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What's in a stove? A review of the user preferences in improved stove designs

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ABSTRACT

2.9 Billion people lack access to secure and affordable clean cooking fuels and technologies. Numerous studies and initiatives have attempted to design and implement more efficient stoves, but often these efforts fail as the combination of stove design, fuel access, or management issues does not meet the cook's needs or preferences. This review analyzes the stove functions, characteristics, or features that households value in their cook stove. From these data, we explore user preferences, which we catalog within the Technology Acceptance Model along seven dimensions that arose in the literature: technical design and stove operation, fuel characteristics, technical details or features, kitchen space, household food and taste demands, household schedules, and social and cultural aspects. Overall, households need a stove that meets their large cooking demands and can perform a range of cooking functions at a range of cooking speeds. In order to meet these requirements, we advocate that private and public stove programs bundle stove models to meet all the households' needs to ensure both adoption and consistent, exclusive use.

1. Introduction

Clean[1] cooking stoves and fuels are a primary focus for innovation and dissemination to meet Sustainable Development Goal (SDG) 7, which calls for *"universal access to affordable, reliable, modern energy services"* [1] (pg. 1). The adoption and continued use of clean-burning stoves by the 2.9 billion people relying on traditional fuels is necessary for health, gender equality, and climate [1]. Access to clean cooking fuel would help prevent up to 3.7 million untimely deaths annually that are attributed to household air pollution (HAP) [2]. HAP leads to respiratory infections, ischemic heart disease, stroke, and cancer [3]. Globally, women conduct 91% of the household work to obtain fuel [4] and women account for over 60% of all premature deaths from HAP because they are typically the primary cooks [5]. Unimproved stoves (e.g. three-stone fires or inefficient stoves that burn traditional fuels) contribute an annual 120 megatons of climate pollutants, specifically black carbon, which is the second largest contributor to climate change [6]. Household cookstoves produce ~ 25% of the total annual anthropogenic black carbon emissions globally [7]. Biomass stoves range from simple firewood- and charcoal-burning devices to improved Rocket, forced-draft, and more efficient charcoal stoves. Although improved stoves produce fewer emissions than three-stone fires [8–10], a review of 19 widely disseminated stove types shows that even improved stoves pose a public health risk [11] and in addition, lack of culturally

Abbreviations: BLEEN, Biogas, LPG, electricity, ethanol, and natural gas; ESMAP, Energy Sector Management Assistance Program; EThOS, e-theses online service (from the British Library); HAP, Household Air Pollution; ISO, International Organization for Standardization; IWA, International Workshop Agreement; LILACS, Caribbean Health Sciences Literature; LMIC, Low- and middle-income country; LPG, Liquified Petroleum Gas; NDLTD, Networked Digital Library of Theses and Dissertations; SDG, Sustainable Development Goal; WHO, World Health Organization; $\mu g/m^3$, Micro-gram per cubic meter.

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[1] The Energy Sector Management Assistance Program (ESMAP) defines clean cookstoves as "cookstoves that produce significantly less household air pollution than traditional three-stone open-fire stoves and meet a specified emissions standard"[233] (pg. viii). However, we will explicitly refer to fuels or cookstoves as "clean" only if they meet the WHO's air pollution limits of $<35\ \mu g/m^3$ Particulate Matter and $<7 mg/m^3$ Carbon Monoxide.

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appropriate training means that many are often used incorrectly. Currently, only a single firewood pellet stove has been proven to meet international standards for particulate matter and carbon monoxide[2], nearing the low emissions of liquified petroleum gas (LPG) or other liquid fuels [12]. Biogas, LPG, electricity, ethanol, and natural gas (BLEEN) stoves meet these strict health and emission standards.

Despite the health risks, there are widespread barriers to the adoption, and to the continued and exclusive use, of improved stoves. Notable barriers include affordability, unreliable supply, social acceptability, household education levels, household socio-economic and demographic characteristics, low total perceived benefits, and preference for the traditional stove [1,13–17]. Progress towards SDG 7 has been slow: From 2010 to 2017, the global population with access to clean cooking fuels and technology only increased from 57% [CI: 51, 62] to 61% [CI: 54, 67] [1].

Adoption and consistent use of clean fuels and stoves are crucial to achieving SDG 7, and yet many stove programs focus on the hardware and not long-term user acceptance, feedback, or continued stove maintenance. Even when households obtain a clean-fuel stove, they may use it in addition to their traditional, unclean stoves [18], a behavior called stove stacking. Stove stacking is problematic as the benefits from reduced exposure occur under 1000–2000 $\mu g/m^3$ of particulate matter [19], and conventional stove usage must fall to under three hours a week to achieve the HAP particulate matter target from the World Health Organization (WHO) [20]. Numerous studies and initiatives have attempted to design and implement more efficient stoves, but often these efforts fail as the stove design does not meet the cook's needs or preferences [21]. The earliest improved stoves were designed by aid workers and engineers without input from the local cooks [21]. The designers often ignored input from national experts and most notably local cooks, who for centuries had been the true stove designers [22]. This gender lens on stoves is, remarkably, still not a core tenet in stove programs. There have been calls to incorporate user perspectives into clean cooking interventions [23]; however, there has not yet been a review to compile the field's understanding of these preferences. This review aims to isolate and better understand the stove features that households require and prefer to ensure the adoption and consistent use of clean(er) cooking.

The objective of this review is to extract stove functions, characteristics, and features that households value in their cook stove and collect positive and negative use cases to further understand household stove preferences. Previous reviews have focused on the drivers and barriers to the adoption of improved biomass and clean fuels [24,25], the characteristics of clean fuel adopters [26], the market/supply side barriers [27,28], the technological advancement of stoves [29], the health impacts of different stoves, and even the behavior change strategies utilized to promote clean fuel use [30,31]. However, this review attempts to shift the paradigm to looking at the literature to understand what the cook would actually want, rather than understanding the challenges of the current options. Review papers, particularly in the field of clean cooking which spans multiple disciplines, are crucial to condensing the vast number of studies from very different contexts to draw out common themes and lessons in order to quickly and efficiently achieve SDG 7. This review aims to reflect the nuances of a cook's intimate cooking experience within the context of the demands of their household, their communities, their culture, and their own preferences. By providing a deeper understanding of these nuances, we aim to inform stove designers, developers, and policy makers to design and promote stove programs that households will actually adopt and consistently use.

The remainder of the review will detail the methods utilized to conduct this review, the results which are organized by the theoretical lens and regional differences, a discussion of the findings, and finally a conclusion from these results.

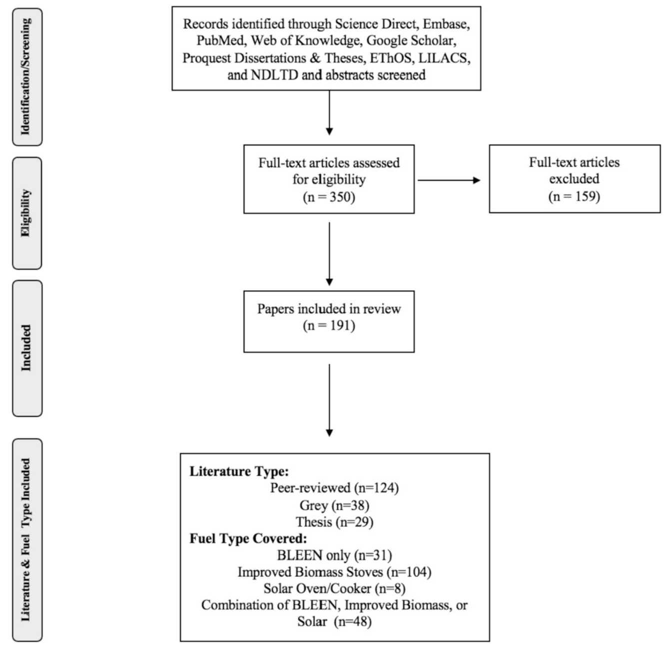

Fig. 1. Literature selection process from identification and screening to the papers included and finally broken down by literature and cooking fuel type.

2. Methods

We conducted a comprehensive review of peer and grey literature as well as theses between October 2020 and December 2020. We searched through Science Direct, Google Scholar, Embase, PubMed, Web of Knowledge, LILACS, Proquest Dissertations & Thesis, Ethos, and NDLTD. We searched through grey literature databases from the Clean Cooking Alliance, the Energy Sector Management Assistance Program (ESMAP), the WHO, and improved stove start-ups.

The primary criteria for inclusion in our review of the grey and peer-reviewed literature was an improved cookstove or clean stove intervention report or commentary published between 1980 and 2020, in a low- and middle-income country (LMIC), in which users' or households' stove preferences were explicitly discussed. We focused on low- and middle- income countries as the World Bank reports that as of 2019 these countries represent the populations with the largest clean cooking deficits [1]. The term searched within each database was "clean cooking" and "cookstove" with "preference." We excluded studies that focused solely on stove technical characteristics, emissions, and those in extreme settings such as refugee camps if they did not explicitly discuss user or household experience. This resulted in a total of 92,272 papers[3] from our initial search. Throughout the studies found, we also conducted hand searches from their references. Although this is a comprehensive and not a systematic review, the range in papers from the large initial result compared to the studies ultimately included reveal that there are numerous disciplines and publication types working on improved cooking technology, but only a small percentage evaluated users' preferences.

From this initial search, we identified 350 papers through abstract screening based on our primary criteria. From those 350 papers, we ultimately included insights from 191. The majority of the papers came

[2] International Organization for Standardization (ISO) and the International Workshop Agreement (IWA) Tier 4 and Tier 5 designations for indoor emissions during in-use testing of particulate matter of diameter 2.5 μm and carbon monoxide.

[3] This large number was due to the calibration of Proquest Dissertations and Thesis' and Google Scholar's algorithms.

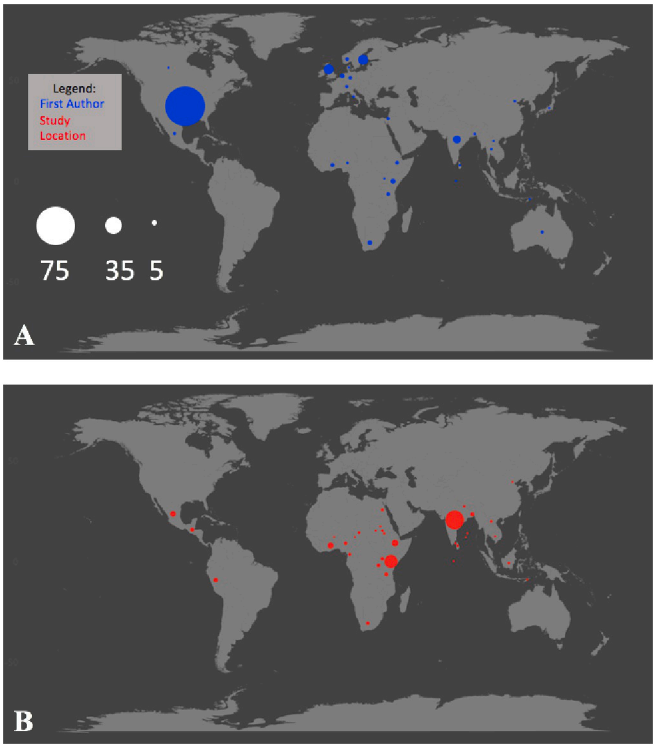

Fig. 2. Panel A illustrates the location of the first (n = 191) authors for each of the studies included in this review. If the paper included was from grey literature, we recorded the authors' location as the headquarters of the organization. Panel B details the location of the study site within each paper included (n = 156). Please note that some papers covered multiple case studies within a region. Twelve studies focused on Sub-Saharan Africa, two studies focused on Asian case studies, and one on Latin American case studies. Twenty studies had a global outlook or included study locations across regions. These multi-location studies were not included in the graphic.

from Google Scholar and Science Direct and were peer literature sources (n = 124). Thirty-eight of these papers were grey literature, and 29 were theses. Studies on improved biomass stoves composed the majority of the papers (n = 104), while 31 papers covered BLEEN fuels/stoves. Eight studies covered solar ovens/cookers, and 48 papers discussed a combination of improved biomass, BLEEN, or solar (Fig. 1). The 191 papers spanned Africa (n = 94), Asia (n = 52), and Central/South America (n = 25). Twenty papers covered multiple sites across continents. Fig. 2 depicts both study site locations and first author locations. A master list of all the included studies can be found in Appendix A.

The studies included referred to the preferences of the household, cook, user, consumer, customer, women, respondents, participants, and beneficiaries. No term was universal to all studies, but household and user were the most commonly used terms (n = 124 and n = 105 respectively). Forty-two studies explicitly referred to women's preferences. However, in this review, our unit of analysis is a paper, and therefore, we will refer to household/user preferences to reflect the majority of papers. The term household was not universally defined in these studies; Therefore, we default to the United Nations' definition of "*a small group of persons who share the same living accommodation, who pool some, or all, of their income and wealth and who consume certain-types of goods and services collectively, mainly housing and food'* [32] (pg. 21).

3. Theoretical framework

Our review of the literature revealed a variety of stove characteristics, attributes, features, and functions that households in the studies reviewed identified as important. To evaluate these results, we utilized two nested frameworks. The first of which we developed ourselves while

Table 1
Definitions of dimensions that arose in the literature.

Dimension Arising from the Literature	Definition
Stove Operation	This dimension covers the characteristics that users preferred related to stove use, including a stove that is easy to assemble, operate, clean, and maintain. It also includes the common theme of convenience, which refers to users desiring stoves that were easy to operate throughout the cooking process from loading to turning the stove off (e.g., not having to go out and collect wood, quick ignition, etc.) especially in time crunches or emergencies. It also covers studies in which households requested information on how to use the stove, recipes for making traditional foods, etc. Finally, this dimension covers whether standing or sitting was preferred while cooking.
Fuel Characteristics	This dimension covers user preferences surrounding the attributes of the fuel such as the quality of firewood, size of firewood, smell, soot, ash, or smoke produced. This dimension also covers the user preference for the ability to utilize multiple fuels.
Stove Design or Features	This dimension addresses aspects that users preferred related to the stove design. This is not in a technical sense, but rather the stove design characteristics that affect the user. This includes the durability, portability, height of the stove, and if it was cumbersome (i.e., the stove was heavy or awkward to transport). This dimension covers whether the heat can be adjusted or if the stove retains heat. This includes user preferences regarding being able to use the stove in all seasons (e.g., rainy or dry), all weather (e.g.., rainy or cloudy), and the stove flame not extinguishing from wind. This dimension differs from the Stove Operation category as in this section preferences refer to the stove itself, rather than the user interacting with the stove during use. The aspects do affect stove operation, but not directly.
Kitchen Space	This dimension considers preferences that addressed certain stove aspects that affect the kitchen space (i.e., temperature in the kitchen, indoor/outdoor cooking locations, soot/ash in the kitchen).
Household Food and Taste Demands	This dimension focuses on user preferences related to meeting the quantity and quality of household cooking demand. This includes users' desire for the stove to meet the cooking needs of large households, to accommodate a range of pot sizes and types (i.e., clay, metal, etc.), to allow the user to cook multiple items simultaneously, and to reliably meet cooking demand. In regard to quality, users prefer that the stove is able to perform a range of cooking functions and not change the taste of the food.
Household Schedule	This dimension comprises certain stove characteristics associated with household schedules. This includes the time of day the household is able to use the stove, how the stove affects the households' daily routine, and whether the stove requires the user to supervise or tend to the stove more or less compared to traditional cooking methods.
Social and Cultural Aspects	This dimension encompasses stove characteristics associated with social or cultural aspects. Social aspects include how the stove affects household dynamics (children and spouses), social capital, and community gatherings. Within this framework, we conceptualize culture through the United Nations Educational, Scientific, and Cultural Organization (UNESCO) definition, which defines it as "*the set of distinctive spiritual, material, intellectual, and emotional features of society, or a social group, that encompasses, not only art and literature, but lifestyles, ways of living together, value systems, traditions and beliefs*"[33] (pg. 9). For example, in India, the traditional stove, the chulha, holds religious significance. It is important to note that local dishes are often considered a part of the culture. However, we include local dishes within the Household Food and Taste Demands dimension as the preferences around stoves and these specific foods are

(*continued on next page*)

Table 1 (*continued*)

Dimension Arising from the Literature	Definition
	actually related to the stove functions rather than the culture (e.g., households in Mexico required a smooth iron griddle to make tortillas). This tortilla example is not a cultural conflict, but rather is simply a case of limited stove function.

analyzing our results. We organized the recurring themes from the literature into a framework of seven dimensions. These dimensions are: (1) Stove operation, (2) Fuel characteristics, (3) Stove design or features, (4) Kitchen space, (5) Household food and taste demands, (6) Household schedule, and (7) Social and cultural aspects. We define each of these dimensions in Table 1.

We then grounded our results in the Technology Acceptance Model (TAM), which stipulates that user acceptance is a factor of perceived usefulness and perceived ease of use which affect the user's attitude towards use [34,35]. External factors which affect the perception of usefulness and ease of use are also considered in this model [36]. We utilized an extension of the TAM which includes social influence as a factor affecting the users' attitude [34,37]. Although originally developed for the acceptance and adoption of information technology, we adapted the model for improved stove adoption and then organized our seven dimensions within the TAM's chief factors (Fig. 3). Nesting our framework into this theoretical lens allowed us to evaluate the drivers of these user preferences and how they may affect a users' intention to use and ultimately adopt a clean stove.

4. Results

4.1. Perception of ease of use

Within the TAM, Davis describes perception of ease of use to be "*the degree to which a person believes that using a particular system would be free of effort*" [35] (pg. 320). Adapting this model for an improved stove, we found user or household preferences related to the operation of the stove and characteristics of the fuel. These preferences on Stove Operation and Fuel Characteristics were driven by the desire to ease or improve the work of cooking.

4.1.1. Stove operation

The literature revealed user and household preferences related to stove use. We identified that this dimension composes elements such as easy to use, to reload, to maintain, etc. (Table 1). Papers found that households wanted a stove to be easy to use from assembly through cooking and even clean up. Overall, seven studies reported that households desire an easy to assemble stove. Households across Sub-Saharan Africa appreciated an improved biomass stove that was easily constructed [38–42]. Studies globally found that users complained that it was difficult to construct improved stoves by themselves [43,44].

After construction, 29 studies mentioned that households value an easy to light stove (Fig. 4, Panel A) [45,46,55–62,47–54], disliked stoves that were difficult to light [47,63,64] and preferred stoves that heat up quickly once lighted [44,55,58,65–67]. Households in the rural district of Trans Nzoia, Kenya, previous kerosene users from six regions in Java and Sumatera, Indonesia, and urban biomass pellet users in Lusaka, Zambia disliked that with the three-stone fire the user has to kindle the stove and that it often takes multiple matches to light [41,68,69]. Households who had adopted an improved biomass stove across three villages in Zambia noted that it was difficult to remake the three-stone fire once the fire went out [70].

The ability to easily load and reload fuel into the stove was an important stove feature highlighted in the literature (n = 19) (Fig. 4, Panel A) [71,72]. In an ethanol intervention in Tigray, Ethiopia, users complained that refilling the canisters was hard because the user had to turn the sharp edged stove upside down without handles [73]. Users of improved biomass stoves in Kenya, Zambia, Mexico, India, and Cambodia preferred a front-loading stove [74] as they did not want to have to move the cooking pot to reload the stove with fuel [45,48,57] as it caused smoke to be released [48]. However, users surveyed during a field intervention trial of an improved biomass stove in Nepal, Peru, and Kenya disliked side-loading the biomass as it made it difficult to add small pieces of fuel (dun or garbage) without extending the user's hand into the fire [75]. Households involved in two evaluations of improved biomass stoves in rural Kwale County, Kenya, expressed a clear desire for fuel cannisters, firebox, etc. to be large enough so that they could cook continuously without having to load the stove during the cooking process [47,76]. Studies in Gulu, Uganda, Antiqua, Guatemala, and across rural Mexico reported that households requested and sometimes even modified the improved biomass stove themselves to create a larger feed entrance [77,78]. Other studies in India and Indonesia found that users complained of a too small or narrow opening for the firebox [39,59,79,80], which prevented the easy loading of larger pieces of firewood [81]. An ideal stove design would allow users to feed the fuel effortlessly [82,83].

After loading, 20 distinct studies found that users wanted a stove that was easy to use (Fig. 4, Panel A) [67,79,92,93,84–91], reducing the cook's workload [55,94–100]. A few studies in India, Sri Lanka, and Nepal covering both BLEEN and improved biomass stoves vaguely mentioned that users appreciate the convenience of certain stoves [86,101–103], such as LPG, particularly for emergencies [93]. In contrast, a study of a solar cooker in India mentioned that users did not find solar convenient as they had to climb up to the roof to cook which made the stove difficult to use [104]. This study was based in urban Gujarat and thus the roof was one of the only suitable places where

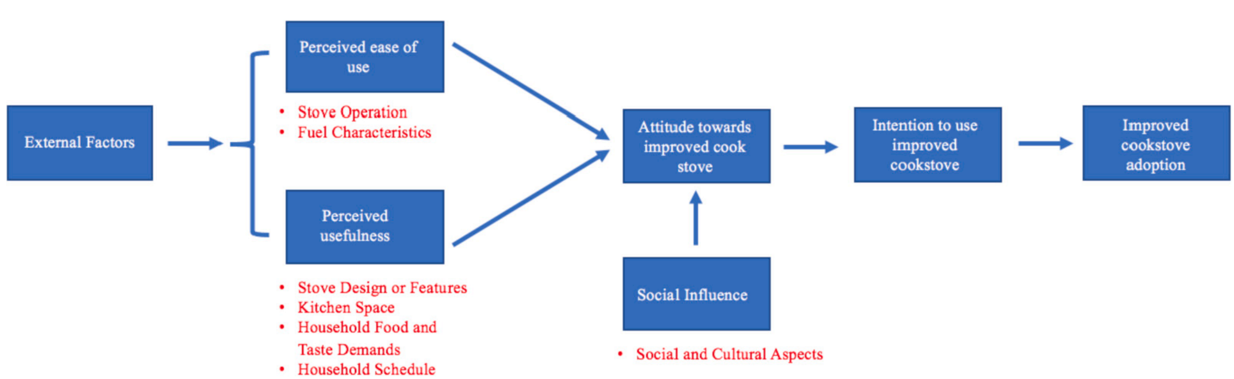

Fig. 3. This figure depicts our adaption of the Technology Acceptance Model for improved stove adoption. The red text indicates how we nested the seven dimensions of the framework that we developed from the thematic analysis of our results. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

households could utilize the available sunshine [104].

Only a few studies (n = 5) mentioned whether the users preferred the sitting or standing position while using their stove. Overall, there was no consensus on whether sitting [105–108] or standing [109] was the preferred cooking position or considered to be easier. However, Ford reported a detailed narrative on the importance of the sitting position in Cameroon:

"The hearth is located in the center of the kitchen with older stools carved of wood and newer stools made from bamboo around it. These stools, hold the cook while she is 'turning' (vigorously stirring) the corn foo-foo (a kind of thick porridge like stiff grits), pounding the cocoyam foo-foo (rather like stiff mashed potatoes), preparing the soup, nursing the baby, and conducting any number of other domestic tasks that allow for a sitting position. Women can cook an entire elaborate meal without ever leaving the kitchen stool. By placing the water, food, spices, and necessary tools in proximity to the cooking stool, women cook very efficiently in full view of the children so that they too learn, even the boys. Although it may appear physically difficult to cook on a floor-level three-stone hearth to those unaccustomed to doing so, it seems much more practical than standing over a waist-high stove after a hard day at the farm. The vigorous two-handed stirring that it requires is easier if the cooking pot is firmly wedged between the stones and the cook's foot to keep it from jumping about as the porridge is stirred" [106] (pg. 114–115).

A World Bank report outlining a strategic plan for multiple stove programs (both BLEEN and improved biomass) for Laos revealed that cooking position was based on a rural/urban divide. The report noted that urban households have transitioned to cooking while standing, while rural communities still have not adjusted [108]. Given this lack of consensus on standing vs. sitting, stove designers should survey respondents further and determine the local preference. Different contexts may view one cooking position "easier" than the other.

After operating the improved biomass stove, studies in rural Mexico and peri-urban Indonesia stressed that users appreciated stoves that did not require frequent cleaning [78,79]. Studies on ethanol and improved biomass stove interventions in South Africa, Cambodia, and India noted that households mentioned that if cleaning was required they preferred that it was easy to perform [45,110,111] (n = 5) (Fig. 4, Panel A). Chimneys of improved biomass stoves in India were particularly hard to clean [111], especially when they were smaller [79]. Therefore, designers need to envision how households will not only cook with the stove, but also clean it.

This review found that households strongly prefer a stove that requires little maintenance [55,71,91,95,96,112] and when maintenance is required, they want to be able to easily repair the stove themselves [45,78,99,100,113–116] (n = 20) (Fig. 4, Panel A). Households across studies on a range of stove types and regions were less likely to continue using a stove if maintenance was frequent and considerable repair work was required (e.g., restoring cracked tops or renewing grates) [65,69,75,99], if repair parts were hard to obtain [117,118], and if there was no maintenance back up [119]. Therefore, an ideal stove design would either require little or simple maintenance or stove companies and policy makers should prioritize training users on stove maintenance or providing convenient and available maintenance. While this finding is coupled with user behavior (i.e., pursuing maintenance), designers and policy makers should understand that users prefer low maintenance designs that ease their work.

Households stressed their requirement of a safe stove (n = 37) (Fig. 4, Panel A) [45,56,73,85,103,120,121]. There were mixed reviews on the safety of the traditional stove. An evaluation of an improved stove program targeting households with pregnant women in rural Palwal District, Haryana, India found that some users thought that the traditional stove was safe [62]. Contrastingly, in evaluation of an improved stove intervention in West Kochieng, Kenya, households mentioned that the Upesi stove reduced accidents in the house because the three-stone fire had unwieldy flames [122]. Numerous studies found that households were especially concerned about LPG [87,115,123–126]. Some Peruvian households who were part of a free LPG research trial feared turning on the stove because stove knobs were sensitive and would burst if turned on too high [125]. They were afraid of gas leaks and the smell of LPG [125]. Households across studies were also afraid of electric shocks or electrical fires [127,128], explosions [117,124,129], or burning down their house from the improved biomass or BLEEN stove [43,47,65,130]. Safety fears stemmed from households not having proper information on how to use the stove. These preferences also related to easing the cook's work as risk of any substantial accident increases the caution and attention required surrounding daily cooking. Therefore, stove designers should be mindful to incorporate safety features with household education on proper and safe stove use.

Studies on improved biomass stoves and LPG stoves found that households are wary of stove designs that lead to frequent burns [39,41,51,55,115]. Frequently, the handles and external surface of improved biomass, ethanol, and biogas stoves are too hot to touch [54,73,109,131,132]. The literature identified features for improved biomass stoves that prevent burns such as an insulated outer surface [63,98], a clay chimney that dissipates heat [79], or a solid base that prevents pot tipping or flames from escaping [41]. Stove designers should therefore think through designs that may lead to higher risk of burns for the consumer.

Households in a few studies in Ethiopia, Tanzania, Peru, India, and South Africa wanted a stove that came with educational materials or training for all stove types [110,118,125,133,134] (n = 5) (Fig. 4, Panel A). Households specifically asked for recipes, stove demonstrations, instructions on fuel quantity, information on the location of the fuel canister, and general information on how to properly use the stove. Information regarding the stove would also ease the cook's work as they would be better prepared to smoothly utilize the stove. Although this information would not affect the design of the stove, stove designers and policy makers should understand the preference for information regarding stove operation.

In summary, from stove assembly, lighting, loading, cleaning, and maintenance, user preferences stemmed from desiring features of stove operation and fuel characteristics to ease their workload.

4.1.2. Fuel characteristics

The literature revealed specific characteristics of different fuels that households preferred, which could be related to odor, fuel size, fuel quality, etc. (Table 1). All these preferred characteristics were related to either easing or making the work of cooking more difficult. Smoke reduction was by far the most important stove/fuel feature mentioned across all studies and stove types (n = 65) (Fig. 4, Panel B) [38,45,57,58,61,65,67,69,70,74,75,79,48,80,82–84,95,100,105,109,112,114,49,116,120,121,125,128,129,134–137,50,138–147,51,148–157,53,158–160,54–56]. Interestingly, although households disliked the smoke from the traditional stove, it did ward off insects and mosquitos in their homes [44,94,111,151,161–163]. In these cases, users balanced smoke's useful ability to deter mosquitos and its negative consequences of difficulty breathing and seeing. Therefore, stove developers and policy makers must consider that the user is facing a tradeoff between no smoke for insect protection in the choice to adopt or not adopt the stove. Separate from smoke, soot and ash production was also a feature that households disliked in stoves [58,72,82]. Improved stove evaluations in the towns of Nyahururu and Embu and the Trans Nzoia district in Kenya found that rural users complained that ash would get into food and ruin the taste [41] and make the kitchen area dirty [58]. One study covering three different regions in Ghana (Greater Accra, Ashanti and Western) noted that households wanted a stove with an ash collector to prevent ashes from spreading onto the floor [60].

Nine studies found that households disliked fuels that produced a noticeable odor (Fig. 4, Panel B) [58,65,86,110,119,155]. Households in South Africa, Kenya and India for example did not like the synthetic smell of liquid fuels such as LPG and ethanol [86,110,119] or briquettes

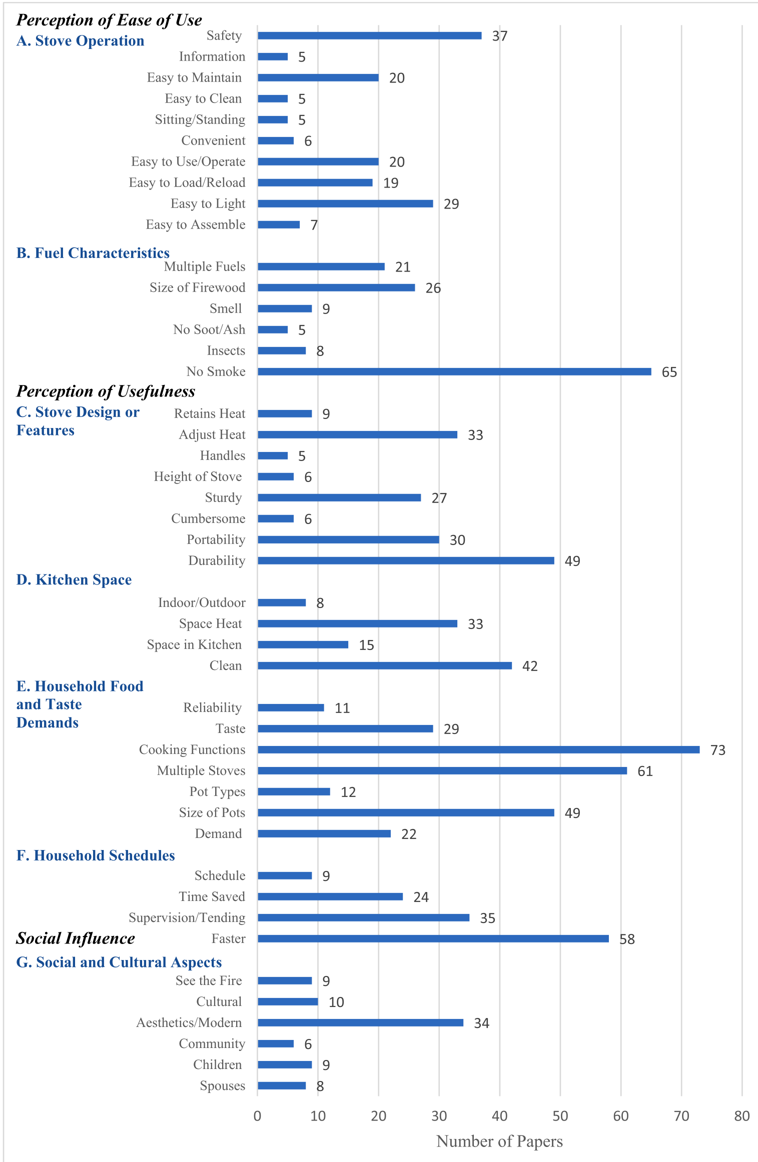

Fig. 4. This figure reports the frequency of papers that note these specific aspects that arose in the literature regarding the preferred characteristics, features, etc. of a cook stove. We organized these recurring themes into seven dimensions defined in Table 1We nested these seven dimensions within the Technology Acceptance Model's factors of Perception of Ease of Use, Perception of Usefulness, and Social Influence.

which smelled like dung or waste [58,65]. In Ghana, consumers across the regions of Greater Accra, Ashanti, and Western complained that the stove's surface paint burned off at high temperatures, producing a strong odor [60].

In 26 of the studies, households expressed that they wanted a stove that does not require a specific fuel size as this would make the cooking process more difficult (Fig. 4, Panel B) [40,47,51,61,63,71,82,105,164]. Users felt that they cannot use a stove that requires small pieces of firewood because preparing the fuel is burdensome [39,58,121,128,139,147,154,165,166,61,63,65,68,70,74,80,113]. In a study attempting to redesign an improved stove in the Tambogrande region of Peru, households required the ability to burn the same type of fuels that they are accustomed to using [72]. A technical, social, and environmental assessment of traditional fuels in Zimbabwe mentioned that households wanted an improved biomass stove that could utilize thick logs of firewood which required less attention and reloading [167]. Therefore, designers should consider the effort necessary to prepare the fuel for the stove and strive to design fuel size flexibility.

The literature discussed the quality of wood in five of the studies (Fig. 4, Panel B). With regard to the EcoZoom stove, 32.2% of Rwandan consumers reported not using the stove because they could not find dry firewood [168]. Often, households are forced to burn moist wood, which is compatible with the three stone fire but often not with the improved cookstoves [65,79,164]. During the rainy or monsoon seasons in Malawi, households may have to cook with wet wood [169].This preference for not having to have a certain quality of wood directly relates to users being able to easily cook during any season and indicates the importance of context with regard to climate.

In addition to fuel size and wood quality, households wanted the ability to have their stove accommodate multiple fuels (n = 21) (Fig. 4, Panel B) [42,44,171,48,52,70,72,75,157,163,170]. Throughout the literature, households were accustomed to using a range of biomass fuels (firewood, charcoal, dung, twigs, leaves, crop residues, etc.) with their traditional stove [50,59,173,74,111,116,130,154,162,170,172]. Stove designers should strive to provide as much flexibility in fuel use as possible and not create further work for the cook.

4.2. Perception of usefulness

Besides the perception of ease of use, the TAM indicates that the perception of usefulness is another driver of preference towards a technology. Davis describes usefulness as "*the degree to which a person believes that using a particular system would enhance [their] job performance*" [35] (pg. 320). Adapting this model for an improved stove, we found user or household preferences related to stove features, the kitchen space and the household's cooking demand and schedule. These preferences were driven by whether or not the user found a certain aspect of the stove useful to the cooking process.

4.2.1. Stove design or features

The next dimension covers stove design and features that households appreciated which were largely related to durability, sturdiness, portability, weight, the height of the stove, handles, chimney and ovens (Table 1). Durability was cited as one of the most important aspects of the stove, arising in 49 of the papers (Fig. 4, Panel C) [39,42,66,67,70,72,76,79,83,84,87,91,43,95,98,103,108,113,119,128,139,144,150,53,160,170,172–176,54–56,58,60,63]. In the case of the Wisconsin cooker in Sudan, there was a gradual reduction in the reflexivity of the aluminized Mylar films, which only lasted two years [98]. Another study developing a prototype of an improved biomass stove in Sichuan province of Southwest China noted that the stove's igniter frequently broke every two to five weeks [177]. Some LPG stoves in Chiapas, Mexico were reported to only last three months [55]. Other improved biomass stoves started cracking [43,76] or crumbled over heavy pots [170]. Envirofit offered households a warranty on their improved biomass stoves in Kenya and India, which was the first in the industry [95]. The World Bank notes that stoves are often fragile because there are no official standards [108]. The low durability led households to not value the investment in a stove as it was not useful in the long run. Thus, any stove must prove durable to meet household needs. This review did not include studies that only conducted technical assessments; however, throughout the review, we encountered numerous technical assessments that were done by and for technologists and stove designers, and not for the actual user. If user perspective was included in these technical assessments, it was often a single reference or cooking demonstration, not an evaluation of how the user would actually cook with the stove over time.

Another highly valued useful characteristic of an ideal stove is portability (n = 30) (Fig. 4, Panel C) [42,56,178,179,58,71,74,89,137,139,140,143] allowing the household to cook in different rooms at home and travel with it [41,44,170,171,180,45,50,54,59,62,128,143,157]. This was because often households wanted to be able to move the stove based on the weather, particularly in tropical climates (i.e., Malawi, Kenya, Southern India [70,95]); however, households in Indonesia also favored portable stoves because they can be resold increasing the stove's value compared to fixed stove [79]. In a consumer segmentation study in Ghana, users in focus groups appreciated the ability to move the stove to cook on the floor or on a tabletop [60]. Climate and resale value were not the only reasons portability was seen as so useful. Occupational context also affected this preference. In India, researchers evaluating the National Programme on Improved Cookstoves in Himachal Pradesh found that portable stoves were especially important for communities with high migrant labor [81]. Overall, a portable stove was more useful to users depending on their climate, economic interest, and occupation.

Related to portability, multiple studies noted that households disliked stoves that were cumbersome or heavy (n = 6) (Fig. 4, Panel C). Households in studies from Sub-Saharan Africa, India, and Peru did not want a heavy stove that was difficult to move [54,60,63,72]. In a study of the adoption of an improved biomass cookstove with USB charging capability, Wilson reported that rural Indian households found the improved stove too small, but cumbersome to use [80]. In one study in Malawi, participants noted that elderly people may find it hard to move the stove in the case of rain or extreme heat as it weighs around 10 kg [70]. The improved stove is not as useful if it cannot be easily moved from place to place. Policy makers and designers must take into consideration how households will move the stove to different locations and attempt to make that as easy as possible for the user.

However, as opposed to the value placed on portability, a number of studies (n = 27) found that households expressed that any stove they would adopt needed to be sturdy [21,41,82,157], as they are often worried that the pot may slip or the stove could tip over [39,52,67,70,100,150,167,181].This was often due to the fact that many traditional dishes require vigorous stirring or mixing of ingredients [41,43,47,64,75,182,183]. Throughout the literature, households wanted a sturdy stove that would not fall over or lose its flame from high winds [41,45,54,98,116,180,183,184]. Rural Ugandan households outside the Kachung Forest noted that they wanted a stove that was fixed in the ground, as even the stones in the traditional fire would move around [43]. Sturdiness has to be balanced with the household's desire for portability. Many improved biomass stoves in Kenya were light and portable, but then not sturdy [185]. This preference in the literature reveals how households must balance whether it is more useful to have a sturdy stove, or one that can be moved easily.

The literature revealed that households expressed preferences on stove specifics such as height, handles, chimney, and ovens. Only six studies commented on the height of the stove (Fig. 4, Panel C). Users in Indonesia reported that the improved biomass stove was built too high and preferred an adjustable stove that could conform to each user [79]. Akolgo found in a study of improved biomass stoves in Ghana that the height of the stove should allow the user to sit on the stool and stir the cooking pot [84]. Households involved in stove projects in rural Mexico, Sudan, and Guatemala used large pots, which made it difficult to use a high stove because it was hard to lift the pot onto the stove [78,98,186]. The stove was less useful if the user was unable to stir while cooking or use a larger pot. Households were accustomed to and therefore preferred cooking close to the ground. In a review of different improved biomass stoves, Gill found that no pot was higher than 30 cm [167]. Overall, an adjustable stove may be the most useful option, given the conflicting responses in the literature.

The literature also discussed handles, ovens, and chimneys for the stove. Handles were a specific design consideration that households prioritized in five of the studies (Fig. 4, Panel C). The households in Panama, Ethiopia, and Malawi gave particular design specifications such as that the handles needed to be higher to allow them to move it with ease [100,133] and allowed them to cook foods that require vigorous stirring [70]. However, it was important that the handles were insulated [72,95]. Therefore, stoves would need to have handles for ease of use and portability. Some households desired ovens; however, ovens were found to more often than not serve as additional cabinets rather than a cooking device [18,69,79,150]. A few studies noted that households appreciated chimneys to remove smoke out of the house (n = 4) [42,163]. However, certain design adjustments were suggested. South African and Indian households using improved biomass stoves wanted a wider chimney mouth [63] and for installations to have a 135-degree bend because the 90-degree chimneys were blocked too quickly [150]. Ovens and chimneys may be added on a case-by-case basis if useful for households.

Households expressed interest in stove features related to heat delivery and the ability to fine-tune stove performance. Several studies noted that the ability to modulate the temperature of the stove was an important design consideration (n = 33) (Fig. 4, Panel C) [21,39,187,45,79,91,94,137,155,156,179]. Users reported wanting their stove to have even heat distribution [42,163,188] and a wide range of power output [18,71] that they could easily control [42,63,163] to regulate at both low temperatures [47] and high temperatures. Without

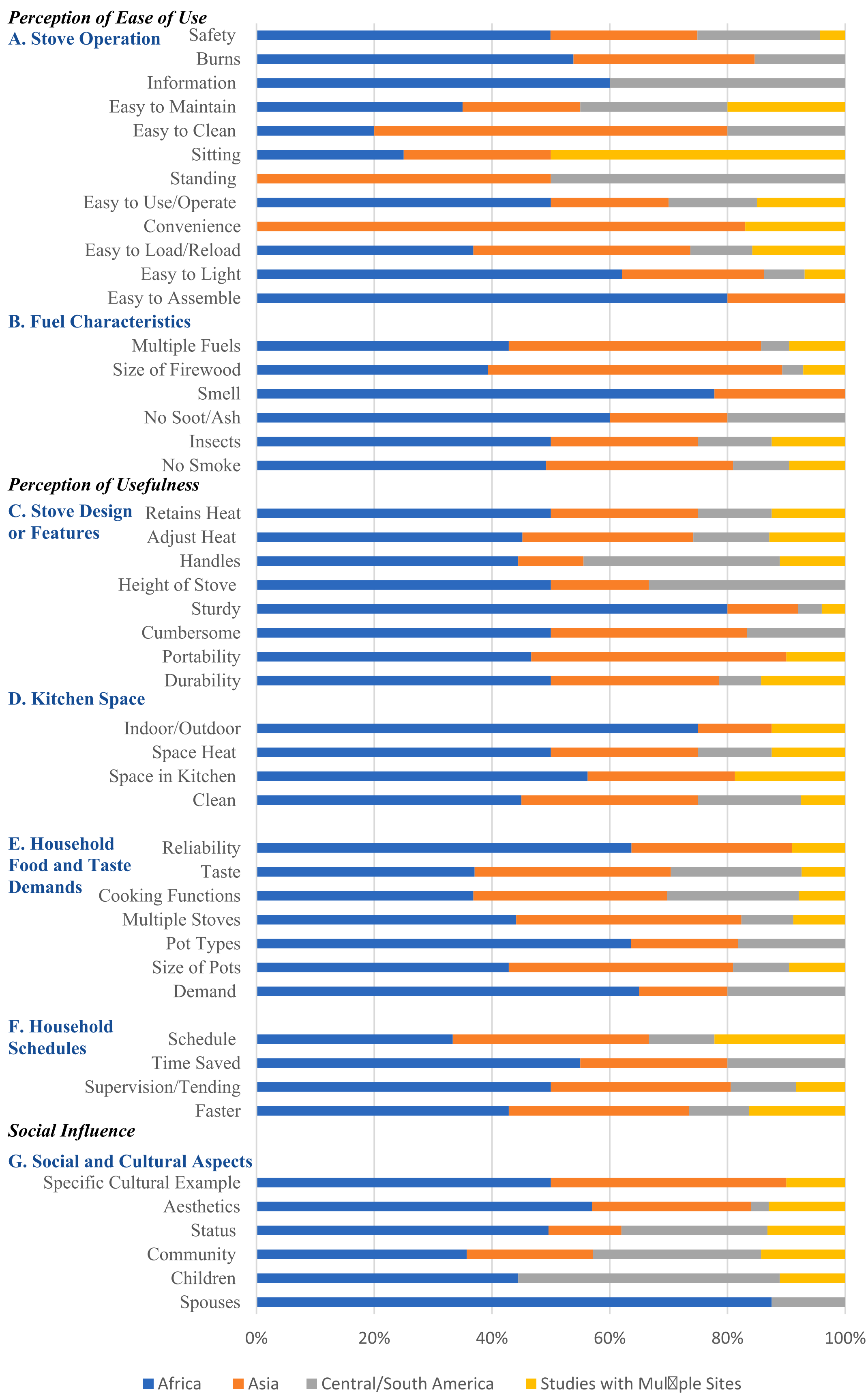

Fig. 5. This figure reports the percentage of papers by region that note specific aspects that arose in the literature regarding the preferred characteristics, features, etc. of a cook stove. We organize these recurring themes into seven dimensions as defined in Table 1. We nested these seven dimensions within the Technology Acceptance Model's factors of Perception of Ease of Use, Perception of Usefulness, and Social Influence.

Table 2
This table depicts the stove features that were discussed equally between regions.

Dimension	Equally represented aspect as defined in Table 1.
Technical Design and Stove Operation	Easy to Load Easy to Maintain Easy to Use
Fuel Characteristics	Size of Firewood Multiple Fuels No Smoke Insects
Technical Details or Features	Adjust Heat Retain Heat Durability Handles Height of Stove Cumbersome
Kitchen Space	None
Household Food and Taste Demands	Cooking Functions Taste Pot Sizes Multiple Stoves
Household Schedules	Faster Schedule Supervision/Tending
Social and Cultural Aspects	Community

this ability to control, the food often easily burned [49,75]. Some Indian households had to add in cow dung to their biomass stove to regulate the heat [157]. Additionally, users from studies in Kenya and Indonesia wanted a stove that could become sufficiently hot and sufficiently low [38,79]. A study in Chiapas, Mexico found that cooking certain staple foods required high heat [55], while users in rural Kenya also wanted to be able to turn the stove on low and move away from the stove for short periods of time [50]. Specifically, the literature revealed that households did not like that charcoal could not be regulated [41,69,100], and studies noted stoves that had poor controllability [44,79,145,189]. A stove with heat regulation capabilities is more useful to the household.

Households, in nine studies, wanted a stove that retained heat (Fig. 4, Panel C) [41,42,59,116,123,152,180,190]. In rural Kenya, households used this heat for drinking or bathing water or simply to use the residual heat to keep the food warm [41], while in central Uganda, users complained that LPG does not retain heat after it is shut off [190]. While households wanted heat retention, some individuals in India had safety concerns if the body of the stove remained very hot [59]. Stove designers should definitely include the ability to adjust and retain heat.

A few studies mentioned some interesting features that households wanted, but overall, these were not common or mainstream in the literature (Fig. 4, Panel G). In an LPG study in Peru, users wanted the stove to tell them when the gas supply was running low [125]. Another study on a range of stove types in Mozambique noted that households wanted a stove that burned fuel that was easy to store [114]. Studies in rural Uganda, Guatemala, and India found that households were skeptical of stoves in which you could not see the flame (n = 9) (Fig. 4, Panel G) [77,191]. Households did not understand that certain stoves can heat food without a flame. This was particularly an issue for solar cookers which do not create a flame [107]. More commonly, studies found that households value a stove that can also serve as a source of lighting [44,71,132,188,192].

Two studies tested stove designs that incorporated USB charging capabilities, or other non-traditional stove functions (e.g., fans). One study in India found that households appreciated the USB port on an improved biomass stove [80]. Another study also in India noted that men preferred this USB stove and would use it not to cook, but simply to charge electronics [191]. These additional features seem largely to be needless features of the stoves. The households in these cases seemed to value the secondary use more than the primary cooking function of the stove. Electricity access is an important related, yet separate goal.

4.2.2. Kitchen space

User and household stove preferences arose in the literature surrounding how the stove affects the cooking area (Table 1). In 15 studies, household reported that they needed a stove that fit within their limited kitchen space [51,87,171,175,179,193,94,98,104,105,128,144,152,153] (Fig. 4, Panel D). This was particularly notable with solar cookers and biogas digesters in Tanzania and Ethiopia respectively which both require a large open space [94,193]. A stove is less useful to a household if it does not fit within their designated kitchen space. On the other hand, two studies on improved biomass stoves noted that users appreciated a stove that provided worksurface around the stove [109,152]. Designers should be mindful of the typical kitchen space or set up of their customer base and consider incorporating built in table space to increase the usefulness of the stove.

Users appreciated a stove that kept their kitchen area clean [18,42,102,130,136,137,144,152,194,195,47–49,67,69,87,100,101]. The three-stone-fire often turned the walls of the kitchen black [139], cracked walls [139], and also blackened pots [42,47,94,125,129,140,143,157,165,181,196,48,49,51,65,74,78,84,90]. LPG, firewood pellets, and other improved stoves kept their kitchen, pots, clothes, and hands clean [91,108,123,124,137]. This preference stemmed from the fact that the clean kitchen area was an additional useful quality associated with the improved stove.

There are conflicting narratives in the literature as to whether households wanted a stove that provided space heat (n = 33) (Fig. 4, Panel D). Numerous studies noted that households relied on their stoves to produce space heat for their homes to keep the cook warm [52,55,165,168,188,192,197,198,64,65,67,81,105,111,150,162] In warmer climates, other studies noted that space heat was a negative quality [44,51,136,139,147,157,71,74,75,81,86,87,123,128]. The space heat factor often dictated whether households cooked indoors or outdoors. Stove designers and policy makers should consider the climate, which will dictate if space heat is useful. This is admittedly difficult in settings with mixed climates or where the temperature can vary drastically during the day. In settings such as South Africa, Peru, Nepal, and Kenya, indoor/outdoor cooking was seasonal as the traditional stove became too hot for indoor use in the summer [44,65,75], while households in the monsoon or the wet season were often forced to cook indoors [59,115,130,147]. Globally, households wanted a stove that they could use regardless of the weather [60,65,93,107,139,199] which was problematic for solar cookers.

The preference for cooking indoors versus outdoors encompasses a number of factors that go beyond the desire to warm a home. Eight studies addressed this issue (Fig. 4, Panel D) [200]. In general, indoor cooking was preferred because of its association with status and privacy [114,127,130,201]. In Kibera, Kenya where living quarters are tight, households wanted a stove where their neighbors could not see them eating the same simple food every day [127]. In this case, the stove was useful for maintaining social status. In West and East Africa, outdoor cooking was only necessary for boiling water [178] or for cooking large quantities of food (e.g., for a celebration) [132], even noting that the ideal kitchen is a separate outside structure [122]. Portability is therefore important as households fluctuate between indoor and outdoor cooking.

4.2.3. Household food and taste demands

Next, this review found stove attributes related to household food and taste demands. Elements in this dimension include preferences regarding the quantity and quality of foods households need to prepare (e.g., larger pots, multiple burners, consistency of food) (Table 1). A commonly cited issue (n = 48) is that the improved or clean stoves were not useful as they too small to meet all of the large household's cooking demands (Fig. 4, Panel E) [43,65,188–190,199,69, 79,100,114,132,154,171,176]. Even smaller households in Peru, Nigeria, and Sudan noted that they would need a larger stove or more burners for periodic parties, cultural festivals, or commemorations [125,129,202]. Multiple studies found that the traditional stove was better for larger meals [123,128,129]. Beyond cooking, a study in Mbale, Uganda reported that users complained that the improved stove could not support the boiling of water [166]. Therefore, new stoves should be sized to meet the household's full cooking demands to ensure adoption and exclusive consistent use.

Households often meet their food demands through cooking with larger pots. Thus, the ability to accommodate large pots was a commonly cited feature that a stove must have if households are to view the stove as useful and ultimately adopt it (n = 49) (Fig. 4, Panel E) [21,41,82,83,93,95,97,98,114,128,189,203,44,204,45,52,58,65,76,78,79]. Households across studies reported that they were unable to use their improved stoves with large pots [48,65,140,170]. Pot skirts on an improved biomass stove in Kenya specifically limited the size of pots that could be used [76]. A study on seasonal variation for cooking in Southern African contexts found that cooking large pots on the modern stove was very slow because the pot would sit too far above the firebox [65].

Although accommodating large pots was problematic, the literature revealed that households want a stove that can accommodate a range of pot sizes [40,42,112,132,154,157,163,170,187,190,66,67,72,81,84,99,105,111] as sometimes the stove could not accommodate small pots [72,133,153]. Therefore, promoted stove designs should consider the ability to accommodate a range of pot sizes.

Additionally, to be considered useful the stove must also accommodate a range of pot types [123,171,183] (n = 12) (Fig. 4, Panel E). For instance, flat bottom, [59] round bottom pots [133,181], or clay pots [125] are all commonly used. Some households in Peru purchased specific pots for LPG because the more powerful efficient stove perforated their old pots [125]. Policy makers and stove designers should consider that households want a stove that does not damage pots [41,49,69,125,137].

Households utilize a range of pot sizes and types, but also multiple burners and stoves to meet their large cooking demands. Sixty one studies noted that households require a stove with at least has two burners because they want to be able to cook multiple pots at once (Fig. 4, Panel E) [42,43,74,79,105,113,128,132,136,138,139,141,52,147,150,152,155,157,168,176,178,192,194,55,205,59,60,64,65,69,72]. However, households using ethanol in Ethiopia and improved biomass in Bangladesh and India wanted the ability to switch to a single burner [73,130,172]. In a study from rural Uganda, households wanted this feature without having the other burners on wasting fuel or releasing smoke from the pothole [43]. Flexibility in the number of pots a stove can accommodate increases the likelihood that households will not revert back to unclean fuels.

Seventy three studies found that stoves use is correlated with different dishes [206] as specific aspects of different stoves are more useful for certain types of dishes (Fig. 4, Panel E). In general, improved biomass, LPG, ethanol, kerosene or electric stoves were often used for reheating food or lighter cooking tasks such as boiling water [15,80,207–209,98,114,126,132,135,139,145,170], but not beans, corn, or traditional foods [56,92,114,115,182,210]. In Kenya, charcoal stoves are reserved for roasting meat and maize, cooking rice, bananas or chapatis [170]. This is largely due to the fact that bean, corn, and traditional foods require longer cooking times compared to boiling water or heating food. Households see the improved stoves as expensive and thus want to ration when and how they use them [145,207].

To prepare different types of dishes, households wanted a stove that could perform specific cooking functions [187] such as frying [64,92,104,176,208,211,212], grilling [60], baking, drying [106], smoking [92,100], brewing [65,192], roasting [42], etc. For example, some staple foods such as chapati and bakri require high frying temperatures [104], and solar cookers could not reach these high levels [211]. The Ecostove incorporated a steel griddle top for frying foods [64]. In studies on improved stove adoption across Zimbabwe, households required stoves that supported brewing beer which typically involves large pots [65,167]. Households involved in an improved biochar stove deployment study in Cambodia and India brought up the fact that any stove needed to accommodate cooking specific foods, typically the local staples [45].

Tortillas, injera, chapati, roti, banku, and tô (all staples in specific countries) were especially challenging for an improved biomass, BLEEN, or solar stove to prepare [18,39,55,73,79,161,194,206,213]. For tortilla making in Mexico, nixtamal and traditional dishes cooked for parties, fuelwood is always used [18,206]. Even if the stove (such as LPG) could make a tortilla, rural Mexican households from two different studies complained that it could only fit one tortilla, while the traditional comal stove could make three or four at a time [55,206]. Additionally, rural households in Michoacan, Mexico found that the Patsari, an improved biomass stove, worked well to make tortillas, but then it was unsuitable for other common stove tasks (boiling water, making other dishes) [214]. To be useful, any stove deployed in Mexico must accommodate a smooth flat iron griddle (a *comal*) for tortillas [161].

In Ethiopia, any practical stove will need to accommodate making the large injera bread which is baked 2–3 times per week. A review of all technologies designed to bake injera bread found that metal pans on an improved stove did not produce the same small burns in the baked bread [39]. In Somali, improved stoves were not large enough to accommodate the curved clay griddle (a myrtle) used to make the injera [73].

In India and in countries with Indian cooking influence (e.g., East Africa), a stove must be able to make chapati or another flat bread called, roti, to be a feasible choice for households [42,56,62,81,99,139,157,165,205,215]. For example, an induction stove cannot make chapatis because the dough must make direct contact with the flame [210]. Households participating in an improved biomass stove intervention study in Haryana, India complained that chapati made with LPG did not taste the same [56].

In other studies, households used specific stove types for specific dishes [60,176,194,206]. Ghanaian households preferred charcoal for making banku, a traditional dumpling made of fermented corn and cassava dough [60], while households used the CleanCook for boiling water or making coffee [194]. In Burkina Faso, households struggled to make Tô, the traditional "polenta like" dish, on the Cookit solar cooker while rice, couscous, potatoes, soup, sauces, etc. were easy to prepare [199]. Some households in Jarácuaro village in Mexico using LPG adjusted to the different taste [18], while households in rural Western Nepal using electric stoves shifted the types of food prepared [215], but this was the exception not the rule.

Many traditional dishes require slow cooking [57,68,206]. Therefore, a study on long-term cook stove adoption in Karnataka and Andhra Pradesh, India found that households needed a stove that could accommodate a range of different cooking speeds and flame distributions [99]. The ability to cook the traditional dishes was often what "anchors" households to their traditional stoves [186].

These preferences for specific stove types for specific tasks, specific cooking functions, and specific dishes do have implications for stove designs. Households want a stove that can perform these different functions and meet the diversity of the traditional dishes as well as water boiling, etc.

Beyond wanting a stove that simply could make the staple foods, households from 29 studies really valued a stove that did not affect the taste of their food (Fig. 4, Panel E) [18,45,135,139,148,157,216,56,97,104,107,114,123,126,127]. There were conflicting reports regarding whether smoke was essential to maintain the taste of the household's foods. Some studies noted how smoke from traditional firewood and charcoal provides a distinctive flavor, [129,147], while others noted that the high eucalyptus content of firewood pellets in their improved biomass stove changed the flavor [49]. A few studies did note that food tasted better without smoke [43,67,204,217]. Some Peruvian households merely perceived that LPG would affect the taste of food, while others speculated that it was the difference between the metal pots used with LPG and clay with traditional three stone fires that affected the taste of food [123,126]. Households across studies stated that the quality of the meals dominated other factors for stove choice [89,100,142,198]. A stove is not useful if the food cooked is not acceptable to the household members. Therefore, stove designers should determine whether smokey flavor is important to their consumer base and possibly have taste tests throughout the community to demonstrate that the new stove does not change the taste of food.

Finally, a review of the literature revealed that a top priority is that the stove is reliable [57,127,144,148,157] with readily available fuel [84,101,195] to meet the demands of their household (n = 11) (Fig. 4, Panel E). Studies from both urban Zambia and rural India found that households did not trust electricity due to the unreliable grid [57,128]. In a study of four villages in Haryana State, India, households wanted to have a backup stove because they did not trust the supply of LPG [157]. In Ethiopia, households using the CleanCook stove mentioned that they liked that ethanol is always available [194]. Households in Cambodia using LPG did not want to be limited to buy a certain brand of fuel [196]. To be seen as useful and then adopted, stoves must be designed to reliably meet household needs.

4.2.4. Household schedules

The literature identified a group of stove characteristics that households preferred related to time and tending within the context of their demanding schedules and responsibilities (Table 1). The most commonly cited feature that households wanted is faster cooking speed (n = 58) (Fig. 4, Panel F) [41,45,71–73,75,79,81,87,95,97,98,49,100,112,116,119,125,128,130,132,135,136,51,138,142–144,146,152,164,165,167,171,55,175,192,194,195,199,204,218–220,56,58,62,65,67]. Households prioritize a faster stove, but in a few cases, this feature conflicts with an equal desire for a stove that can be left unattended [57,68,108]. Regarding case studies in peri-urban Kenya and urban Zambia, Jurisoo writes that "*somewhat ironically, seven respondents complained that the stove cannot be left unattended since it cooks so quickly compared with charcoal or fuelwood cooking*" [48] (pg. 170). Studies in Eastern Uganda and numerous Kenyan districts found that some households complained that the improved biomass stoves may be faster, but required the user to be more involved (e.g., stir food more frequently) [166,185]. These findings suggest that faster cooking is frequently preferred, but not always as it requires more intense tending. The user balances whether faster cooking or the ability to multi-task is more useful.

Thirty-five studies found that households wanted a stove that did not require intense tending [58,71,77,104,132,139,193] or active monitoring[43,50,117,126,130,155–157,171,178,185,193,51,199,204,207,217,221,54,57,59,64,68,78,92] (Fig. 4, Panel F). Indian households did not want to have to be constantly blowing air to keep the flame strong or adjusting the fuel frequently throughout cooking [59]. Households are accustomed to leaving stoves unattended. In urban Rwanda, users found their improved biomass pellet stove was typically faster leading to overcooked food [137]. Users have demanding household chores beyond cooking and find more use in a stove that gives them the option to multi-task. A study of 55 households in rural Kenya found that heat regulation allowed the cook to draw their attention away from the stove [50]. Therefore, stove designers and policy makers should prioritize stoves that provide the user the ability to both leave the stove unattended at lower temperatures and other times cook at higher settings. Designers should consider including variable heat settings.

Faster cooking with improved stoves resulted in time savings for the users (n = 24) (Fig. 4, Panel F). Across the literature, households found the time saved from improved stoves useful [53,70,140,155,222,223,74,78,83,85,92,94,96,101] as the cook could do a variety of other activities (e.g., washing utensils, cleaning and tending their animals, etc.) [221]. This saved time comes from shortened cooking times, less frequent cooking times [153], reduced time needed to clean the pots (since they are not blackened from smoke) and no longer needing to collect firewood [70,96,114,153,154,165,223].

Faster cooking does also have some drawbacks. For instance in a study of improved biomass stoves in Mbale, Uganda, the households reported having less social time and were unable to do other tasks while cooking [166]. Households often noted that collecting firewood is social and a welcome break from their daily chores [57,108,147,222]. In a study of subjective satisfaction for cookstove adoption across six Indian states, the authors noted that the households did not mind the burden of firewood collection, but viewed trips to market to buy fuel as inconvenient [142]. However, these findings are simply related to faster cooking, and should be evaluated within the context of the well-established literature on the other burdens associated with fuel collection (e.g., risk of violence while collecting, time consuming given limited and dwindling resources, less time for family time or productive activities, and the physical burden of walking far distances and carrying heavy biomass [50,224,225]).

Regardless of cooking time and level of supervision, households did not find a stove useful if it forced them to change their current cooking schedule. This was particularly an issue for solar cookers [98,104,107,193,211]. In evaluations of solar cooker interventions in Sudan and urban India, households did not like that the solar cooker could not be used after 3 pm [98] or that it took sufficiently more planning and preparation [104]. Households had specific times for serving dinner and did not want to have to change these household schedules [98,104,107,193,211]. Households in Bangladesh, South Africa, and Mexico found that LPG and biogas actually fit their morning schedules better as it was able to cook food the fastest and improved the household routine [51,65,206]. This revealed that if households found the stove to be useful within their established schedule, they preferred that stove model.

Related to these household schedules, the time of day also affected which features of a stove a household prioritized. For example, wood users in rural Ashanti, Ghana and three villages in Michoacan, Mexico would use charcoal or LPG if they were in a hurry trying to get the children off to school [60,206]. Users have many responsibilities and chores that demand their time and attention. Therefore, they appreciate stoves and stove characteristics that allow flexibility in cooking time, intensity of tending, and cooking schedule.

4.3. Social influence

Further work has extended the TAM to include social influence in order to evaluate how others affect attitude towards adoption [34,37]. The literature revealed multiple social influences driving preferences around the improved stove both within and outside of the individual household.

4.3.1. Social and cultural aspects

Households described specific stove features that stem from social and cultural aspects within the home and the local community at large (Table 1). Stove preferences revolved around spousal dynamics in eight studies (Fig. 4, Panel G). For instance, studies in Nigeria, Mexico, Kenya, Rwanda, and Ghana found that women preferred a smokeless stove as their spouse no longer complained about smoke [41], would now join her around the stove while she cooked [78,122], and in some cases, even offered to help with the cooking [64,90,204]. However, these dynamics did not always encourage clean stove use. In two studies in Uganda and Burkina Faso, men discouraged their spouses from using cleaner stove types in fear that the food would not be ready on time [180,199]. Understanding spousal dynamics may lead stove designers to include certain stove features depending on the context such as temperature settings, reliability, and reduced smoke.

Children also affected preferences around stove use as explained in nine studies (Fig. 4, Panel G). Previous research has found that households with children are more likely to adopt improved stoves [30,226]. In this review, the literature revealed that women want a stove that they feel comfortable having their children around [41,57,78,109,136,152] and even have them help cook [167]. There were conflicting discussions around children and LPG. One study in Eastern Rwanda noted that children could now help cook [90], while another in peri-urban Guatemala noted that children would play with the nobs and turn on the gas [124]. Designers and policy makers should ensure that household are aware of the safety features which allow for children to be around the stove.

The literature also revealed that any stove must provide a space for the family and community to gather together (n = 6) (Fig. 4, Panel G) [18,41,81,188]. For example, across India, the hearth is the center of home life [147], and in Botswana as a part of the Tswana culture, people gather and host guests around the fire (called Leiso) [107]. Households saw a key feature of the stove was the social status from the community associated with owning the appliance [18,66,70,114,119,124,148,170].

The status in the community gained from the stove was related to the stove being aesthetically pleasing and having a modern exterior (n = 34) (Fig. 4, Panel G) [45,47,83,90,95,98,112,117,127,143,144,150,48,165,220,227,50,52,55,58,63,71,79].For example, households in urban Burkina Faso did not find a cardboard cooking device appealing [199], while users across three districts in Malawi did not want a stove made out of local materials [70]. Households in peri-urban Kenya and rural India valued a stove design that was beautiful and modern [143,205], as these characteristics were a sign of affluence for households [205]. In India, households wanted bold colors and components [212], while in Ghana, households preferred stainless steel, cast iron, or metal with a black or matte finish and even specified wanting handles to add beauty to the stove [60]. Other households in Indonesia changed the base of their stoves for aesthetic purposes [79]. Thus, stove designers should prioritize aesthetics in stove design for adoption.

In some instances, there were specific cultural factors beyond making traditional dishes that affected which attributes a stove needed (Fig. 4, Panel G). For example, in some societies (e.g., Nigeria, Peru, etc.), smoke is a symbol of wealth [129] and many view smoke as a symbol of God's presence [212]. In India, the chulha (the traditional stove) was a central place of worship, and individuals would consecrate it and pray before it daily [212]. A few households in Mexico felt that the traditional stove connected them to their roots [57], while others in Uganda kept the three stone fire to show their children the tradition [43]. These are context specific factors, but designers should be aware that there may be different yet important cultural aspects that will affect the acceptance of their design.

Cultural factors affect stove design. In India, households bless a new cooking stove by boiling over cream on the stove [147]. This requires households to have a stove made with non-corrosive materials [191]. Indian households believed that a cookstove has to be purified with water or by applying cow dung, and therefore, do not prefer stoves with plastic parts (even plastic handles) [59]. In an evaluation of improved cookstove programs in India, some households would not construct the top of the improved biomass stove or purposefully break it because of religious beliefs associated with stove use [81]. Other households across three study sites in North Central Nigeria rejected the Abacha improved stove because they had to reload the stove mid-cooking by lifting the pot from the flame which was considered culturally inappropriate [129]. Muslim communities in Catembe, Mozambique were not able to use ethanol due to their beliefs around alcohol [114]. Gratz writes in detail all the cultural beliefs and traditions in the Sabaot community in Nigeria around the three stone fire and specifically martial issues [41]. For example, destroying the hearth was a sign that the woman had been unfaithful [41]. These examples are extremely specific to individual communities, but in general, social influences whether from intra-household dynamics or a community's cultural belief's affected preferences regarding the stove. Stove designers should investigate whether cultural beliefs around the stove will affect the features or attributes of a stove. From these stove attributes, it is clear that stove designers and policy makers must appreciate the social and cultural dynamics within households and the community that will affect stove use.

4.4. Versatility

In summary, a core theme throughout all these results is that households want versatility and flexibility [71,95,126,148], both of which ease the work of cooking and prove the most useful for the household. These terms were frequently used in the literature yet were never explicitly defined. However, throughout this review we recognized that a number of the reported user preferences revolved around versatility within the stove design, or as we define it from the reviewed literature as the ability to cook at a range of speeds, use any pot, use any fuel, use multiple pots or fuels, or even a pressure cooker with the stove [56,62,74,170]. These households have busy, stressful lives and want a 'versatile' stove that can easily fit their diverse and changing needs. Versatility as we have defined it does not represent all the reported preferences found in this review (i.e., reduced smoke, durability, etc.); however, it does summarize some of the more common aspects both across the seven dimensions identified in the review and within the TAM.

5. Regional trends

We assessed each identified stove aspect by location and region to determine if particular stove features or characteristics were associated with geographic region which may have similar climates, cultures, etc. Although we generalize by region, this high level evaluation that is not meant to disregard the importance of climate, socio-demographic characteristics, local and national policies, and the economic market. Fig. 5 reports the regional break down by aspect; however, in the main text we will only discuss the aspect if the region represented a majority (over 50%) of the examples.

5.1. Africa

Studies based in Africa represented 94 out of the total 191. Within Stove Operation, studies in African contexts disproportionately noted the preference for a stove that was easy to assemble (80%), easy to light (62%), did not burn the user (~54%), and was accompanied with stove information (60%). For Stove Design or Features, households in studies based in Africa preferred a sturdy stove (~80%). Studies in Africa mentioned households noting the importance of fuel and a stove not producing odor (~78%) or soot/ash (60%) in the dimension of Fuel Characteristics. With regard to Kitchen Space, studies in Africa found that users preferred the ability to move the stove between indoor and outdoor locations (75%) and mentioned the space the stove takes up in the kitchen (~56%). Within Household Food and Taste Demands, households from studies in Africa disproportionately mentioned the need for a stove to reliably (64%) meet their household's large cooking demand (65%) through the accommodation of large pots (60%) and multiple pot types (~64%). While households in studies based in Africa appreciated the time saved from an improved cook stove (55%), they wanted to be able to leave the stove unattended (~67%) in the category of Household Schedules. Finally, for social and cultural aspects, African studies held a slight majority in users noting the importance of the status that came with stove ownership, concerns about aesthetics (~57%), and spouses playing a larger role in cooking (~88%). The only two stove characteristics that African studies did not contribute to were: (1) a stove with table space and (2) a standing cook stove.

5.2. Asia

Seventy-two papers out of the 191 were from Asia. Asian studies disproportionately reported convenience (~83%) and wanting a stove that was easy to clean (60%) in Stove Operation. Households in studies from Asia were also more likely to mention the desirability of chimneys (75%) in Stove Design or Features. In Kitchen Space, papers in Asia mentioned that households wanted a stove that did not produce space heat as it would overheat the cook (~53%). Finally, papers based in Asia contributed no examples to stove characteristics pertaining to children, spouses, associated information, providing table space, easy construction, or use associated with time of day.

5.3. Central and South America

Studies from South and Central America accounted for only 25 of the 191 papers and did not hold the majority for any stove characteristic. This is likely due to the relatively small case study numbers, not regional preference.

5.4. Universal representation and regional differences in most popular features

We report in Table 2 the stove features that were generally equally represented between regions. Among the stove features that were most commonly cited (portability, smokeless, size of pots, specific cooking functions, multiple stoves, and faster) only portability was not equally balanced. No study in Central or South America mentioned portability, but the feature was balanced between Africa and Asia. The elements that were not mentioned should not be considered necessarily unimportant to households in all regions, as these aspects could simply be understudied. However, designers and policy makers should consider these regional trends, but still conduct their own assessments.

6. Discussion

In summary, this review found that although there were many commonly-cited stove features that households value in their cook stove, a few appeared dominant—and even universal among regions. On one hand, the multitude of cited features across a range of themes reveals a wide range of household preferences, but further investigation exposes a quasi-universal narrative. Preferences range across seven dimensions, but all relate to either the perception of ease of use, perception of usefulness, or social influence. Our key finding is that households largely want versatility; they have large cooking demands and want a clean, durable stove (or stoves) that can meet that demand and perform a range of cooking functions at a range of cooking speeds. Although this finding corroborates previous results, this is the first large scale, comprehensive review to evaluate user preferences. This review calls for stove designers and policy makers to consider user preferences, particularly across these seven dimensions, and promote bundles to meet this need for versatility.

We now turn to address the results in regard to context, stove type, rural/urban settings, gender differences, and culture. We discuss the policy implications from the most commonly valued features for stove designs, designers, and policy makers. Finally, we advocate stove designers to meet both the technical and social requirements, which will be both extremely challenging and necessary to meet SDG7.

6.1. Interpretation of results

Our results reveal that although context is very important there are multiple commonly cited preferences that were universal by region. Stove programs have been fairly criticized for not taking context into consideration in the deployment of stove programs [21,22]. However, this review reveals that there are certain preferences that are commonly desired. Understanding these seemingly universal preferences, of course, would need to be complemented by field assessments. However, the compilation of common preferences that arose in the literature and the seven dimensions provide a roadmap for stove designers and policy makers to collect consumer feedback.

Common themes arose in the preferences around the stoves evaluated in the included papers, regardless of stove type (e.g., faster cooking was appreciated in both improved biomass and LPG stove evaluations). Both improved biomass and BLEEN stoves will be necessary to reach universal access [228]. Therefore, stove designers and policy makers should consider these dimensions and the elements within them regardless whether the stove is an improved biomass or a BLEEN stove.

Accommodating these preferences found in the literature presents a difficult task requiring tradeoffs for stove designers. This is particularly salient regarding theme of Stove Designs or Features. Incorporating height and heat adjustment, handles, and durable, yet portable materials may come at a cost. Meeting these preferences may come at a higher cost from more expensive materials or yield a more complicated design. However, the cost of not meeting these preferences and the low adoption that follows is also high.

There is a growing literature on previously understudied socio-cultural factors [86] that affect cooking practices [40,57,219].Understanding user preferences regarding stove features adds to this body of literature. However, cultural aspects (as defined in Table 1) did not dominate the results on user preferences regarding improved stove features. Households did require that the stove be able to prepare the local, traditional dishes. On the surface this may present as a cultural preference, however, actually, this preference was related to versatility of cooking function and the usefulness of the improved stove. Households in India and East Africa needed a stove to make chapatis, while in Ethiopia, households required the stove be able to prepare injera. The stove's ability to do so is related to stove size, design, the ability to adjust the heat, etc. It is important the stove designers and development practitioners do not blame culture for failure to adopt an improved stove, rather than admit to a limited design that did not meet household needs [75,147,188].

Urbanity and gender differences were not prominent in the results either. One study noted that the preference of standing vs sitting may be related to the rural/urban divide. The difference was thought to be related to the fact that households in urban settings have been exposed to standing stoves, while rural populations have not. Therefore, this difference may have more to do with exposure rather than inherent rural/urban differences. Another article noted that urban women who worked outside of the home could not use a solar cooker. This is another example in which the issue is related to women having additional occupations, rather than an innate rural/urban divide. As noted in the introduction, papers use the terms households, users, respondents, and women often interchangeably. Therefore, this review was unable to parse out gender differences that could affect preference in stove features.

6.2. Policy recommendations

The results of this review reveal practical policy recommendations and lessons for stove designers. Studies showed that durability, lack of smoke production, and keeping the household's kitchen clean were of the most frequently cited favorable stove attributes. These features were universal across regions and should be implemented in any new stove design.

We advocate for stove designs or stove bundles that meet the entire cooking demand as households will otherwise continue to stack with unclean fuels. A single stove design must have multiple burners (at least two) and accommodate different pot sizes and types. Alternatively, designers and policy makers could pursue stove bundles of multiple types of clean stoves that could handle all typical cooking needs, perform a range of cooking functions (frying, simmering, etc.), accommodate a range of pot sizes, and cover occasions with increased cooking demand such as holidays. Meeting a household's entire cooking demand will prevent stacking with clean and unclean stoves, which has been shown to actually increase emissions as the household expands their energy use with the clean stove [229]. Stacking, or the use of multiple fuels, is not inherently problematic, but becomes a problem when unclean fuels are incorporated with clean options. An optimal clean stove (or clean stove bundle) that meets WHO's standards must accommodate total household cooking demand, or it will potentially do more harm than good.

Finally, faster and unattended cooking were also highly desired stove characteristics. These features on the surface may seem contradictory: wanting a fast stove, but then complaining that a fast stove has to be monitored more intensely. However, these two features reveal that really what the main cook wants is versatility and the ability to adjust the stove's heat. Users constantly have multiple tasks requiring their attention. In some instances, they will want to cook fast before their spouses return, and in others, they will want to be able to leave the beans cooking while they help their child with homework. A stove bundle that allows for different cooking functions and a range of cooking speeds can accommodate both these needs.

The overwhelming literature suggests that additional stove features (e.g., USB ports, etc.) are well received, but often the accompanying stoves are not. Therefore, stove designers should focus on designing stoves that meet the primary need of clean meal preparation, rather than attempting to diversify stoves that do not meet the primary objective.

Although not directly affecting stove design, designers and policy makers should honor the preference for education, information, or training around the stove. There is emerging research into leveraging local outreach workers to increase household education about stove safety [230].

The fact that not all features were universally endorsed suggests that stove designers and policy makers should still perform local surveys for preference in their specific context (i.e., for portability, space heat). Despite the universality of the most frequently preferred features, context is still extremely important. It is vital that stove designers incorporate actual consumers into the design process to test prototypes and critically evaluate how the user interacts with the stove in real world scenarios. It is especially crucial to make sure that the user is satisfied with the technical dimensions and loading the stove because if not users will modify the design on their own. These modifications often affect the emissions and efficiency of the stove. Balancing the user's preference is crucial for both uptake and realizing performance beyond the laboratory.

Meeting both the technical specifications and this extensive list of user preferences and requirements is a tall order for stove designers. However, both technical and social requirements must be met in order to insure both initial adoption and consistent, continued, exclusive use of the clean stove [231]. Although it is unlikely that a stove would be able to meet every desired feature or please every user, it is still very important for stove designers, developers, and policy makers to understand the users' preferences and the tradeoff they face in considering adopting a new stove. The onus should be on the stove designers and program implementers to meet the needs of those without access to clean fuel. Households without access face compounding hardships and should not be expected to adapt to a stove that inherently does not fulfill their needs. Although many stove designs and programs will scale through the private sector, it is crucial that developers and policy makers reframe their mission to provide a beneficial service to customers, rather than a product households have to unwillingly adopt [232]. Reaching SDG 7 and providing for the 2.9 billion people without access to clean cooking stoves and fuels will only be achievable if the individuals who lack access are satisfied with a sufficient clean alternative.

6.3. Future research

This review identified numerous pathways for future research. This includes further work investigating whether urban/rural settings, gender differences, or local outreach have an empirical effect on stove preference. We support calls for further ethnographic work to understand bioenergy and incorporate emic perspectives into cooking energy policy [86]. Finally, although this review provides high level context for these preferences, we advocate for further research into the factors driving these preferences such as climate, socio-demographic characteristics, local and national policies, and market characteristics.

7. Limitations

The sample size of papers is large for a review but does not represent all stove designs that have been or are currently being deployed in the developing world. Considerable literature addressed only the technical components of the stove without mention of social aspects. This review was by design, comprehensive, rather than systematic. With less strict inclusion criteria than a systematic review, we hope to offer a wider range of discussion to this topic for review. Generalizability is also a limitation of this review. In the effort to synthesize findings across themes and regions, we risk over generalizing across vast continents and the multiple cookstove projects that have diverse contexts. This is a coarse evaluation that is not meant to disregard the importance of climate, socio-demographic characteristics, local and national policies, and the economic market. Finally, this review has the limitation of reviewing only English language papers.

8. Conclusion

This review reveals a set of quasi-universal stove qualities among a multitude of stated preferences. Ultimately, these findings can be boiled down to the need for versatility. Stove developers need to design, and policy makers need to promote stoves (and perhaps stove bundles) that are versatile in size and function (e.g., can perform a range of cooking functions at a range of cooking speeds) in order to meet all of the household's cooking needs. Incorporating these user preferred stove features, characteristics, and attributes into new stove designs is requisite to ensure adoption and consistent, exclusive use of the clean stove.

If the stove designs fail to meet both technical and socially acceptable standards, low uptake and unclean stove stacking will continue to plague any progress towards SDG7. It is time that clean stove initiatives refocus to stop blaming low adoption on culture and prioritize the user, rather than the technology.

Declaration of Competing Interest

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

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Appendix A. Supplementary data

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