Behavioural factors that drive stacking with traditional cooking fuels using the COM-B model

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Abstract

Globally, 2.8 billion people cook with biomass fuels, resulting in devastating health and environmental consequences. Efforts to transition households to cooking with clean fuels are hampered by "fuel stacking", the reliance on multiple fuels and stoves. Consequently, there have been few interventions that have realised the full potential of clean cooking. Here we conduct a structured literature review (N=100) to identify drivers of fuel stacking and specify them according to a psychological model of behaviour, the Capability-Opportunity-Motivation (COM-B) model. We create a taxonomy of stacking and find that the Physical Opportunity domain accounted for 82% of drivers. Our results have important implications for intervention design as they suggest improving opportunity is the most effective pathway to adoption of cleaner fuels. The findings are used to derive recommendations about how policy makers and practitioners can proactively address drivers of stacking in order to foster adoption of clean cooking stoves and fuels.

Sustainable Development Goal (SDG) 7 calls for universal access to affordable, reliable and modern energy services by 2030 [1], yet 2.8 billion people still cook with traditional biomass fuels (e.g. wood and charcoal) that produce high levels of pollutants with known health effects [2]. This causes four million premature deaths per year [3] and extensive environmental damage that is particularly pertinent in light of the climate crisis [4]–[6].

It is widely accepted that there is no “one stove fits all” resolution to the clean cooking problem, which has long been regarded as primarily a technological issue [7]. The armoury of solutions includes: improved cookstoves (ICS), which are manufactured devices that vary considerably in size and design, aiming to burn biomass more efficiently than their traditional counterparts; liquefied petroleum gas (LPG); biogas; ethanol; electricity; solar; and processed biomass, e.g. briquettes and pellets [8]. Each is suited to different contexts and user needs [9]–[11], meaning that multiple fuels and technologies are likely required for a complete shift from traditional biomass.

Evidence shows that technology provision is only one aspect of the solution, as a new stove rarely completely displaces the old one [12]. This parallel use of multiple stoves and fuels is known as fuel stacking, and, as concluded by a recent review, “everybody stacks” [13]. This is problematic for two reasons: firstly, stacking behaviour still risks exposure to household air pollution [14]; and secondly, some studies have found that the provision of a new stove can increase overall carbon emissions by enabling households to prepare more complex meals that use more energy [15],[16].

There have been notable efforts to aggregate evidence on fuel stacking. Puzzolo et al. performed a systematic review of the barriers and enablers to clean fuel adoption [17]. However, the article combined short-term adoption of clean fuels with factors affecting their sustained use and did not specifically consider stacking. Vigolo et al. specifically examined drivers and barriers to the adoption of ICS [18]. Shankar et al. focused solely on quantitative stacking measurements, and found all papers observed parallel use (28-100%) with traditional stoves [13].

These reviews offer valuable insights into the complex factors that influence fuel stacking. However, they overlook some of the rich detail that can be found in the original sources, such as how the food being cooked or the weather can influence the choice of stove. None of them drew upon behavioural theory, despite mounting consensus that behavioural interventions are required to completely transition to clean fuels [19]–[21].

This Analysis addresses this gap through a review of academic and grey literature to synthesise drivers of stacking for domestic cooks in low and middle-income countries. It finds that stacking is largely driven by the Physical Opportunity domain of the COM-B model. This suggests that the persistence of biomass cooking is less culturally anchored than has previously been assumed, and highlights the importance of providing reliable, affordable access to clean stoves and fuels. Each of the stacking drivers identified were subsequently mapped onto the Theoretical Domains Framework (TDF) and the COM-B model of behaviour, which was used to analyse the results. Please see the Methods for more details.

Fuel Stacking Drivers

Data was extracted from each included article about the year of publication, country of focus, location type and cooking technology (please see the Methods section or further details). Publications about stacking have been increasing rapidly over the past decade (Figure 1). This reflects a growing interest in clean cooking, driven by emerging evidence about its impacts and the inclusion of energy in the SDGs [1]. There has been a recent move away from ICS research in favour of LPG and electric cooking, mirroring a sector-wide shift towards “making the clean available” [22].

A full list of reviewed documents is provided in Table 1. Most papers used mixed-methods (56%) versus qualitative (28%) or quantitative (16%) approaches. The countries with most publications based on the search terms were Kenya (N=13), India (N=12), and Ghana (N=9), likely driven by research links to funding countries, particularly the US and UK. Supplementary Figure 1 contrasts the geographical focus of documents in the review against global access to clean cooking and highlights how little is known about cooking practices in many countries with the lowest access.

The current knowledge base is highly focused in rural locations and sub-Saharan Africa (Figure 1). Much more is known about stacking with LPG, ICS and electric cooking than other fuels. This is unsurprising as LPG and ICS are the most established clean cooking technologies and one of the literature sources, MECS, has an electric cooking focus. The most common electric devices were induction stoves, rice cookers and electric pressure cookers (Supplementary Table 1).

Stacking Taxonomy

Drivers of stacking were extracted from each paper and were thematically grouped into 61 distinct stacking drivers, which fell into 11 categories (Table 2). Each stacking driver was then mapped onto the TDF and the COM-B model (please see the Methods section for more details).

Each technology was associated with different sets of stacking drivers (Figure 2). For example, the affordability category dominated for LPG, especially household income constraints (AFF_2, 7%), the high price of fuel (AFF_1, 6%), the availability of cheaper alternatives (AFF_5, 5%), and the need to buy whole cylinder refills at once (AFF_3, 5%). Supply issues were common, particularly the monetary or time cost to travel to purchase fuel (SUP_4, 6%) and shortages at retail points (SUP_1, 5%). LPG was unable to perform certain cooking tasks (TEC_2, 5%), which usually referred to the high cost of cooking foods with long boiling times on LPG, and tasted worse than traditional alternatives (CUL_1, 7%).

Technical issues were responsible for the largest share of ICS stacking, particularly the stove being too small (TEC_5, 13%), arduous fuel preparation requirements (TEC_10, 9%), and difficulties controlling temperature (TEC_3, 7%). There were frequently reported issues with the compatibility of large pots (EQU_1, 16%) and broken stove equipment (FUN_1, 9%). Affordability issues were notably absent for these stoves, probably because ICS do not require a change to a different purchased fuel.

Stacking of electric cooking devices was heavily driven by inadequate voltage supply (SUP_2, 22% of total drivers identified), with fuel price being a secondary factor (AFF_1, 10%) often compounded by the availability of cheaper alternative fuels (AFF_5, 6%). Electric cooking devices tended to be designed for specific purposes (e.g. boiling water in a kettle) leading to limited ability to perform all tasks (TEC_2, 6%).

Meanwhile, 60% of papers noted that certain foods drove fuel stacking through association with individual drivers, specifically: perception that it is too expensive to cook foods with clean fuel (AFF_6), taste (CUL_1), need for large pots (EQU_1), and the stove being physically unable to perform certain cooking tasks (TEC_2). Table 3 synthesises foods that featured in multiple countries by region. The full list is shown in Supplementary Table 2.

COM-B Analysis

Applying the COM-B model showed that absence of Physical Opportunity was the overwhelming driver of fuel stacking, accounting for 82% of all drivers (Figure 3).

This section discusses each of the COM-B components in turn. The analysis disaggregates by technology only, because of the highly uneven distribution of data by region and location type. It is limited to ICS, LPG and electric because of small sample sizes of the alternatives and draws upon Figure 4 to compare stacking between technologies. There were no drivers for Physical Capability.

Psychological Capability accounted for 3% of all stacking drivers extracted through the literature review. These fell into the Knowledge and Training and Household Dynamics categories of the stacking taxonomy, specifically not all household members (HHD_3) or the main cook (KNO_2) knowing how to use the stove correctly.

Stacking due to a lack of Psychological Capability was more pertinent for electric cooking than for other technologies (6% of total drivers). These were not knowing how to cook chapati on an induction stove [23], not understanding how to use power packs in a battery-powered solution [24] and not knowing how to use the appliances themselves [32],[33] (all KNO_1).

Reflective Motivation was responsible for 5% of all drivers. These fell into the Cultural Compatibility, Knowledge and Training, and Household Dynamics categories. The most frequent drivers were traditional stoves being preferred during festivals (CUL_8), a lack of motivation to use the cleaner stove (KNO_3), and the belief it is healthier to use traditional stoves (CUL_2).

Stacking drivers pertaining to Reflective Motivation were more significant for LPG than for electric cooking. There were misconceptions that LPG directly harms health [27] and that food cooked on LPG is less nutritious that traditional alternatives [33],[35]. During festivals, traditional fuels were often preferred over LPG (CUL_8) [29]–[33], although the extent to which this was driven by Physical Opportunity barriers was often unclear (e.g. the need to cook multiple items simultaneously).

Automatic Motivation was the second most common COM-B element, contributing 9% of all drivers in the Safety, Cultural Compatibility and Technical Characteristics categories. The most common were traditional stove preferred for taste (CUL_1), fuel perceived as dangerous (SAF_2), and fear of gas explosions (SAF_3).

Automatic Motivation was particularly linked to LPG (14% of drivers). This was mostly because of taste preferences [33],[35],[41]–[44], such as food perceived to taste generally unpleasant on LPG [29] or specific dishes tasting better on traditional stoves, like beans [45],[46] and rotis [47],[48]. Concern about general safety issues was common for LPG [34],[36],[41],[42],[49], and was exacerbated by poor quality equipment such as rusting cylinders [43].

This COM-B component was largely irrelevant for ICS. This is likely because switching to ICS does not involve a fuel transition, therefore there is no impact on food taste or new safety risks.

Physical Opportunity consisted of 82% of all drivers and dominated the majority of stacking categories. There were 40 distinct drivers, the most common being: fuel price being too high (AFF_1), broken equipment (FUN_1), and incompatibility of stove with large pots (EQU_1). This component accounted for almost all stacking for each technology (76-91%).

Financial constraints were most significant for LPG, specifically the price of fuel being too high (AFF_1) and income constraints (AFF_2), which were often interrelated. Root causes of income constraints included absence of regular sources of income [51],[52], seasonal income fluctuations [46] and households rationing LPG because they could not afford to buy more fuel [38],[42],[46],[48],[54]. The travel cost of purchasing fuel was also a frequent barrier for LPG (SUP_4), specifically the high financial cost of transportation to fetch refills [36],[40],[51],[53], or the distance and therefore effort requirement [34], [37],[45],[49],[50],[54].

The largest Phy_Opp driver of stacking for electric cooking devices was inadequate voltage supply leading to blackouts and brownouts (SUP_2). This was usually due to unreliable electricity supply, particularly for off-grid consumers [28],[31],[55],[56], although for grid-connected customers load shedding [57],[58] and unreliable power supplies [59],[60] were also limiting. Cooking with electricity often resulted in high energy bills, particularly in comparison to alternative fuels (AFF_1 and AFF_5), [33],[40],[58],[59],[61]. Finally, electric cooking devices were sometimes unable to perform certain tasks (TEC_5), namely long boiling for induction stoves and hot plates [62],[63], and frying in EPCs [57].

For ICS, Phy_Opp stacking was frequently attributed to the stove being too small (TEC_5) and therefore unable to support large cooking pots (EQU_1) [40],[52],[65]–[68]. This made them unsuitable for feeding large groups of people [40],[69]–[71] or for making dishes that are usually cooked in bulk [65]. This is because ICS are usually single-burner devices that cannot physically support large pots. Problems with broken equipment were also common with ICS (FUN_1), particularly battery failures on fan-driven gasifier stoves [58] and low-quality equipment resulting in durability issues [51].

Social Opportunity was responsible for just 1% of all stacking drivers. These fell into the Household Dynamics and Cultural Compatibility categories and applied similarly to ICS, LPG and electric stoves. They included: the social aspects of cooking on traditional stoves (CUL_7), such as grilling corn over open fires being a social pastime during harvest season [62]; and the person who cooks being different to the one buying fuel (HHD_1), such as instances when the cooks do not bear the burden of firewood collection so are less incentivised to move away from traditional fuels [66], when landlords who cover bills do not allow tenants to use electrical appliances [56] or the husband being unwilling to provide cash for LPG refills [45]. Gender norms around use of cooking fuels (HHD_2) applied solely to LPG, such as the accepted norm that men cook with LPG but women with firewood [67].

Discussion

This review has revealed that stacking is a complex and dynamic practice that is sensitive to both the technical characteristics of the stove used, and externalities in the wider cooking system, such as the prices of alternatives, fluctuations in availability, and changes in household circumstance. The review identified 61 drivers, which were grouped into 11 categories. The top three were Affordability (20% of drivers identified), Technical Characteristics (19%) and Fuel Supply Issues (15%), showing that the sustained adoption of clean cooking fuels is not solely a technological problem. Furthermore, 60% of papers noted that certain foods drove stacking. If these dishes form a large part of local diets then they can retain anchorage to traditional cooking fuels. Targeted interventions may be required to decouple reliance on traditional fuels for these foods, e.g. providing pressure cookers that enable beans to be cooked cost-effectively [68].

Different technologies were associated with distinct sets of stacking drivers. ICS allow customers to continue to burn the same fuel, eliminating any affordability, cultural, safety and supply stacking drivers. However, all papers noted technical limitations that hindered their adoption, and there were often compatibility issues with existing pans. Developing a deep understanding of the context-specific user experience of using ICS can ensure that appropriate stove models are deployed.

A relative absence of technical issues for LPG and electric cooking suggested high usability of these technologies. However, they are both purchased fuels requiring a transition away from biomass, leading to affordability barriers that were particularly significant for LPG. This could be because electric devices are usually designed to cost-effectively fulfil specific purposes (e.g. kettles boiling water), whereas LPG cookstoves are used for a wider range of tasks with varying efficiencies. Although not covered in this review, the upfront affordability of electric cooking devices may be a larger barrier to adoption due to this specificity. LPG also suffers from large minimum purchase quantities of fuel, although new business models like pay-as-you-go attempt to overcome this [69], [70].

Supply issues were also prevalent for both fuels but affected electric cooking more than LPG. This could have been because of the frequency with which consumers were affected: electric supply issues are due to blackouts and brownouts, which can occur on a daily basis. LPG supply issues relate to purchasing new fuel cylinders, a task that is likely performed once every few weeks.

The COM-B analysis showed that absence of Physical Opportunity accounted for the vast majority (82%) of all drivers found in the literature review. The dominance of this single component suggests that most stacking with traditional fuels is due to contextual factors, many of which can ultimately be attributed to poverty. However, a review of behaviour change techniques in the clean cooking space found a lack of capability or motivation on behalf of the cook to be the underlying assumption of most interventions [21]. To our knowledge, the only instances of near-exclusive clean fuel use are randomised controlled trials with LPG that focussed heavily on addressing Physical Opportunity barriers [16],[71],[72],[73],[74]. None of these interventions are feasible at scale as they involve providing participants with free fuel, but their results support our conclusions about the importance of increasing Physical Opportunity in promoting stove adoption. Table 4 draws upon these findings to derive recommendations about how policy makers and practitioners can proactively address stacking barriers relating to the top five stacking categories identified. These strategies could promote effective transitions to stacks of cleaner fuels, thus accelerating progress towards SDG7.

The evidence base on fuel stacking is growing exponentially, but is fragmented in its coverage of urbanisation types, technologies and geographies. Therefore, we advocate for research that addresses these gaps and proposes policies that support effective transitions. We also echo the systematic review performed by ESMAP in recommending that more work is needed to understand urban cooking transitions [76].

Our results are limited by the design of the underlying studies, which rarely focussed explicitly on stacking, and generally did not consider the full spectrum of the categories identified here. This meant that the quality of evidence varied greatly and there was sometimes inconsistency in reporting the root cause of behaviour. More rigorous examination of stacking is warranted in future studies. This could be achieved by using the stacking taxonomy identified through this review, or by directly applying COM-B as a data collection and analysis framework.

Conclusion

Fuel stacking is a ubiquitous and persistent practice that undermines the health and environmental benefits of clean cooking. Understanding why people stack is an essential first step in designing effective interventions for transitioning relevant populations to exclusive use of clean fuels. This review aggregated knowledge on this topic and derived insights through the application of a behaviour change framework, the COM-B model. In so doing, it has provided fine-grained detail on the household level drivers of stacking.

Our results reaffirm that different technologies serve separate niches and are suited to varying contexts. It is unrealistic to eliminate fuel stacking, and clean cooking transitions should focus on nudging consumers towards cleaner stacks with a reduced reliance on biomass. We found that stacking is largely driven by the Physical Opportunity domain of the COM-B model, and identified ways that policy makers and practitioners can proactively address drivers of stacking in order to foster adoption of clean technologies.

This review has also revealed that the evidence base needs strengthening. There is a need for further research on a wider range of fuels and on urban locations. The work has also highlighted the limited geographical focus of studies. Alarmingly little is known about most countries whose populations continue to rely heavily on biomass.

SDG7 requires that access to clean fuels and technology for cooking is met by 2030. However, progress is slow and the world is not on track to meet this target. Rather than simply focusing on the provision of clean stoves and fuels, implementers also need to proactively design solutions to limit stacking with polluting alternatives. We believe the insights derived from this review will form a springboard for this shift.

Methods

The COM-B Model

As fuel stacking is a human behaviour, behaviour change interventions are necessary to reduce the harmful environmental and health impacts of cooking with biomass. The behavioural sciences offer a range of theories and models to help in the process of intervention development. One such example is the Capability-Opportunity-Motivation (COM-B) model, which was selected because it was synthesised from 19 other behaviour change frameworks, thus providing a comprehensive model of behaviour that explicitly overcomes the limitations of the frameworks it is constructed from [77]. COM-B is a well-established psychological model of human behaviour that provides a useful framework for identifying the various individual (*e.g., memory, attention, decision making, attitudes, beliefs, values*), socio-cultural and situational influences on a behaviour. This model has been primarily used in clinical applications [78]–[81] and is growing in popularity in other research domains with strong behavioural components, such as the cookstove sector. Examples include a study investigating LPG use amongst pregnant women in Guatemala [82] and the design of a comprehensive intervention to promote exclusive LPG use in Guatemala, India, Peru and Rwanda [74]. In the healthcare sector, using theoretically-grounded approaches is recognised to improve intervention design, enhance knowledge aggregation on the topic of interest and facilitate evaluations of effectiveness [83]; therefore there is great potential utility in applying COM-B as a theoretical framework for examining fuel stacking behaviours.

The COM-B model asserts that an individual's **C**apabilities (psychological and physical), **O**pportunities (social and physical) and **M**otivations (automatic and reflective) interact with each other to influence **B**ehaviour. A consideration of these three components helps to identify barriers to the desired behaviour for a target population. Definitions are as follows [77]:

- **Capability**: refers to physique and stamina (Physical Capability, Phy_Cap) or knowledge, intellectual capacity and memory and decision-making processes (Psychological Capability, Psy_Cap)
- **Opportunity**: refers to the social environment of cultures and norms (Social Opportunity, Soc_Opp) or the physical environment of objects and events with which people interact (Physical Opportunity, Phy_Opp)
- **Motivation**: refers to reflective intentions, evaluations and values (Reflective Motivation, Ref_Mot) and/or automatic habits, emotions and instincts that direct human behaviour (Automatic Motivation, Aut_Mot)

The COM-B model is part of a wider intervention development framework called the Behaviour Change Wheel (BCW) that can aid researchers and practitioners in moving from a 'behavioural diagnosis' i.e., identifying influences on a behaviour (such as the one in this review) to intervention development. Basing the design of interventions on a theoretical understanding of behaviour increases the likelihood that the desired changes in behaviour will occur [84].

Here, COM-B is used as a data analysis framework. We identify and synthesise the factors associated with fuel stacking and organise them according to whether they are aspects of capability, opportunity or motivation. In doing so, we provide a theory- and evidence-based behavioural analysis of the fuel stacking issue.

Literature Search Strategy

Literature was identified through an academic database, Scopus, and four sources of grey literature: the Modern Energy Cooking Services (MECS) research programme (https://mecs.org.uk/); the Clean Cooking Alliance (CCA, https://cleancooking.org/); the World Bank (WB, https://www.worldbank.org/); and the Energy Sector Management Assistance Programme (ESMAP, https://www.esmap.org/). Scopus was chosen because it is the largest multidisciplinary database of peer-reviewed literature [85]. The literature review was not registered.

The Scopus search terms (Supplementary Table 3) were developed using a list of pre-identified criteria papers that met the inclusion requirements (N=20, Supplementary Table 4), which were used to provide confidence in the accuracy and precision of the search strategy. The initial Scopus search across all subject areas produced an unmanageable number of results (N=10,025) containing 15 (80%) of the criteria papers. The search terms were limited to certain subject areas: environment, social science and energy, yielding N=2637 papers. Although this likely excluded some relevant articles, there was still an 80% match against the criteria papers, suggesting that the gain in accuracy outweighed the loss of breadth.

The same literature inclusion criteria produced N=51 relevant MECS documents, N=40 CCA documents, N=8 WB documents and N=2 ESMAP documents.

Literature Eligibility Criteria

An initial screening process was performed on the key words, article types, titles and abstracts of papers found through the searches. The inclusion criteria were: original research articles only; Low- and Middle-Income Country focus only; articles written in the English language only; primary focus on domestic clean cooking; and featured use of clean cooking technology stacked alongside traditional biomass. The full papers were then read, and further exclusions were made for papers that did not cover the reasons behind any patterns of stacking that were measured or observed, producing a final list of N=67 academic papers and N=33 grey literature documents (Table 5).

There was one example where a MECS report [86] had also been published as an academic paper found in the Scopus search [23]; in this case the MECS report was excluded to avoid duplication. Both ESMAP documents were also found in the WB search so were excluded.

Data Extraction and Analysis

The primary author read each paper and recorded the following information in an Excel spreadsheet (see Supplementary Data file):

- Year published
- Country (or countries) of focus
- Technology (or technologies) used
- Location type: rural, urban, peri-urban and displacement
- Quantitative research methods used
- Qualitative research methods used
- The maximum N of any research method in the paper
- All barriers to exclusive use of clean cooking devices and fuels: ICS, LPG, electric, biogas, processed biomass, solar and ethanol
- Mention of specific foods that require a particular stove or fuel

The full list of papers reviewed is shown in Table 1.

As a quality control measure, one of the co-authors independently coded a 10% of the included academic papers. Initially the similarity score was lower than desired (58%), revealing disagreements on two particular papers. The authors resolved these divergences and repeated the process for an additional five papers, resulting in an acceptable similarity score of 87%.

Thematic analysis was chosen as a method to organise the data because of its ability to highlight similarities and differences across data sets that can lead to unanticipated insights [143]. Initially the barriers to exclusive use of clean cooking devices were recorded as free text. These were then descriptively coded into distinct stacking drivers through an inductive approach that aimed to capture the range and richness of why people stack [144]. It was therefore deemed acceptable for a stacking driver to only have one instance of occurrence.

The stacking drivers were then grouped into stacking categories that represented common patterns or themes across the full data set [143]. Categories needed to contain at least two stacking drivers and to represent all of the drivers. Deriving them was an iterative and reflexive process that forms the basis of "goodness" for qualitative inquiry [145]. The final list of stacking categories was validated by taking a 10% sample of the data set and checking that the stacking drivers and categories adequately described the initially recorded free text barriers to exclusive use of clean fuels, thus ensuring interpretive rigour [146]. This analysis produced 61 **stacking drivers** that fell into 11 clusters of **stacking categories.**

The components of the COM-B model map onto the Theoretical Domains Framework (TDF, see Supplementary Table 5), another model used to interrogate determinants of behaviour through 14 theoretical domain functions (Knowledge, Skills, Social / Professional Role and Identity, Beliefs about Capabilities, Optimism, Beliefs about Consequences, Reinforcement, Intentions, Goals, Memory, Attention and Decision Processes, Environmental Contexts and Resources, Social Influences, Emotions, Behavioural Regulation) [147]. Like other studies [74], [79], [148], [149] we used the more granular TDF model as a stepping stone to categorising influences on behaviours according to the COM-B model, thus ensuring that the COM-B mapping was consistent with best practice.

Some papers featured multiple location types or technologies. These papers were disaggregated into multiple data entries in the analysis and stacking drivers were assigned to each paper, location and technology combination accordingly. There were also some instances of ambiguity about how to classify drivers of stacking, for example whether the stove being too small (TEC_5) was the same as the pot being too large (EQU_1). We took a non-reductionist approach of coding each of these reasons separately, in the knowledge that both drivers would map to the same COM-B component and thus not affect the analysis.

This work formed part of a doctoral study. Because of this, the literature screening and the qualitative coding of the data was conducted by one person, and one academic database was used. Scopus was chosen because it is the largest database of peer-reviewed literature and our use of criteria papers confirmed that the database covered relevant literature. Single-person coding enabled methodological consistency and a validation process was undertaken with one of the co-authors, as described above, to ensure the stacking drivers were correctly extracted from the literature in a way that was compatible with use of the COM-B model. The thematic analysis was validated through discussion with the wider research team. Further applications of this method could involve inputs from several individuals and the use of multiple academic databases.

Data Availability

The data that support the findings of this study are available in the Supplementary Information and Supplementary Data files.

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Author Contributions Statement

TP, ALA and PP conceived the study. Formal analysis was done by TP and ALA. Data visualisation was done by TP. The methodology was designed by TP and ALA. JE and PP supervised the study. Validation was conducted by ALA, PP and JT. TP wrote the original and final draft. TP, ALA, JT and PP were responsible for reviewing and editing drafts.

Competing Interests Statement

The authors declare no competing interests.

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Tables

Ref	Author & Year	Technology	Country	Location type	Source	Methodology	Max N
EAST ASIA & PACIFIC							
[87]	Zhu, 2019	Biogas	China	Rural	Academic	Quantitative	34,000
[88]	Christiaensen, 2012	Biogas	China	Rural	WB	Quantitative	2700
[24]	Amperes, 2020	Electric	Myanmar	Rural	MECS	Mixed	7
[89]	Leary, 2019	Electric	Myanmar	Peri-urban, rural	MECS	Qualitative	98
[90]	Leary, 2019	Electric	Myanmar	Peri-urban, rural	MECS	Mixed	22
[91]	Nansaior, 2011	Electric, LPG	Thailand	Peri-urban, rural, urban	Academic	Mixed	Not provided
[26]	International Developmen Enterprises, 2020	Electric, LPG	Cambodia	Peri-urban, rural, urban	MECS	Mixed	Not provided
[59]	Nguyen, 2019	ICS	East Timor	Urban	Academic	Qualitative	22
[92]	Clark, 2017	Processed biomass	China	Rural	Academic	Mixed	204
LATIN AMERICA & CARIBBEAN							
[49]	EarthSpark, 2020	Electric	Haiti	Rural	MECS	Mixed	28
[62]	Bielecki, 2014	ICS	Guatemala	Rural	Academic	Qualitative	20
[32]	Ruiz-Mercado, 2013	ICS	Guatemala	Rural	Academic	Quantitative	80
[93]	Gould, 2018	ICS	Peru	Rural	Academic	Mixed	699
[94]	Pine, 2011	ICS	Mexico	Rural	Academic	Quantitative	259
[95]	Ruiz-Mercado, 2015	ICS, LPG	Mexico	Rural	Academic	Mixed	100
[36]	Keese, 2017	ICS, LPG	Peru	Rural	Academic	Mixed	41
[34]	Thompson, 2018	LPG	Guatemala	Peri-urban	Academic	Mixed	187
[28]	Hollada, 2017	LPG	Peru	Rural	Academic	Qualitative	31
[35]	Williams, 2020	LPG	Peru	Rural	Academic	Qualitative	22
[29]	Nuño Martinez, 2020	LPG	Peru	Rural	Academic	Mixed	48
[30]	Pollard, 2018	LPG	Peru	Rural	Academic	Mixed	375
[38]	Troncoso, 2019	LPG	Mexico	Rural	Academic	Mixed	190
[39]	Williams, 2020	LPG	Peru	Rural	Academic	Mixed	180
[96]	Labriet, 2015	LPG	Guatemala	Urban, peri-urban	CCA	Qualitative	60

[97]	Berkeley Air Monitoring Group, 2016	Processed biomass	Haiti	Urban	CCA	Mixed	20
[66]	Bauer, 2016	Solar	Nicaragua	Rural	Academic	Mixed	57
SOUTH ASIA							
[98]	Chalise, 2018	Biogas	India	Rural	Academic	Mixed	20
[99]	Shankar, 2014	Biogas, electric	Nepal	Peri-urban	CCA	Quantitative	1538
[100]	Herington, 2017	Biogas, LPG, solar	India	Rural	Academic	Qualitative	40
[48]	Banerjee, 2016	Electric	India	Rural	Academic	Mixed	1020
[23]	Clements, 2020	Electric	Nepal	Rural	Academic	Mixed	10
[40]	Jagadish, 2018	Electric, LPG	India	Rural	Academic	Qualitative	33
[60]	Rosenbaum, 2015	ICS	Bangladesh	-	Academic	Mixed	120
[101]	Wilson, 2018	ICS	India	Rural	Academic	Quantitative	72
[61]	Lam, 2017	ICS	Nepal	Rural	Academic	Mixed	110
[102]	Singh, 2014	ICS	India	Rural	CCA	Mixed	320
[103]	WASHPlus, 2014	ICS	Bangladesh		CCA	Mixed	120
[41]	Wang, 2015	ICS, LPG	India	Rural, urban	Academic	Mixed	43
[31]	Raynes-Greenow, 2020	LPG	Bangladesh	Rural	Academic	Mixed	50
[27]	Gould, 2018	LPG	India	Rural	Academic	Quantitative	8500
[104]	Billah, 2020	LPG	Bangladesh	Rural	Academic	Mixed	299
[67]	Malakar, 2018	LPG	India	Rural	Academic	Qualitative	31
[105]	Lambe, 2012	LPG	India	Rural	CCA	Mixed	13
[106]	Nathan, 2018	LPG	China, India and Nepal	Rural	Academic	Mixed	Not provided
[107]	Thurber, 2014	Processed biomass	India	Rural, urban	Academic	Mixed	998
SUB-SAHARAN AFRICA							
[108]	Lwiza, 2017	Biogas	Uganda	Rural	Academic	Qualitative	174
[109]	Nape, 2019	Biogas	South Africa	Rural	Academic	Mixed	Not provided
[110]	Berhe, 2017	Biogas	Ethiopia	Rural	Academic	Qualitative	300
[111]	CREATIVenergie,, 2020	Biogas	Tanzania	Rural	MECS	Mixed	Not provided
[55]	Chirwa, 2010	Electric	South Africa	Rural	Academic	Qualitative	120
[57]	Serenje, 2020	Electric	Zambia	Urban	MECS	Qualitative	11
[112]	Pesitho, 2020	Electric	Uganda	Displacement	MECS	Mixed	20
[113]	Kachione, 2020	Electric	Malawi	Rural	MECS	Mixed	65
[114]	PowerGen Renewable Energy Ltd, 2020	Electric	Tanzania	Rural	MECS	Quantitative	22
[115]	Leary, 2019	Electric	Tanzania	Urban	MECS	Mixed	22
[52]	Leary, 2019	Electric	Tanzania	Peri-urban, rural, urban	MECS	Qualitative	Not provided
[25]	Leary, 2019	Electric	Kenya	Urban	MECS	Mixed	19

[54]	Coley, 2020	Electric	Malawi	Peri-urban, rural, urban	MECS	Mixed	57
[56]	Leary, 2019	Electric	Zambia	Peri-urban, rural, urban	MECS	Qualitative	Not provided
[50]	Leary, 2019	Electric	Zambia	Urban	MECS	Mixed	20
[51]	Pailman, 2018	Electric, ICS	South Africa, Mozambique, Malawi, Zambia	Peri-urban, rural, urban	Academic	Mixed	126
[33]	Jewitt, 2020	Electric, ICS, LPG	Nigeria	Peri-urban, rural, urban	Academic	Qualitative	49
[53]	Mguni, 2020	Electric, processed biomass	Uganda	Urban	Academic	Qualitative	Not provided
[116]	Mudombi, 2018	Ethanol	Mozambique	Urban	Academic	Mixed	341
[117]	Benka-Coker, 2018	Ethanol	Ethiopia	Displacement, urban	Academic	Mixed	50
[118]	Gitau, 2019	ICS	Kenya	Rural	Academic	Mixed	50
[119]	Akintan, 2018	ICS	Nigeria	Peri-urban	Academic	Mixed	350
[58]	Dickinson, 2019	ICS	Ghana	Rural	Academic	Mixed	200
[120]	Namagembe, 2015	ICS	Uganda	Peri-urban, urban	Academic	Mixed	50
[63]	Onyeneke, 2019	ICS	Nigeria	Rural	Academic	Mixed	400
[64]	Person, 2012	ICS	Kenya	Rural	Academic	Qualitative	40
[121]	Burwen, 2012	ICS	Ghana	Rural	Academic	Mixed	768
[122]	Dresen, 2014	ICS	Ethiopia	Rural	Academic	Mixed	148
[123]	Jagger, 2016	ICS	Malawi	Rural	Academic	Mixed	383
[124]	Lozier, 2016	ICS	Kenya	Rural	Academic	Mixed	45
[125]	Martin, 2013	ICS	Uganda	Peri-urban	Academic	Qualitative	48
[126]	O'Shaughnessy, 2015	ICS	Malawi	Rural	Academic	Quantitative	10
[127]	Piedrahita, 2016	ICS	Ghana	Rural	Academic	Quantitative	200
[128]	GIZ, 2012	ICS	Kenya	Rural	CCA	Mixed	1249
[129]	Alemu, 2020	ICS	Ethiopia	Rural	WB	Quantitative	504
[130]	Samad, 2019	ICS	Kenya	Rural	WB	Quantitative	3002
[131]	Beyene, 2015	ICS	Ethiopia	Rural	WB	Quantitative	504
[65]	Ochieng, 2020	ICS, LPG	Kenya	Rural, urban	Academic	Qualitative	71
[45]	Agbokey, 2019	ICS, LPG	Ghana	Rural	Academic	Qualitative	113
[44]	Abdulai, 2018	LPG	Ghana	Rural	Academic	Mixed	200
[43]	Ronzi, 2019	LPG	Cameroon	Peri-urban, rural	Academic	Qualitative	15
[132]	Treiber, 2017	LPG	Kenya	Peri-urban, rural	Academic	Mixed	320
[42]	Pye, 2020	LPG	Cameroon	Peri-urban, rural	Academic	Quantitative	3343
[46]	Asante, 2018	LPG	Ghana	Rural	Academic	Qualitative	200
[133]	Iribagiza, 2020	LPG	Rwanda	Rural	Academic	Qualitative	10

[134]	Wiedinmyer, 2017	LPG	Ghana	Rural, urban	Academic	Quantitative	248
[47]	ClimDev, 2020	LPG	Nigeria	Peri-urban	MECS	Qualitative	150
[135]	SCODE, 2020	LPG	Kenya	Rural	MECS	Quantitative	168
[136]	Ipsos Ltd, 2014	LPG	Kenya	Rural, urban	CCA	Mixed	818
[137]	Global Alliance for Clean Cookstoves, 2014	LPG	Ghana	Urban, rural	CCA	Qualitative	Not provided
[138]	Bailis, 2020	Processed biomass	Kenya	Peri-urban	Academic	Mixed	150
[139]	Lambe, 2020	Processed biomass	Kenya	Peri-urban	Academic	Mixed	30
[140]	Global Alliance for Clean Cookstoves, 2018	Processed biomass	Rwanda	Displacement	CCA	Mixed	100
[141]	Jürisoo, 2018	Processed biomass	Kenya and Zambia	Peri-urban, urban	Academic	Qualitative	36
[142]	California Polytech State University, 2020	Solar	Ghana	Rural	MECS	Qualitative	10

Table 1: Summary of papers included in literature review

Category	Code	Description	TDF	COM-B	N	
AFFORDABILITY (AFF)	AFF_1	Fuel price too high	Environmental context and resources	Phy_Opp	26	103
	AFF_2	Income constraints	Environmental context and resources	Phy_Opp	22	
	AFF_3	Can't afford to buy fuel in the quantities it is sold in	Environmental context and resources	Phy_Opp	13	
	AFF_4	Fuel price changes	Environmental context and resources	Phy_Opp	7	
	AFF_5	Availability of cheaper alternative fuels	Environmental context and resources	Phy_Opp	18	
	AFF_6	Too expensive to cook certain foods on clean stove	Environmental context and resources	Phy_Opp	14	
	AFF_7	Distortions in affordability caused by subsidies	Environmental context and resources	Phy_Opp	3	
CULTURAL COMPATIBILITY (CUL)	CUL_1	Traditional stove preferred for taste	Reinforcement	Aut_Mot	22	38
	CUL_2	Belief that it is healthier to cook on traditional stove	Beliefs about consequences	Ref_Mot	3	
	CUL_3	Traditional stove necessary for ceremonial rituals	Beliefs about consequences	Ref_Mot	1	
	CUL_4	Importance attached to cooking the traditional way	Social, professional role and identity	Ref_Mot	2	
	CUL_5	Culturally inappropriate to remove a pot from flame whilst cooking	Social, professional role and identity	Ref_Mot	1	
	CUL_6	Belief that wood smoke solidifies walls of buildings	Beliefs about consequences	Ref_Mot	1	
	CUL_7	Social aspects of cooking with traditional stoves	Social influence	Soc_Opp	1	
	CUL_8	Traditional stoves preferred during festivals	Social, professional role and identity	Ref_Mot	7	
END USES OF TRADITIONAL STOVES (END)	END_1	Wood smoke is used to preserve meat and fish	Environmental context and resources	Phy_Opp	2	27
	END_2	Space heating	Environmental context and resources	Phy_Opp	13	

	END_3	Space lighting	Environmental context and resources	Phy_Opp	2	
	END_4	Wood collection is an important source of income	Environmental context and resources	Phy_Opp	1	
	END_5	Wood smoke keeps insects away	Environmental context and resources	Phy_Opp	1	
	END_6	Embers and ashes from traditional stove are used in cooking	Environmental context and resources	Phy_Opp	8	
EQUIPMENT COMPATIBILITY (EQU)	EQU_1	Clean cooking device cannot be used with large pots	Environmental context and resources	Phy_Opp	25	33
	EQU_2	Clean cooking device damages traditional pots	Environmental context and resources	Phy_Opp	8	
STOVE FUNCTIONALITY (FUN)	FUN_1	Broken equipment	Environmental context and resources	Phy_Opp	29	50
	FUN_2	Customers do not know how to fix and maintain equipment	Knowledge	Psy_Cap	7	
	FUN_3	Lack of local technicians to fix and maintain equipment	Environmental context and resources	Phy_Opp	6	
	FUN_4	Lack of access to spare parts	Environmental context and resources	Phy_Opp	7	
	FUN_5	Stove use minimised to avoid damaging stove	Environmental context and resources	Phy_Opp	1	
HOUSEHOLD DYNAMICS (HHD)	HHD_1	Person who cooks is usually different to the one paying for fuel	Social influences	Soc_Opp	3	15
	HHD_2	Gender norms around use of cooking fuels	Social influences	Soc_Opp	2	
	HHD_3	Not all members of the household know how to use stove	Knowledge	Psy_Cap	6	
	HHD_4	Safety concerns from other members of the household	Beliefs about consequence	Ref_Mot	1	
	HHD_5	High labour requirement for feeding biogas digester	Environmental context and resources	Phy_Opp	3	
KNOWLEDGE AND TRAINING (KNO)	KNO_1	Low awareness of how to use stove correctly	Knowledge	Psy_Cap	9	16
	KNO_2	Belief certain foods cannot be cooked on stove	Beliefs about consequence	Ref_Mot	2	
	KNO_3	Lack of motivation to use clean cook device	Intention	Ref_Mot	5	
SAFETY ISSUES (SAF)	SAF_1	Fear of short-circuiting electricity in the house	Emotion	Aut_Mot	1	20
	SAF_2	Fuel perceived as dangerous	Emotion	Aut_Mot	8	
	SAF_3	Fear of gas explosions	Emotion	Aut_Mot	7	
	SAF_4	Fear of burns	Emotion	Aut_Mot	4	
FUEL SUPPLY ISSUES (SUP)	SUP_1	Fuel shortages at retail points	Environmental context and resources	Phy_Opp	19	75
	SUP_2	Inadequate voltage supply	Environmental context and resources	Phy_Opp	18	
	SUP_3	Lack of raw materials to produce fuel	Environmental context and resources	Phy_Opp	14	
	SUP_4	Travel cost or distance to purchase fuel	Environmental context and resources	Phy_Opp	12	
	SUP_5	Weather impacts on fuel supply	Environmental context and resources	Phy_Opp	9	
	SUP_6	Distrust in local fuel retailers	Optimism	Ref_Mot	3	
TECHNICAL CHARACTERISTICS (TEC)	TEC_1	Stove doesn't get hot enough	Environmental context and resources	Phy_Opp	4	98
	TEC_2	Stove is physically unable to perform certain cooking tasks	Environmental context and resources	Phy_Opp	21	

	TEC_3	Difficulties controlling temperature	Environmental context and resources	Phy_Opp	17	
	TEC_4	Difficulties lighting stove	Environmental context and resources	Phy_Opp	6	
	TEC_5	Stove too small	Environmental context and resources	Phy_Opp	22	
	TEC_6	Stove produces unpleasant smell whilst cooking	Reinforcement	Aut_Mot	2	
	TEC_7	Stove is smoky	Environmental context and resources	Phy_Opp	3	
	TEC_8	Can't track fuel use and therefore expenditure	Environmental context and resources	Phy_Opp	7	
	TEC_9	Stove not portable	Environmental context and resources	Phy_Opp	3	
	TEC_10	Inconvenience of fuel preparation for clean stove	Environmental context and resources	Phy_Opp	8	
	TEC_11	Difficulties reloading fuel for clean stove	Environmental context and resources	Phy_Opp	5	
TIME ASPECTS (TIM)	TIM_1	Need to cook multiple items at once	Environmental context and resources	Phy_Opp	13	39
	TIM_2	Cannot multi-task whilst using stove	Environmental context and resources	Phy_Opp	3	
	TIM_3	Seasonal variation in fuel usage	Environmental context and resources	Phy_Opp	13	
	TIM_4	Stove takes too long to cook	Environmental context and resources	Phy_Opp	10	

Table 1: Taxonomy of stacking drivers mapped to the TDF and COM-B models. *Phy_Cap = Physical Capability; Psy-Cap = Psychological Capability; Soc_Opp = Social Opportunity; Phy_Opp = Physical Opportunity; Ref_Mot = Reflective Motivation; Aut_Mot = Automatic Motivation*

Region	Foods that drive stacking across multiple countries
East Asia & Pacific (N=9)	Grilling meat (N=2)
Latin America & Caribbean (N=17)	Beans / fava beans (N=8), maize / corn (N=4), nixtamal (N=4), soup (N=3), tortillas (N=3), heating water (N=3)
South Asia (N=19)	Chapatis / rotis (N=6), preparing animal feed (N=4), heating water (N=3), rice (N=2)
Sub-Saharan Africa (N=55)	Beans (N=8), ugali (N=7), githeri / makande (N=6), tuo zaafi (N=3), chapatis (N=3), heating water (N=3), matoke / plantain (N=3), injera (N=2), coffee (N=2), green peas (N=2), preserving meat and fish (N=2), banku (N=2)

Table 2: Regional foods that drove stacking. *Note that nixtamal is grain (usually maize) soaked in an alkaline solution, most often used to make tortillas; ugali is a stiff maize flour porridge; githeri or makande is a traditional stew of corn and beans; tuo zaafi is a millet / maize porridge; and banku is a white paste made from fermented corn and cassava*

Stacking category	Policy makers	Practitioners

Affordability	• Reaching the bottom of the pyramid with purchased clean fuels is likely to require policy interventions such as targeted subsidies, tax exemptions or price caps (AFF_1, AFF_2, AFF_5). • Consumers may need protection from market price volatilities for sustained adoption (AFF_4), particularly through times of economic hardship, when they are most at risk of reverting to cheaper biomass fuels • Increase prices and availability of polluting alternatives (AFF_3) e.g. by raising kerosene taxes or logging bans aimed at reducing charcoal production • There is a complex relationship between household energy and food security [75]; clean fuels must be sufficiently affordable to meet the dietary and cooking needs of families (AFF_1, AFF_2, AFF_5).	• Important to target demographics with sufficient purchasing power to afford clean fuels (AFF_1, AFF_2, AFF_5) • Reduce the minimum purchase requirement to match polluting alternatives (AFF_3) • Price competitively against alternative fuels in order to achieve high levels of adoption (AFF_5)
Technical characteristics	• Recognise that multiple fuels and technologies are likely required to transition away from polluting fuels in clean cooking strategy, especially if traditional stoves fulfil other end uses such as space heating (AFF_6, END_2, END_3, EQU_1, TEC_2, TIM_1, TIM_2)	• It is critical to consider the compatibility of stoves with cooking practices and cuisines (TEC_2, TEC_5, TEC_10) • A positive user experience is critical for adoption. Stoves must provide adequate heat and be easy to control (TEC_1, TEC_3, TEC_10) • Stove needs to be adequately sized (TEC_5) • Consider provision of multiple complementary technologies to meet the dietary and cooking needs of families to facilitate transition to stack of clean fuels (AFF_6, END_2, END_3, EQU_1, TEC_2, TIM_1, TIM_2)
Fuel supply issues	• Important to recognise the link between physical infrastructure and cooking fuels. There is a need to match infrastructure to the national strategy for clean cooking adoption (e.g. adequate LPG storage facilities and maintained roads throughout the year for distribution) (SUP_1, SUP_2, SUP_5)	• Prioritise making clean fuels easily accessible, such as through home delivery or increased density of retail points (SUP_1, SUP_4, SUP_5) • Consider physical infrastructure in assessing market expansion opportunities; for example, avoid selling high-intensity electric cooking devices in weak grid areas (SUP_1, SUP_2)
Stove functionality	• Impose technical standards to ensure provision of quality devices (FUN_1)	• Provide equipment warranties to encourage regular use (FUN_1, FUN_5) • Prioritise quickly fixing functionality issues when they occur (FUN_1, FUN_4) • Focus on distributing quality devices (FUN_1) • Train customers in how to conduct simple fixes and maintenance themselves (FUN_2)
Time aspects	-	• Stoves should be able to perform multiple cooking tasks at once, e.g. have two burners on LPG or ethanol stoves (TIM_1) • Consider mechanisms to buffer seasonal variations in clean fuel use. For example, extend small fuel loans to support customers through times of year when cash is short (TIM_3)

Table 3: Recommendations for policy makers and practitioners

Figure Legends

Figure 1: Summary of papers identified in the literature review. *Papers are broken down by (a) publication dates and technologies; (b) regional distribution; (c) location type; and (d) technology only. P_B = processed biomass.*

Figure 2: Radial graphs showing stacking drivers for each technology. *The spokes on the wheel represent individual drivers and the black bars show the number of papers featuring each stacking driver for (**a**) LPG papers, N=35 (**b**) ICS papers, N=34 (**c**) electric papers, N=24. There were considerably more stacking drivers per paper for LPG (n=6.0) than for electric (n=3.2) or ICS (n=2.6). Note this figure excludes technologies featured in <10 papers.*

Figure 3: Proportion of stacking drivers by COM-B component

Figure 4: Breakdown of contributions by COM-B components. *These graphs show the proportion of COM-B components contributing to each technology (**a**) and stacking category (**b**). P_B = processed biomass. AFF = affordability, CUL = cultural compatibility, END = end uses of traditional stoves, EQU = stove and equipment compatibility, FUN = stove functionality, HHD = household dynamics, KNO = knowledge and training, SAF = safety issues, SUP = fuel supply issues, TEC = technical characteristics, TIM = time aspects.*

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