of gaseous fuels (LPG, NG, biogas, and alcohol) achieves very low emissions of health damaging PM, they may produce emissions of other gaseous pollutants that have the potential to impact health (e.g. nitrogen oxides (NOx)) (Lin et al 2013, Kephart et al 2021), and it is critical to review this growing evidence. Similarly, although a systematic review on the health impacts of kerosene by Lam et al (2012) had informed the GIAQ, evidence on risks associated with household kerosene was limited and inconsistent, particularly when stratified by energy use (cooking, heating, and lighting) with user preferences, behaviour and with associated HAP exposures varying substantially (Lam et al 2012).

Given the global priority to address the public health burden from exposure to HAP, there is an urgent and current need to review the state of evidence regarding the potential health impacts associated with the adoption and use of liquid and gaseous fuels in the home. Understanding the full risks to health is crucial in the development of air quality guidelines and policies supporting rapid transition to clean, efficient and safe household energy fuels and technologies. In order to capture the wide variety of household liquid and gaseous fuels and associated potential health effects, this requires a broad search strategy of available literature from different disciplines and sectors (e.g. public health, environment, energy, and development). Collating this available evidence in a database would allow for efficient appraisal of the relevant literature and support further in-depth synthesis. To our knowledge, there is no comprehensive assessment of the health effects of household liquid and gaseous fuels, including any comprehensive database for synthesis. Further reviews since the publication of the GIAQ have focused on specific interventions, exposure-health relationships or are limited to specific fuels (Pope et al 2021), and therefore do not capture the fuel range of evidence and additional risks or benefits to health.

The overall aim of this systematic review was to provide a comprehensive summary on the state of evidence on potential health effects from household use of liquid and gaseous fuels for household cooking, space heating and lighting applications. The review was completed in two parts: (a) creation of database collating and mapping of the available evidence (presented in this paper) and (b) synthesis through meta-analysis of evidence on these health impacts (with the specific focus to be determined following part a, and the subject of a separate publication). The systematic review, and associated database, included peer-reviewed studies that summarised impacts of household use of liquid and gaseous fuels for cooking, heating, and lighting on both (a) exposure to key health damaging pollutants and (a) health effects from exposure to HAP and from burns and poisoning. Specifically, we aimed to systematically identify:

- Evidence on emissions, concentrations, and/or personal exposures to key pollutants from the household use of liquid and gaseous fuels for cooking, space heating and lighting.
• Evidence on potentially associated health effects, as well as the occurrence of accidents and injuries from the household use of liquid and gaseous fuels for cooking, space heating and lighting.

Liquid and gaseous fuels included in the review were those considered both clean and potentially polluting in terms of specific HAP emissions that could impact health. Cleaner liquid and gaseous fuels (those with low emissions of products of incomplete combustion) included NG, LPG, biogas and alcohol fuels (ethanol, methanol and gel fuel). Liquid fuels used for household energy with greater emissions from combustion (including gasoline, diesel, oil and kerosene/paraffin) were also included. Studies meeting the published inclusion criteria for the review have been compiled in a new WHO Health Effects of Liquid and Gaseous Fuels Database (www.who.int/data/gho/data/themes/air-pollution/health-effects-of-liquid-and-gaseous-fuels-database), which can be used as a resource to address bespoke research questions on the potential effect of household liquid and gaseous fuels for household energy.

In this paper, we describe the first part of the review and subsequent mapping of available evidence. Evidence mapping is an emerging method that systematically identifies, organises, and describes the quantity and characteristics of available literature (Bragge et al. 2011, Lam et al. 2019). Evidence mapping can help support development of pertinent research questions in addition to highlighting evidence gaps, providing a starting point for further investigations (Kim et al. 2022). Quantitative synthesis through meta-analysis of the positive and negative effects of gaseous fuels for cooking and heating on health outcomes is currently being undertaken and will be published separately.

2. Methods

The methods were developed iteratively following a scoping review of relevant studies (to define and refine an exhaustive list of search terms) and through discussions between the wider review team. The review protocol, covering both parts a and b, was registered with PROSPERO (CRD420211227092). The review database and subsequent meta-analysis is reported using the criteria recommended in the preferred reporting items for systematic reviews and meta-analyses (PRISMA) guidelines.

2.1. Eligibility criteria

The scope of the review and resulting database was framed by the PICO (population, intervention, comparator, outcomes) framework. Predefined and ascribed inclusion and exclusion criteria were developed, with additional criteria considering the study design (table 1) according to the PICO framework as follows:

• Population: human populations from both high-income countries (HICs) and LMICs were eligible with all geographical contexts considered.
• Intervention: all liquid and gaseous household fuels were considered as interventions or study focus fuels, whether they were considered ‘clean’ or ‘polluting’ in terms of emissions.
• Comparator: in terms of comparator fuels, studies were eligible when gaseous and/or liquid fuels (intervention) were compared to (a) cleaner no-emission fuels/energy (e.g. electricity, solar), (b) more polluting fuels (e.g. solid fuels/kerosene), (c) non-users of the intervention/focus fuels (where a reference technology/fuel is not clear) or (d) with no comparison where studies were descriptive (e.g. in the case of personal exposure to health damaging pollutants or records of hospitalisations/mortality from burns or poisoning).
• Outcome: outcomes included (a) emissions/concentrations of specified household air pollutants and/or (b) disease outcomes, health symptoms, injuries (e.g. burns and scalds) and poisoning.

In terms of study design, no restrictions were placed on publication language of selected studies with an active interrogation of the Chinese literature and translation of other languages.

2.2. Search strategy

Following the initial scoping searches, comprehensive and systematic literature searches were conducted in January 2021 according to an a priori transparent and detailed search strategy (piloted and published as part of the study protocol). The review team comprised experienced systematic reviewers from the University of Liverpool and Peking University (appraising the Chinese literature). No restrictions on language or publication date were applied to the searches.

Scoping searches were carried out during December 2020, results of which were discussed within the review team to refine the search terms, filters and the exact approach used to interrogate each bibliographic database to maximise the identification of relevant studies. Results of the scoping search were used to validate the search strategy through checking whether a list of relevant studies, known to the review team, were included within the search results.

Bibliographic databases interrogated for international publications of studies (other than Chinese) included: Ovid MEDLINE, PubMed, CENTRAL, Scopus, Environment Complete, Green File, Google Scholar, and Web of Science. In Ovid MEDLINE and PubMed, filters were applied to exclude animal studies. In Scopus and Web of Science, filters were applied to exclude conference papers. Chinese bibliographic
Table 1. Inclusion and exclusion criteria, following the PICO framework.

| Category                      | Inclusion criteria                                                                 | Exclusion criteria                                                                 |
|-------------------------------|-------------------------------------------------------------------------------------|------------------------------------------------------------------------------------|
| Population                    | Any population that uses the intervention/focus liquid and gaseous fuel(s) for household cooking, space heating or lighting | Populations that do not use the intervention/focus fuel(s) for household cooking, space heating or lighting |
| Intervention/focus fuels      | Liquid and gaseous household fuels, as follows: alcohol fuel, biogas, butane, diesel, dimethyl ether (DME), ethanol, methanol, gas, gasoline, gel fuel, kerosene, liquefied petroleum gas (LPG), methane, natural gas, paraffin, piped natural gas, oil, propane | Not a liquid or gaseous fuel as per the inclusion criteria or where fuels have been grouped and it was not possible to establish the effect of each fuel type |
| Comparator                    | (a) Zero emission at the point of use energy sources (e.g. solar or electricity)     | Not a comparator as per the inclusion criteria                                      |
| (b) Other polluting fuels/energy sources (e.g. charcoal, firewood, coal, and other biomass fuels) |
| (c) Non-users of the intervention/focus fuels (or not described) |
| (d) No comparator where studies are descriptive (e.g. emissions) |
| Outcomes                      | Primary Disease and injury outcomes including: acute lower respiratory infection (ALRI), airway inflammation, all-cause mortality, all-cause mortality under 5 years, asphyxia, asthma, birthweight, bronchial reactivity, bronchitis, bronchoconstriction, burn, cancer, cardiovascular disease (CVD), cataract, chronic obstructive pulmonary disease (COPD), cognitive development, cognitive impairment, congenital defects, congestive heart failure (CHF), coronary heart disease (CHD), diabetes, heart attack, hypertension, ischaemic heart disease (IHD), lung function, lung infection, pneumonia, poisoning, respiratory conditions/diseases, scald, small for gestational age, stillbirth, stroke, stunting/stunted growth, tuberculosis (TB), tumour. | Health effects that cannot be linked to impacts from choice of fuel type or energy source (i.e. aspects related to system efficiency, such as increased warmth from more efficient heating systems (which may be realised by different heating system and associated fuels)). Studies that do not include health outcomes and do not have relevant emissions data with at least 24 h sampling, as specified in the inclusion criteria. Studies that are not based in household settings (e.g. laboratory studies) |
| Secondary                     | Health Symptoms including breathlessness, chest pain, confusion, cough, disorientation, dizziness, drowsiness, fatigue, headache, insomnia, memory loss, nausea, paraesthesia, phlegm, runny/sore eye, speech problem, tired, unconsciousness, weakness, wheezing | Laboratory and non-field-based studies. Studies which have not been peer-reviewed |
| Emissions                     | including: acenaphthene, acenaphthylene, anthracene, benz[a]anthracene, benzene (C6H₆), benzo[a]pyrene, benzo[k]fluoranthene, benzo[g,h,i]perylene, benzo[k]fluoranthene, butadiene, carbon monoxide, chrysene, dibenzo[a,h]anthracene, fluoranthene (C16H10), fluorene, formaldehyde, indeno[1,2,3-c,d]pyrene, naphthalene, nitric oxide, nitrogen dioxide (NO₂), nitrogen oxide (NOₓ), nitrous acid (HONO), particulate matter (PM), phenanthrene, polycyclic aromatic hydrocarbon (PAH), pyrene, sulphur dioxide (SO₂), ultrafine particle (UFP). | |
| Study design                  | Included studies had the following designs: randomised controlled trials, before-and-after designs with or without a control group, observational study designs (cohort, case-control and cross-sectional designs) as part of primary health research or programme evaluations conducted in the field. To be eligible for inclusion, studies must be peer-reviewed or in submission stage for peer-review | Laboratory and non-field-based studies. Studies which have not been peer-reviewed |

Databases reviewed included Wanfang DATA (www.wanfangdata.com.cn/index.html) and CKNI (https://oversea.cnki.net/index/).
household energy use for cooking, heating and lighting; (b) intervention or focus fuels: liquid and gaseous fuels included in the studies (e.g. kerosene, ethanol, methanol, biogas, oil, NG and LPG); (c) emissions: concentrations/emissions/exposures of key air pollutants that could impact health (e.g. PM, CO, nitrogen dioxide, etc); (d) health outcomes: disease outcomes and/or symptoms potentially related to exposure to air pollution and/or from injuries/poisoning from use of domestic fuel; and (e) study context: specified setting (e.g. household, community, etc).

2.3. Study screening and selection
Study selection involved a two-stage screening process. Titles and abstracts identified from merging results from initial searches of the bibliographic databases (and removing any duplicates) and screening the results against a priori inclusion criteria, as specified in the protocol. Rayyan systematic review software (http://rayyan.qcri.org) was used to collate identified studies (Ouzzani et al. 2016). Studies identified as potentially relevant from first stage screening were exported into EndNote and further screened through an appraisal of the full text. At both screening stages, samples of approximately 10% of the studies were independently screened by a second reviewer to check for repeatability between reviewers. Any disagreements between reviewers were reconciled through discussion within the wider review team with an inclusive approach adopted in cases of uncertainty. Initial differences by between reviewers from UK and Chinese revealed the inclusion of papers that grouped fuels and did not allow the effects of fuel type to be established, this issue was addressed, and it led to five papers to be excluded where the effects could not be determined. At the full text stage, the few identified studies earlier than 1980 were excluded as it was considered these were not relevant to current household liquid and gaseous technologies upon careful assessment.

2.4. Data extraction and database creation
Following the two-stage screening process, relevant information from selected studies was extracted using a bespoke, online data extraction form, and used to populate the evidence database. The electronic data extraction form was developed using the online platform Mobenzi Researcher (www.mobenzi.com/), allowing for completion of the forms to be carried out simultaneously by multiple reviewers.

Data extraction forms (see supplementary materials) included key descriptive components for each study, including author and year, article title, abstract, language, country/setting and context, household energy end-use (cooking, heating and lighting), study design, population characteristics (sex, age), sample size, liquid and gaseous fuels and comparator fuels included, the health effects reported (either disease outcomes, symptoms or burns/injuries and poisoning) and/or air pollutants assessed, and details of monitoring periods, if reported. The data extraction form was tested for usability and refined through piloting for a subset of the included papers by the review team before finalising. Due to the heterogeneous evidence base, some grouping was initiated including for pollutants (e.g. ‘PM’ to cover all particle sizes rather than separate specification) and for health outcomes (e.g. cardiovascular diseases). The extraction form included a further field for ‘notes’, where additional details could be recorded pertinent to the data extraction—these were checked during the quality control process (see below).

The data extraction form was designed to record information relevant for the evidence database only and therefore did not directly record detailed results (including estimates of effect and/or statistical results) or evaluate study quality. Foreign language studies were translated and extracted by an individual with the language skills required and (if necessary) with use of an online translation tool (e.g. Google Translator). For each study data extracted was by one reviewer, with 10% independent verification by another reviewer to ensure consistency of recording.

Upon completion of the data extraction, the synthesised information was exported into Microsoft Excel where it was checked for errors through careful review by two systematic reviewers by cross-checking to the original full papers. Microsoft Excel was selected for the final database to allow maximum accessibility, due to its widespread use globally. Other formats, such as database specific software are less widely used and was deemed not appropriate. An additional step of reviewing information for the database included standardisation and grouping of key study attributes (e.g. grouped outcomes according to diseases, injuries and symptoms) to improve accessibility of the database for subsequent searching. Data were sorted in long data format to facilitate this searching. Information was structured under sections of study information (e.g. authors, date of publication), study context, study population, study design, household energy end use, liquid or gaseous fuel, emissions, concentration and personal exposures, health outcomes, biomarkers and symptoms. An overview of the database is detailed in the supplementary material.

2.5. Data analysis and visualization
An analysis of the main content of the database was undertaken to highlighting the evidence base and requirements for further research. The study locations, household energy end use, and timeframe were outlined to indicate the typical context of available evidence. Study design and target populations were described to indicate the type and extent of available research evidence. In addition, the range of
fuels used, and health outcomes/pollutants studied were described highlighting the breadth and extent of the evidence base. For illustration, information was presented visually through bar charts, Venn diagrams, bubble plots, tables and other infographics employing geographic information (maps) using Python and R software. Bar charts were used to indicate the spread of studies across categories (e.g. for cooking, heating or lighting). Bubble plots were used to highlight potential gaps in the evidence base, particularly concerning the relationship between type of fuel and pollutants/outcomes studied. The summarised evidence was reviewed by the full review team to determine the focus of any subsequent meta-analysis.

3. Results: summary of the evidence

The stages of study selection are shown in the PRISMA study flow diagram below (figure 1). A total of 48,130 records were identified through the comprehensive search strategy (reduced to 31,433 after removal of duplicates). Following screening of titles and abstracts, 1,103 articles were selected as potentially relevant and appraised with full text review (956 from international databases, 142 from the Chinese databases and a further 5 identified through expert consultation). 587 were selected as relevant for inclusion in the WHO health effects of liquid and gaseous fuels evidence database.

3.1. Study location, household energy use and year of publication

Studies were conducted across a total of 74 countries with 217 in HICs, 115 in upper-middle-income countries, 164 in lower-middle-income countries, 78 in low-income countries, and 13 where multiple countries were examined (see table 1). Study country was classified according to the World Bank income classification (World Bank 2021). India (n = 110), China (n = 83) and the United States (n = 73) were the most frequently studied locations, with the United Kingdom (n = 30), Nigeria (n = 20), Australia (n = 18), and Nepal (n = 16) also providing multiple studies. A total of 21 countries had only one study providing evidence. Figure 2 highlights the distribution of studies by WHO region, including 139 studies in the South-East Asia region, 127 in the Western Pacific, 123 in the Americas, 103 in Europe, 55 in Africa and 31 in the Eastern Mediterranean region (figure 2).

In terms of energy use, most studies (n = 518, 88.2%) considered cooking, with 220 (37.5%) focused on heating and only a small number considered lighting (n = 47, 8.0%). About a third (n = 175; 29.8%) of the studies looked at both cooking and heating. Studies that focused on heating were predominantly located in high income countries (n = 135; 61.4%), and those that focused on cooking were mostly from lower-middle- or upper-middle-income countries (n = 258; 49.7%). Those studies focused on lighting were mostly located in lower-middle- and low-income countries (n = 39; 83.0%).

Considering the dates of when studies were conducted, the number of studies on cooking fuels has greatly increased since 1980 (figure 3(A)), with by far the majority of studies being published in the last decade (2010–2020), particularly in LMICs. This recent rapid increase in evidence is unique to studies of cooking fuels (and to some extent lighting) (figure 3(D)) with studies of heating fuels (or a combination of heating and cooking) remaining constant after a slight increase in 2000 (figures 3(B) and (C)).

3.2. Study design and target population

The majority of evidence is derived from cross-sectional studies (n = 348; 59.3%) collecting information on household energy use and health effects simultaneously (table 2, supplementary material figure S1). Observational analytic studies including cohort studies (n = 90; 15.3%) and case-control studies (n = 53; 9.0%) were less frequently reported but allow a summary of temporality for associations. In total, 15 studies (2.6%) using a randomised controlled trial study design focused on specified health outcomes following random allocation to a clean (gaseous or liquid) fuel intervention, all conducted in LMIC settings. A total of 40 studies (6.8%) were based on a review of hospital records, with the majority (n = 24) focusing on burns/injuries. Other study designs included case studies (n = 13, 2.2%), or before and after studies with (n = 2, 0.3%) or without (n = 8, 1.4%) a control group. In terms of geographical context, 264 (45.0%) studies were located in urban settings, 195 (33.2%) in rural settings and 50 (8.5%) in peri-urban settings. For 195 (33.2%) studies, the context was not specified (table 2).

In terms of population, 440 studies identified a specific target demographic representing age and/or gender (table 2). Most of these studies (n = 234; 53.3%) focused on adult females, with 122 (27.8%) looking at associations in adult males (supplementary material figure S4). Studies looking at children or adolescent populations included 99 (22.6%) looking at children under 5 years, 142 (32.3%) looking at children ages 5–12 years and 61 (13.9%) concerning children older than 12 years.

3.3. Range of household liquid and gaseous fuels studied

Most studies focussed on gaseous fuels (including LPG and NG) as intervention or focus fuels (n = 509; 86.7%). Kerosene (predominately used for lighting and cooking) was investigated as focus fuel by 182 (31.0%) studies. Of the limited number of studies that investigated other liquid or gaseous fuels, 27 (4.6%) focussed on heating oil, 23 (3.9%) on biogas, 16 (2.7%) on gasoline/petrol, 10 (1.7%) on diesel and 7 (1.2%) on liquid ethanol or ethanol gel. No
evidence on other alcohol fuels, such as methanol, was identified (despite being included in the search strategy). Studies looking at LPG were generally located in LMICs and natural/piped gas in HICs; however, for other fuels, studies were generally conducted evenly across high-, middle- and low-income countries (figure 4).

3.4. Outcomes studied: pollutants, exposures, health outcomes and symptoms
The vast majority \( (n = 415, 70.7\%) \) of included studies focused directly on health outcomes, with 42 \( (7.2\%) \) focusing on biomarkers (e.g. sputum or urinary analysis). Of the studies looking at health outcomes, these either concerned disease and injury outcomes (e.g. burns) \( (n = 209, 50.4\%) \), respiratory and other symptoms \( (n = 42, 10.1\%) \) (e.g. cough), both disease and injury outcomes and symptoms \( (n = 130, 31.3\%) \) or biomarkers only \( (n = 33, 8.0\%) \). 172 \( (29.3\%) \) studies presented results exclusively on pollutant emissions, concentrations, or personal exposures (or a combination of those) from the use of gaseous/liquid fuels. A total of 90 \( (15.3\%) \) studies reported on both health outcomes and air pollutants (figure 5).

Of the studies that measured pollutants, half measured levels of PM (of various sizes) \( (n = 135, 51.5\%) \), half measured NOx \( (n = 133, 50.8\%) \), and over a quarter measured CO \( (n = 34, 13.8\%) \), BTEX \( (n = 13, 5.0\%) \), formaldehyde \( (n = 12, 4.6\%) \), PAHs \( (n = 20, 7.6\%) \), VOC \( (n = 10, 3.8\%) \) and butadiene \( (n = 1, 0.4\%) \). Some studies looked at more than one pollutant \( (n = 101, 38.5\%) \). Studies looking at NOx were generally focussed on usage of NG or LPG (or ‘gas’ in general) for either cooking \( (n = 64) \),
Figure 2. Geographical distribution of studies included in WHO health effects of household liquid & gaseous fuels database by WHO region.

Note: Multi-country studies \((n = 13)\) spanning more than one WHO region were not included in this figure.

Figure 3. Number of studies published between 1980 and 2021 by country income and household energy use.
Table 2. Summary of study design, location, and target population by country income level.

| Characteristic, n (%) | All studies | High-income | Upper-middle-income | Lower-middle-income | Low-income | Multi |
|----------------------|-------------|-------------|---------------------|---------------------|------------|-------|
| **Household energy use (n = 587)** |             |             |                     |                     |            |       |
| Cooking (88.2%)       | 518         | 177 (34.2%) | 106 (20.5%)         | 152 (29.3%)         | 71 (13.7%) | 12 (2.3%) |
| Heating (37.5%)       | 220         | 135 (61.4%) | 47 (21.4%)          | 21 (9.5%)           | 13 (5.9%)  | 4 (1.8%)  |
| Lighting (8.0%)       | 47          | 4 (8.5%)    | 4 (8.5%)            | 20 (42.6%)          | 19 (40.4%) | —      |
| Use unspecified       | 13          | 2 (15.4%)   | 2 (15.4%)           | 6 (46.2%)           | 3 (23.1%)  | —      |
| **Study design (n = 587)** |             |             |                     |                     |            |       |
| Cross-sectional       | 348 (59.3%) | 140 (40.2%) | 61 (17.5%)          | 99 (28.4%)          | 38 (10.9%) | 10 (2.9%) |
| Cohort study          | 90 (15.3%)  | 48 (53.3%)  | 14 (15.6%)          | 16 (17.8%)          | 10 (11.1%) | 2 (2.2%)  |
| Case control study    | 53 (9.0%)   | 11 (20.8%)  | 4 (8.5%)            | 4 (8.5%)            | 20 (42.6%) | 19 (40.4%) |
| Hospital records      | 40 (6.8%)   | 10 (25.0%)  | 11 (27.5%)          | 10 (25.0%)          | 9 (22.5%)  | —      |
| RCT                   | 15 (2.6%)   | —           | 5 (33.3%)           | 8 (53.3%)           | 1 (6.7%)   | 1 (6.7%)  |
| Case study            | 13 (2.2%)   | 4 (30.8%)   | 4 (30.8%)           | 3 (23.1%)           | 2 (15.4%)  | —      |
| Before and after non control | 8 (1.4%) | —           | 3 (37.5%)           | 5 (62.5%)           | —          | —      |
| Autopsy records       | 7 (1.2%)    | —           | —                   | 4 (57.1%)           | 3 (42.9%)  | —      |
| Before and after with control | 2 (0.3%) | —           | 1 (50.0%)           | —                   | 1 (50.0%)  | —      |
| Other                 | 11 (1.9%)   | 4 (36.4%)   | 4 (36.4%)           | 1 (9.1%)            | 2 (18.2%)  | —      |
| **Rural/urban context (n = 587)** |             |             |                     |                     |            |       |
| Urban                 | 264 (45.0%) | 108 (40.9%) | 50 (18.9%)          | 62 (23.5%)          | 40 (15.2%) | 4 (1.5%)  |
| Peri-urban            | 50 (8.5%)   | 16 (32.0%)  | 12 (24.0%)          | 10 (20.0%)          | 11 (22.0%) | 1 (2.0%)  |
| Rural                 | 195 (33.2%) | 25 (12.8%)  | 58 (29.7%)          | 84 (43.1%)          | 24 (12.3%) | 4 (2.1%)  |
| Context unspecified   | 195 (33.2%) | 102 (52.3%) | 24 (12.3%)          | 41 (21.0%)          | 21 (10.8%) | 7 (3.6%)  |
| **Study focus (n = 587)** |             |             |                     |                     |            |       |
| Households            | 181 (30.8%) | 64 (35.4%)  | 43 (23.8%)          | 45 (24.9%)          | 25 (13.8%) | 4 (2.2%)  |
| Population            | 439 (74.8%) | 162 (36.9%) | 83 (18.9%)          | 126 (28.7%)         | 58 (13.2%) | 10 (2.3%) |
| **Population type (n = 449)** |             |             |                     |                     |            |       |
| Female adults         | 234 (53.3%) | 69 (29.5%)  | 47 (20.1%)          | 83 (35.5%)          | 31 (13.2%) | 4 (1.7%)  |
| Children              | 142 (32.3%) | 75 (52.8%)  | 22 (15.5%)          | 26 (18.3%)          | 16 (11.3%) | 3 (2.1%)  |
| 5–12 years            |             |             |                     |                     |            |         |
| Male adults           | 122 (27.8%) | 57 (46.7%)  | 29 (23.8%)          | 17 (13.9%)          | 16 (13.1%) | 3 (2.5%)  |
| Children under 5      | 99 (22.6%)  | 38 (38.4%)  | 16 (16.2%)          | 23 (23.2%)          | 20 (20.2%) | 2 (2.0%)  |
| Adolescents           | 61 (13.9%)  | 29 (47.5%)  | 8 (13.1%)           | 12 (19.7%)          | 11 (18.0%) | 1 (1.6%)  |
| Unspecified demographics | 39 (8.9%) | 5 (12.8%)   | 12 (30.8%)          | 14 (35.9%)          | 7 (17.9%)  | 1 (2.6%)  |

Note: Country income level proportions are calculated by the total studies with that characteristic (e.g. % HIC studies with cross-sectional design = HIC studies with cross-sectional design/All studies with cross-sectional design).

heating (n = 61) or both (n = 8) (figure 6), with the majority (n = 89, 66.9%). Studies focusing on PM or CO tended to concern LPG or NG use for cooking as the ‘intervention’ (figure 6). In terms of location of emission measurement, studies typically focused on primary monitoring of pollutant concentrations in the kitchen (n = 155, 59.4%) or other indoor locations (n = 146, 55.9%), with one-third (n = 85, 32.6%) monitoring ambient conditions. Only about a quarter of studies measured human personal exposure directly (n = 73, 28.0%) (supplementary material figure S5).

Nearly half of all studies assessed health outcomes (both symptoms and disease/injury outcomes) identified by self-report from participants (n = 185, 44.6%), one third of studies used field diagnosis or direct measurement (n = 140, 33.7%), one in four utilised hospital records (n = 101, 24.3%), one in five used physician diagnosis (n = 90, 21.7%) and a small number used laboratory results (n = 37, 8.9%) (supplementary material figure S6).

A wide range of symptoms were assessed (figure 7 A). Of the studies that considered symptoms, most studies assessed wheezing/breathlessness/dyspnoea (n = 120, 69.4%) and cough (n = 106, 61.3%). Other symptoms assessed included phlegm (n = 45, 26.0%), upper respiratory symptoms (36, 20.8%), rhinitis (n = 32, 18.5%), chest pain (n = 24, 13.9%), eye problems (n = 19, 11.0%) and headaches (n = 13, 7.5%). Studies assessing symptoms tended to focus on LPG, NG or kerosene as focus fuels, with very few assessments made for other liquid and gaseous fuel types (supplementary material figure S6).
Of studies assessing disease and injury outcomes, asthma was the most widely studied health effect ($n = 105$, 31.0%), followed by COPD/lung health ($n = 57$, 16.8%), burns and scalds ($n = 56$, 16.5%), bronchitis/lung infections ($n = 51$, 15.0%) and acute lower respiratory infections/pneumonia ($n = 38$, 11.2%). Fewer studies (less than 10% of the overall body of evidence) looked at lung function indicators, adverse pregnancy outcomes, CO poisoning, hypertension, cancer, cardiovascular disease, tuberculosis, accidental poisonings, cognitive development, stroke, cataracts, congenital defects, and diabetes. Similarly, to those studies of symptoms, studies investigating disease and injury outcomes typically focussed on LPG, NG, or kerosene fuels (supplementary material figure S8).

4. Discussion
To our knowledge, this is the first comprehensive synthesis of global evidence of health effects (direct health outcomes/symptoms and emissions of health damaging pollutants) from liquid and gaseous fuels for household energy (cooking, heating, and lighting). The review does not make assumptions about directionality (i.e. looking for both positive and negative health effects from adoption of these various fuels, some of which are considered clean at point of use). An appraisal of the derived evidence-base highlights potential gaps where future research could help improve understanding and lead to informed recommendations where to focus meta-analysis by highlight areas where there is sufficient depth of evidence.
4.1. Gaps in available evidence

Key features of the identified evidence include an uneven proportion of study distribution geographically, with over one third (37.0%) of all studies being conducted in HICs (of which a third were conducted in the United States alone), followed by India and China (18.7% and 14.1% of all studies, respectively). This highlights gaps in evidence of health effects from use of household liquid and gaseous fuels in LMIC geographic locations, such as in sub-Saharan Africa and Latin America, where exposure to polluting fuels remains very high (Lee et al 2020). Evidence on the health impacts of liquid and gaseous fuels in these settings may help elucidate the benefits of cleaner household fuels to policymakers to accelerate policy for clean energy transitions.

In terms of household energy use, the available evidence is dominated by studies focused on cooking, comprising over 88.2% of all studies identified (either alone or in combination with heating) with almost two-thirds of these being conducted in LMICs (63.5%). This is likely the result of increased international attention on cooking with polluting fuels being a modifiable risk factor. Indeed, the number of studies concerning cooking has more than doubled since 2010, when HAP became a key recognised risk factor for global disease burden (GBD) in GBD estimation (Lim et al 2012, Smith et al 2014). Heating was a focus of 37.5% of all studies identified. In contrast to studies of cooking, most studies of heating (61.4%) focussed on HIC settings, where gas (principally NG) is widely used as heating fuel. Very few
Figure 6. Number of studies monitoring health damaging air pollutants by fuel type investigated ($n = 262$).

studies (8.0%) examined lighting, with most these studies from LMIC settings, presumably due to the widespread electricity use in HIC settings and use of polluting fuels (kerosene) in LMICs given the often poor access to reliable supply of electricity in these contexts. These findings highlight the gaps in evidence of the impact of heating in LMICs and an overall paucity of evidence on lighting compared to other household energy uses.

Almost all identified studies (87.7%) focused on use (cooking and/or heating) of gaseous fuels (primarily NG and LPG), rather than liquid fuels. This is likely due to the high availability of gas as a household fuel used for cooking and heating in both HICs and LMICs. According to the International Energy Agency, 43% of the population in LMICs used LPG as a cooking fuel in 2015 and NG is the most common fuel for heating (IEA 2017). LPG is increasingly being promoted to transition away from solid fuels and kerosene across Asia and sub-Saharan Africa, with several countries in the last couple of decades having made important policy commitments to its scale-up (Budya and Arofat 2011, Van Leeuwen et al 2017, Bruce et al 2018, Pollard et al 2018). Countries like India and Indonesia, for example, have achieved significant national transitions to LPG adoption in a very short timeframe (Thoday et al 2018, Smith and Jain 2019). Given such widespread promotion of LPG adoption in LMICs, including prospects for its local production from municipal solid waste and agricultural residues as a fully renewable fuel (bio-LPG) (Chen 2021), understanding any potential adverse health effects linked to use of these fuels is urgently needed.

Of studies focusing on liquid fuels, almost all (86.6%) concerned kerosene. Kerosene is widely used for lighting and cooking in LMICs, as well as for portable heaters in some HICs (Ruiz et al 2010, Hanoune and Carteret 2015); it is classified as a polluting fuel due to emissions of PM (Lam et al 2012, WHO 2014). Potentially cleaner liquid alcohol fuels represented less than 1.8% of all the studies. Bioethanol is now
Figure 7. Number of studies and types of health symptoms (A) and disease and injury outcomes (B) investigated.

Note: The health outcomes shown in these graphs are not mutually exclusive.
being increasingly used for cooking in some limited LMIC contexts due to promotion by international donors, non-governmental organisations and a few private sector players (Puzzolo et al 2016, Mudombi et al 2018, UNIDO 2019, Project Gaia 2022, Whitehouse 2022). While the limited number of studies examining health effects of alcohol fuels likely represents the limited availability of these fuels as routine household energy sources, more evidence on alcohol fuels (including methanol, which is being promoted for blending with ethanol) (Ozier et al 2018, Puzzolo et al 2019, Saraswat and Bansal 2021) will provide better understanding of the risks/benefits to health.

Close to two-thirds of the identified studies (59.3%) included cross-sectional designs with the majority basing findings on self-report of health outcomes. This likely reflects the simplicity/practicality of this type of design and ease of implementation, and wide use of surveys to record health symptoms and conditions from households and in environmental research in general (Odo et al 2021). This is particularly the case for studies targeting young populations where maternal/parental recall is often the primary means for reporting health symptoms and conditions. While cross-sectional study designs and self-reported assessment methods are straightforward to implement, the quality of evidence is likely to be compromised due to known inaccuracies of self-reported assessments (Newell et al 1999) and health effects missed due to single time point in data collection (Wang and Cheng 2020). More research that employs objective and repeated health assessments would confirm associations and strengthen the evidence base.

In terms of populations studied, a considerable proportion of the evidence base related to the health effects among female adults (53.3% of the included studies that included a population sample). This is likely due to the expected impacts of cooking on women, due to gendered household roles and responsibilities (Blackden and Wodon 2006). Another important demographic studied in relation to health effects from fuel use were children; 32.3% of studies focussed on children aged 5–12 years and 22.6% on children below 5 years. Children represent an important study group due to their increased exposure to emissions from cooking and heating whilst being close to their mother and due to their vulnerability in relation to the development of their respiratory system and immune defences (Landrigan 2004, Nandasena et al 2013).

Finally, most studies focused on respiratory illness and diseases, with wheezing, cough, and phlegm being the most commonly assessed symptoms and asthma (31.0% of studies that included a disease or injury outcome) the most common health effect studied. This is likely to reflect the practicality of assessing health indicators that can be measured through self-report in surveys, although this can potentially lead to misclassification in relation to actual health effects. A number of studies (21.5%) concerned health impacts from stove/fuel use other than those from exposure to emissions, including burn and scald injuries and poisoning. These represent an important, and under studied, burden from reliance on polluting solid fuels and kerosene for household energy. Only a small number of studies focused on adverse pregnancy outcomes (5.9%), cardiovascular disease and hypertension (6.4%), cancer (3.5%) and cognitive impairment (0.9%), indicating the difficulty in accurately measuring these health outcomes in epidemiological studies.

4.2. Further research and use of the database

The identified studies for this review are now located in the WHO Health Effects from Liquid and Gaseous Fuels for Household Energy Database, which is hosted by the WHO and accessible online at www.who.int/data/gho/data/themes/air-pollution/health-effects-of-liquid-and-gaseous-fuels-database. This represents a valuable resource to explore a range of research questions focussed on a spectrum of health effects and a range of liquid and gaseous fuels under a variety of contexts. An in-depth quantitative synthesis is currently being conducted investigating the potential positive and negative effects of adoption of gaseous and alcohol fuels for cooking and heating on health.

It is evident from searching the database that future studies and reviews should examine the impact of appropriate kitchen ventilation and gas stove/heater design on reducing emissions and mitigation of the impact ill health (Coker et al 2015, Lebel et al 2022). Future studies should also include a focus on health effects in children from exposure to liquid and gaseous fuels. The database can usefully be expanded in the future by updating searches informed by the study protocol, while no update is currently planned, this may be completed under WHO’s programme of work on clean household energy.

4.3. Limitations of this review

While this systematic review took a comprehensive approach to gather available evidence, only peer-reviewed studies were considered eligible. Searches of grey literature may uncover additional studies; for example, studies looking at the health effects of cooking with methanol or gel fuels are currently lacking in the published literature but might have been undertaken in developmental research by specialist organisations. Such grey literature could be considered in any future updates of the database, pending careful consideration of the robustness and replicability of the research findings.

The current paper should be considered as a mapping of the available evidence to support the
categorisation of studies for further systematic analysis and no conclusions are derived in relation to the positive and/or negative effects of adoption and use of liquid and gaseous fuels for household energy. In addition, studies included in the database have not been directly appraised for quality or synthesized according to specific health effects or exposure to health-damaging pollutants. These steps are encouraged through further reviews that could be conducted using the database as a starting point to identify studies.

5. Conclusions

This is the first time that the evidence on the health effects of liquid and gaseous fuels for household energy use has been systematically collated in a single database and mapped. The review includes liquid and gaseous fuels, which are known to have both negative and positive health impacts in terms of emissions of PM and other pollutants (e.g. kerosene is known to cause high PM$_{2.5}$). A substantial number of relevant studies were identified representing a considerable evidence base on the health effects from the use of liquid and gaseous fuels (587 studies). Studies represent the global state of evidence including both HICs and LMICs conducted over several years, reflecting a substantial increase in research activity over the last two decades, particularly in LMICs. Limited results were reported from Africa and Latin America. Most of the evidence focuses on cooking in LMICs, and around one-third of studies are related to heating in HICs. There is a paucity of evidence on fuel usage for lighting and for fuel types beyond NG and LPG. Women were the most studied population group, with self-reported outcomes the most commonly assessed health symptoms. The majority of studies focused on respiratory illnesses, with LPG, NG and kerosene as focus fuels in these studies. Around a third of studies examining diseases and injuries assessed asthma, and around 70% of studies considering health symptoms focused on wheezing or breathlessness. There is less evidence on other health conditions.

Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: www.who.int/data/gho/data/themes/air-pollution/health-effects-of-liquid-and-gaseous-fuels-database.

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CRediT authorship contribution statement

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