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Perspective

Affording a clean stack: Evidence from cookstoves in urban Kenya

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ABSTRACT

The unaffordability of clean cookstoves and fuels, as defined by the World Health Organization, is one of the most significant reasons for the persistent use of unclean fuels, even when "stacked" alongside a clean stove. To see health benefits, the entire cooking stack must be clean, and therefore the clean stack needs to be affordable. Using a case study of clean biomass pellet stoves in Nairobi, Kenya, we present scenario analyses to measure and evaluate the affordability of adopting a clean stack under various cooking scenarios, income ranges and affordability measures. We find that almost all clean stack scenarios are above the Energy Sector Management Assistance Program's threshold, regardless of displaced baseline fuels. Further research should evaluate multiple measures of affordability to understand the full household budgetary context. Our results indicate a cooking fuel affordability crisis, which can undermine the achievement of multiple Sustainable Development Goals.

1. Introduction

Affordability is one of the most significant barriers to the adoption and consistent use of clean cookstoves and fuels [1]. The World Health Organization (WHO) defines "clean" cookstoves and fuels[1] as those that meet strict particulate matter and carbon monoxide emission standards [3]. Near-exclusive use is necessary for achieving Sustainable Development Goal (SDG) 7's call for "affordable, reliable, sustainable and modern energy for all" [1]. The unaffordability of clean fuels is often cited as the primary reason [4–11], for persistent use of unclean fuels, even alongside a clean stove. This multi-stove phenomenon is known as "stacking".

Unclean fuel use leads to exposure to household and ambient air pollution, contributing to 2–3 million premature deaths per year [12]. Because of non-linear concentration response curves [13], households must drastically reduce exposure to smoke from unclean fuels to see health benefits [14]. However, households with clean cookstoves continue to stack [15–17]; therefore, research and policy need to focus on the design and affordability of a clean stack where exclusive use of a single clean fuel seems unlikely. The entire stack must be clean, and the clean stack must be affordable.

Affordability plays a central role in achieving SDG 7 and ensuring a clean stack, although cost is not the only reason that households stack. A review of 11 case studies on clean stove programs found that recurrent costs, supply challenges, and task-based requirements were the largest categories for reasons households continue to use polluting fuels [18]. Local food and taste preferences also lead to unclean stacks; for instance, users may feel that traditional dishes like chapati in Kenya may not be well-suited to the clean stove [19]. Peer perceptions and influence also play a role. However, the high rates of LPG exclusive use and dirty stove abandonment in the Household Air Pollution Intervention Network Trial [20], and a comprehensive review of the literature [8], reveals that user preference and ultimate use are largely a function of affordability and stove functionality. This literature does not undermine the role of taste and culture, but points to the dominance of user convenience and financial constraints.

Despite the importance of affordability, the clean cooking sector has not converged on how to quantify affordability [21]. The cost of clean cooking can be divided into two components: the upfront stove cost and the continued cost of fuel. Most studies focus on the upfront cost of the stove and per unit cost of the fuel (per kilogram, per meal, per unit energy). They often single out specific fuels, ignoring persistent stacking [21,22], or only address overall fuel poverty without distinguishing between cooking, heating, and lighting [23,24]. Most literature equates cost with affordability and does not consider the household's budget, or essential expenses such as food or rent [21,25]. A better metric for

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[1] 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" [2]. However, we refer to fuels or cookstoves as clean only if they meet the WHO's definition of "clean": <35 Particulate Matter 2.5 (Tier 4) and <7 Carbon Monoxide (Tier 5) [3].

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ongoing affordability is a ratio of fuel expenditure per month to overall monthly expenditure (the conventional affordability ratio (CAR)) [26,27]. The cost of the durable stove can be amortized as part of this calculation. The Energy Sector Management Program (ESMAP)'s Multi-Tier Framework establishes a threshold of 5 % household income to indicate the affordability (or unaffordability) of a cooking stove and fuel [2]; however, the sector rarely invokes this threshold when addressing the affordability of cooking.

Other sectors (such as housing) even acknowledge non-discretionary household expenses, such as loan repayments and medical fees [27,28] or consider affordability at minimum consumption levels. Affordability calculated at an “essential-needs” level is known as the potential affordability ratio (PAR). Essential-needs cooking energy per capita is dependent on caloric needs, age, work schedule, access to appliances and diet. The literature suggests a minimum level of roughly two Megajoules (MJs) of useful energy per capita per day [29]; however, there is substantial variation above this level [24,29,30]. The potential affordability ratio can therefore be considered a very conservative measure of affordability. Affordability calculated relative to a household's budget after subtracting out essential needs, such as rent or food, is known as the residual income approach (RIA). These more nuanced affordability approaches have not yet been applied to clean cooking.

We use data on clean biomass pellet stoves [31] from EcoSafi, a pellet company in Nairobi, Kenya, to present scenario analyses of a clean stack under various affordability measures and realistic income ranges. Biomass pellet companies are attempting to expand across East Africa and pellets are one potential fuel within a clean stack. We ask: should a biomass pellet customer fall into the lowest, median, or highest income quartile for Nairobi, what proportion of household expenditure (or income) (1) would be needed to stack a clean fuel at current consumption levels with other fuel options; (2) would remain after paying for a clean stack at current consumption levels after accounting for food and rent; and (3) would be needed to use clean fuels at a minimum consumption of 2 MJ/capita/day? We delineate the affordability implications of different clean fuel and stove combinations, under different consumption and expenditure (or income) levels.

Systematically measuring and monitoring affordability of a clean stack is critical regardless of context or the specific clean fuels in the stack. The affordability of future clean options will also need measurement and tracking through time. To our knowledge, this is the first application of affordability metrics beyond the conventional affordability ratio to clean cooking, and particularly to clean stacks as opposed to single-fuel analyses.

2. Methods

We anchored a complete dataset of EcoSafi's domestic customers ($n = 744$) to Nairobi specific household expenditure ranges from the 2016 Kenyan Budget Survey, within which our dataset is fully contained. We constructed worst-, median-, and best-case affordability ratios, before pellets were available and then with post-pellet use, between June 15th, 2021, and March 31st, 2022 (Fig. 2) (see Appendix A which includes our Supplemental data/sensitivity analysis). We evaluated “Post pellet” scenarios in which users do not change their baseline cooking energy consumption, as well as scenarios in which users adjust their consumption upwards based on empirical evidence from peri-urban Kenya [32,33]. We constructed the conventional affordability ratio, and then analyzed affordability ratios after accounting for non-discretionary, essential expenditures, forming a ratio out of the residual income approach that we define as the residual income affordability ratio (RIAR). Finally, we estimated the potential affordability ratio based on a minimum consumption of 2 MJ/capita/day. The rest of this section explains our data sources and scenarios.

2.1. Data sources

Our main data source was the complete database of EcoSafi domestic customers ($n = 744$) baseline and pellet purchase data from June 15th, 2021, and March 31st, 2022. The database had information on household size, latitude and longitude, baseline fuels (purchase size, quantity, and frequency of purchase), and pellet order data (date purchased, purchase size, total, and kilograms purchased), all linked to anonymous customer IDs.

Given the limited socio-demographic data from the EcoSafi database, we conducted scenario analysis on a range of expenditures (i.e., 25th, 50th, and 75th percentiles) from the 2016 Kenyan Household Budget Survey for households in Nairobi City, with four or more members, within which our dataset is geographically contained. We also obtained the same ranges of household expenditure on food and rent from the 2016 Kenyan Budget Survey. In doing so, we do not imply that the EcoSafi customers and the 2016 Nairobi households (of four or more members) are equivalent; rather, we present the range of affordability possible if an EcoSafi customer were to be in the 25th, 50th, or 75th expenditure percentile. We limited our expenditure ranges to households with four or more members to mimic our EcoSafi customer database (average: 5.0 standard deviation: 1.4). A more recent Kenyan Budget Survey was not publicly available due to delays caused by COVID-19. Therefore, we obtained additional data on the median urban household income across urban Kenya from a rapid response phone survey conducted by the World Bank, the Kenya National Bureau of Statistics and the University of California, Berkeley from May 2020 to November 2021 [34]. Although not from Nairobi alone, these data allowed us to conduct realistic sensitivity analyses using expenditure versus income for the affordability ratios with more recent values, before, during the height of, and a year after, the start of the pandemic. The results of that sensitivity analysis confirmed our overall findings using the 2016 data (see Appendix A which includes our Supplemental data).

3. Scenarios

3.1. Before pellets: baseline consumption

The EcoSafi database included each customer's self-reported monthly expenditure as well as their self-reported fuel consumption by fuel. We used these data to construct a “Before pellets: Baseline consumption” scenario. For expenditure, we defaulted to the self-reported amount, but confirmed these values by calculating the cost based on their fuel consumption estimates. We compiled the self-reported fuel consumption to calculate their total baseline cooking fuel consumption in the units of megajoules per month (see Table 1).

3.2. Post pellets: unchanged consumption

Using the calculated total baseline cooking fuel consumption from the “Before pellets: Baseline consumption” scenario, we constructed multiple “Post pellets: Unchanged consumption” scenarios. Using EcoSafi pellet purchase data, we calculated the megajoules per month derived from biomass pellets. In these “Unchanged consumption” scenarios, we assumed that total cooking fuel remains static, but we investigated different fuels that pellets could be displacing (EcoSafi does not track the customers' longitudinal purchase data for other cooking fuels). We evaluated a “Post pellets: Displace dirty fuels, unchanged consumption” scenario in which households displace kerosene (if they are using it) or charcoal with their newly adopted pellets, all while keeping overall consumption the same. In order to keep overall consumption the same, in some cases, we assumed users displace LPG (or another clean baseline fuel if not using LPG) once pellets have completely displaced the dirty fuel. This was only the case if users' pellet purchases were higher than their previous dirty fuel consumption (in

Table 1
Affordability ratio scenario descriptions.

Conventional Affordability Ratios/ Residual Affordability Ratios Scenarios	Description of hypothetical post pellet adoption scenario
I. Before pellets: Baseline consumption	
A. Baseline reported	EcoSafi customers' self-reported fuel consumption before adopting pellets
II. Post pellets: Unchanged consumption	
B. All pellets	All the megajoules (MJs) the household was previously using assuming a transition entirely to pellets
C. Post pellets: Displace dirty fuels, unchanged consumption	All the MJs of pellets the household purchased per month displaced any polluting fuels they were previously using. For example, if a household was using both LPG and charcoal, the pellets purchased are assumed to displace the energy equivalent amount of charcoal.
D. Post pellets: Displace LPG, unchanged consumption	All the MJs of pellets the household purchased per month displaced any clean fuels they were previously using (LPG). For example, if a household was using both LPG and charcoal, the pellets purchased are assumed to replace the equivalent amount of LPG.
E. Post pellets: Maintain stacking ratio, unchanged consumption	All the MJs of pellets the household purchased per month displaced both clean and polluting fuels they were previously using, while maintaining the same ratio. For example, if a household was using 75 % LPG and 25 % charcoal, 75 % of the pellets purchased are assumed to displace the energy equivalent amount of LPG and 25 % of the pellets purchased are assumed to displace the energy equivalent amount of charcoal.
F. All LPG	All the MJs the household was previously using assuming a transition entirely to LPG
III. Post pellets: Adjust consumption	
G. Post pellets: Literature derived	All the MJs of pellets the household purchased per month displaced both clean and polluting fuels they were previously using, according to a literature derived ratio. That is, we rely on reported data from peri-urban Kenya to indicate a ratio of how households may displace both clean and polluting fuels. For example, if a household was using both LPG and charcoal, the household is assumed to decrease their LPG and charcoal as found in the literature with the adoption of the purchased pellets; however, beyond that, the pellets are additive.
H. Post pellets: Displace dirty fuels	All the MJs of pellets the household purchased per month displaced any polluting fuels they were previously using; however, if the pellet purchases indicate more MJs than the MJs they were previously using with polluting fuels, we do not assume the pellets displace clean fuels and thus the overall MJs increase. For example, if a household was using both LPG and charcoal, the pellets purchased are assumed to displace the energy equivalent amount of charcoal; however, the household purchased more pellets than charcoal (in terms of delivered energy). In this case, we assume the household increased their overall MJs of energy, by using same amount of LPG and the purchased pellets, while displacing all charcoal.
I. Post pellets: Displace LPG	All the MJs of pellets the household purchased per month displaced any clean fuels they were previously using; however, if the pellet purchases indicate more MJs than the MJs they were previously using with polluting fuels, we do not assume the pellets displace clean fuels and thus the overall MJs increase. For example, if a household was using both LPG and charcoal, the pellets purchased are assumed to displace the energy equivalent amount of LPG; however, the household purchased more pellets than LPG (in terms of delivered energy). In this case, we assume the household increased their overall MJs of energy, by using same amount of charcoal and the purchased pellets, while displacing all LPG.
Potential affordability ratio scenarios	
We conservatively assume that a household needs 2 MJ/capita/day	
75 % LPG 25 % Pellets	75 % derives from LPG and 25 % from pellets
75 % Pellets 25 % LPG	25 % derives from LPG and 75 % from pellets
All LPG	Entirely LPG use
All pellets	Entirely pellet use
Half pellets Half LPG	50 % derives from LPG and 50 % from pellets

megajoules). We also constructed a “Post pellets: Displace LPG, unchanged consumption” scenario, in which households displace LPG with their newly adopted pellets. In order to keep overall consumption the same, in some cases, we assumed users displace dirty fuels once pellets have completely displaced their previous LPG use. This was only the case if users' pellet purchases in megajoules were higher than their previous LPG megajoule consumption. Finally, we explored a “Post pellets: Maintain stacking ratio, unchanged consumption” scenario in which households do not completely displace a clean or dirty fuel, but rather add pellets into their cooking fuel stack, while simply adjusting the amounts of, yet keeping, all baseline cooking fuels. We also explored exclusive scenarios of “All Pellets”, and “All LPG” (see Table 1).

3.3. *Post pellets: adjust consumption*

Recent research reveals that, in practice, households increase their overall cooking energy consumption with access to biomass pellets [32,33]. Therefore, we created three scenarios in which the customers' total overall cooking consumption changes. In the “Post pellets: Displace dirty fuels” scenario, we assumed households displace kerosene (if they are using it) or charcoal with their newly adopted pellets. If pellet purchases indicated more megajoules from pellets than their previous dirty fuel consumption, we did not assume pellets displace clean fuels. Rather, we allowed the total MJs to increase. In the “Post pellets: Displace dirty fuels” scenario, we assumed households displace LPG with their newly adopted pellets. If pellet purchases indicated more megajoules from pellets than their previous LPG consumption, we did not assume pellets displace dirty fuels. Rather, we allowed the total megajoules to increase. Finally, we drew on the recent literature on biomass pellets in peri-urban Kenya [32,33] to obtain a ratio by which LPG, kerosene, and charcoal decrease by with the introduction of biomass pellets. Our “Post pellets: Literature derived” scenario assumes the customers' baseline fuels adjust by this ratio found in the literature and pellets are simply additive (see Table 1).

3.4. *Affordability ratios*

We constructed the conventional affordability ratio (CAR) as the monthly cooking fuel expenditure, under each scenario, as a proportion of the median (or interquartile range) Nairobi household expenditure. Note that in ESMAP's report establishing the Multi-Tier Framework, the denominator of this threshold is income; however, in specific country reports, ESMAP prefers expenditure [2]. We provide both for sensitivity analysis: we replaced the 2016 Kenyan Household Budget Survey median (or interquartile value) with the 2020 and then 2021 COVID Rapid Response Phone Survey median (or interquartile value).

In its usual applications, the residual income approach is treated as a difference metric rather than a ratio [27,35]; however, we define the residual income affordability ratio (RIAR) as the ratio of cooking fuel expenditure and overall household expenditure after subtracting out essential purchases such as food and rent. To construct the residual income affordability ratio, we calculated the monthly amount of cooking fuel expenditure (equal to the value used in the conventional affordability ratio) as a percentage of total household expenditure after paying for food and rent. To obtain this 'residual income,' we subtracted the median (or interquartile value) for food and rent expenditure (from the 2016 Kenyan Household Budget Survey) from the median (or interquartile value) for total household expenditure (also from the 2016 Survey).

To construct the potential affordability ratio, we calculated the monthly expenditure necessary for 2 megajoules/capita/day for each EcoSafi household to stack pellets and LPG, and expressed this as a percentage of a household's expenditure. It is difficult to determine a basic or essential level of cooking fuel consumption. We note substantial variation in the literature for this minimum amount. The Clean Development Mechanism compiled FAO Wood Surveys and established a "universal" minimum of 0.5 tons of wood per capita per year, which is roughly 2 megajoules of useful energy per capita per day. This is confirmed by Daioglou et al. 2012's analysis which found that most estimates hover around 1.5–3 megajoules of useful energy per capita per day [30]. We note that Foster et al. 2000 [24] defined a minimum cooking fuel as 10 kg of wood per household per day, which is roughly 3 megajoules of useful energy per capita; however, we defaulted to the Clean Development Mechanism's comprehensive review and conservative minimum value [24]. For the potential affordability ratio, since it is based on 2 megajoules/capita/day and not the baseline level of consumption, we pursued different ratios of pellets and LPG: 25 % pellets & 75 % LPG, 75 % pellets & 25 % LPG, 50 % pellets & 50 % LPG, exclusive pellets, and exclusive LPG (see Table 1).

We compiled fuel prices from fall 2021 spot prices and confirmed them in the spring of 2022. The price of LPG is from a 2020 spot price. We do not include any value-added-tax (VAT) on LPG as the policy has been rapidly changing. In our own sensitivity analysis, not included given space constraints, the VAT significantly exacerbated the unaffordability of a clean stack. We averaged fuel efficiencies and lower heating values from the US Environmental Protection Agency database procured for cooking fuel lifecycle analysis estimates [36].

We imputed a zero cost to the stove itself because EcoSafi Customers receive the biomass pellet gasifier for free in exchange for a monthly subscription to pellet purchases (minimum of 20 kg per month). A purchased stove is, of course, a further affordability barrier for customers without this type of subscription model. Thus, all our affordability metrics are conservative.

4. Results

4.1. Baseline cooking and affordability in Nairobi Kenya

We find that ~39 % of EcoSafi consumers used more than one fuel before the adoption of biomass pellets (Table 2). On average, EcoSafi's households were using 1.4 fuel types at baseline. The most common stacking combination was LPG and kerosene (16.3 % of all customers), followed by ethanol and LPG (6.3 %), charcoal and kerosene (4.7 %), and charcoal and LPG (4.1 %). Sixty one percent were exclusive LPG users at baseline (Table 2).

Table 2
EcoSafi household customers' baseline fuel use.

Stove combination	%	MJ breakdown
Charcoal	0.3 %	100 % Charcoal
Charcoal and Kerosene	4.7 %	13 % Charcoal; 87 % Kerosene
Charcoal and LPG	4.1 %	45.4 % Charcoal 54.6 % LPG
Charcoal, Electric, and LPG	0.3 %	48.6 % Charcoal; 30.7 % LPG and 20.7 % Electric
Charcoal, Ethanol, and LPG	0.1 %	15 % Charcoal; 70 % Ethanol; 15 % LPG
Charcoal, Kerosene, and LPG	0.7 %	25 % Charcoal; 20 % Kerosene; 55 % LPG
Electric	0.3 %	100 % Electric
Electric and LPG	0.9 %	39 % Electric and 61 % LPG
Electric, Ethanol, and Kerosene	0.1 %	38 % Ethanol; 38 % Electric; 25 % Kerosene
Electric, Ethanol, and LPG	0.3 %	30 % Ethanol; 27 % Electric; 43 % LPG
Electric, Kerosene, and LPG	0.3 %	39 % Electric; 42 % LPG; 18 % Kerosene
Ethanol	0.9 %	100 % Ethanol
Ethanol and Kerosene	1.0 %	98 % Ethanol; 2 % Kerosene
Ethanol and LPG	6.3 %	90 % Ethanol and 10 % LPG
Ethanol, Kerosene, and LPG	0.1 %	48 % Kerosene; 25 % Ethanol; 27 % LPG
Kerosene	2.3 %	100 % Kerosene
Kerosene and LPG	16.3 %	44 % Kerosene and 56 % LPG
LPG	61.1 %	100 % LPG

Of all EcoSafi customers who were using LPG in the baseline, 66 % purchased 6 kg LPG cylinders, as opposed to 40 % purchasing 13 kg LPG cylinders; 6 % purchased multiple sizes. Of all EcoSafi customers purchasing charcoal in the baseline, 94 % purchased the smaller tin size of charcoal, while 10 % purchased larger bags of charcoal; roughly 5 % purchased multiple sizes. Confirming previous literature [21], this result suggests that customers face liquidity constraints as 13 kg LPG cylinders and large charcoal bags are widely available and cost less per kilogram (Table S2). The EcoSafi data only provided information on fuel usage and did not specify if the charcoal was being used in an improved or inefficient charcoal stove. However, for context, ESMAP found that in 2019, 8.6 % of households in urban areas used a traditional charcoal stove, while 10.2 % used an improved charcoal cookstove [37]. Further, the prevalence of purchasing 6 kg LPG cylinders indicates that households are using LPG cylinder and single burner sets in which a burner and potholder screw directly into the cylinder as opposed to a more expensive two burner stove that connects to the 13 kg cylinder through a pipe and regulator.

EcoSafi distributes the Mimi Moto, which is a distinct advanced biomass pellet gasifier that requires the user to add processed, uniformly sized biomass (i.e., pellets), purchased from EcoSafi, into the top of the stove. The single burner stove has a fan that forces air into the combustion chamber, which increases efficiency and reduces emissions (Fig. 1, top panel). EcoSafi customers most frequently purchase pellets in ~8.4 kg bags, even though larger sizes exist and are cheaper per kilogram (Fig. 1, bottom panel). Relatedly, users tend to purchase pellets on shorter time scales than monthly increments (Fig. 1, bottom panel).

EcoSafi does not collect baseline information on the types of food cooked with each baseline fuel; however, other literature from peri-urban Kenya reports that clean fuels like LPG or biogas, when stacked, are used for boiling water (to prepare tea often) and side dishes (vegetables), while charcoal or wood fuels are used for heavier dishes such as staple grains that require longer cooking times [18,38]. Other studies in and outside of Kenya document how multiple stoves with different functions (i.e., simmering, roasting, etc.) are used for a range of dishes, such as roasting fish or meat or preparing chapatis, a staple bread [19,21,39–41]. We do not know what specific foods EcoSafi customers use pellets to prepare; however, studies on pellet-stoves in peri-urban Kenya found that 63 % of users claimed they used the Mimi Moto for all dishes, while 15 % said only for staple grains, 7 % for side dishes, and 7 % for preparing tea [32].

The median household reports spending 8.1 % [Q1:9.8 %, Q3: 4.6 %] of their total expenditure on cooking fuel at baseline, before the adoption of pellets (Fig. 1). This percentage for the median household increases to 16.2 % [Q1:27.8 %, Q3:9.9 %] after accounting for food and

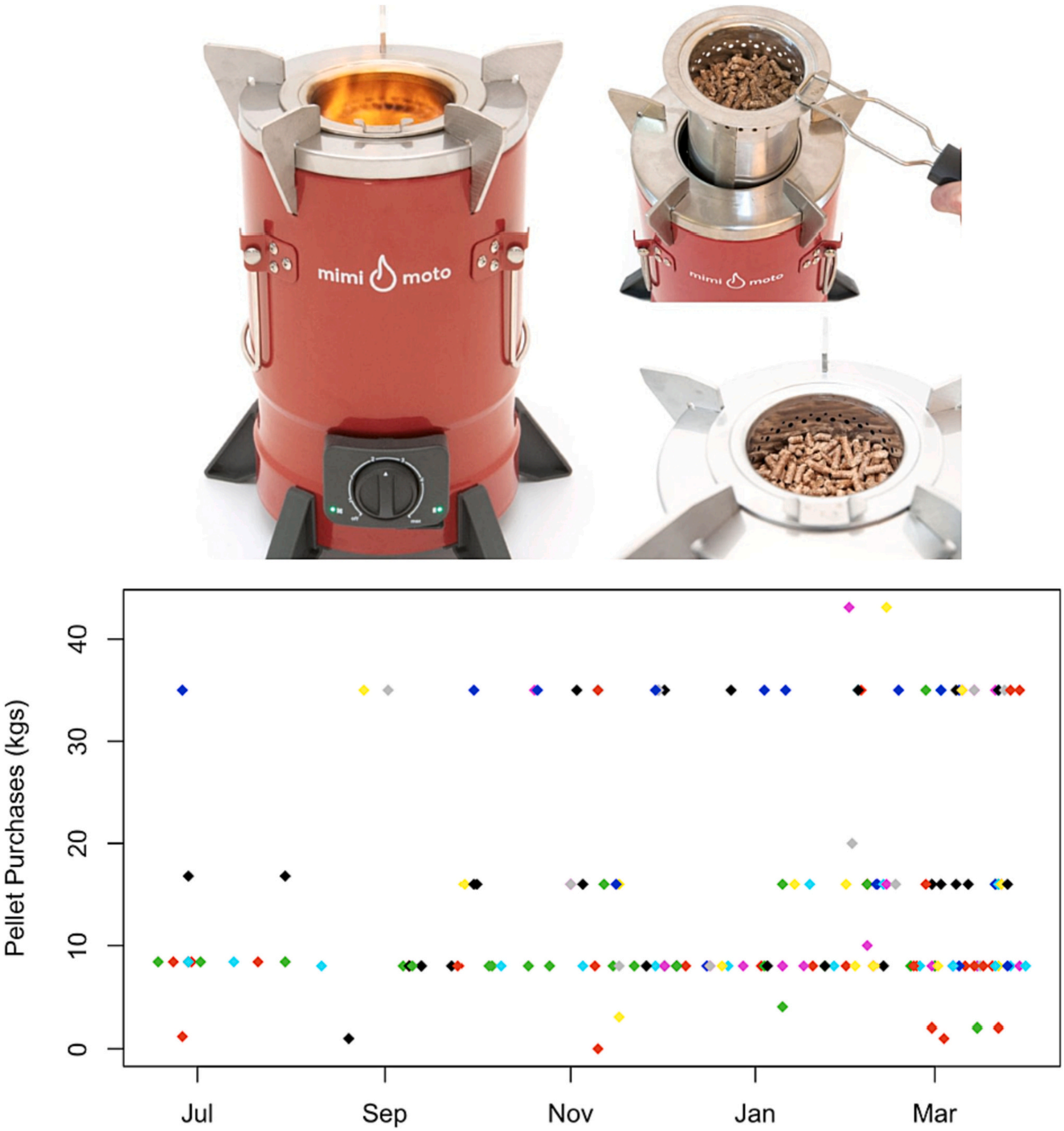

Fig. 1. The top panel depicts the Mimi Moto stove. The bottom panel depicts pellet purchases in kilograms for a sample of 50 EcoSafi customers from June 15th, 2021, until March 31st, 2022. Each color indicates an individual EcoSafi customer.

rent (Fig. 2).

4.2. *Affordability before and after the introduction of a new clean fuel*

We explored "Post-pellets: Unchanged consumption" scenarios in which users adopt pellets, replacing either charcoal or LPG, but maintain their total cooking energy consumption. We model affordability as if the user were to (1) use only pellets; (2) use pellets to displace only dirty fuels while maintaining other baseline clean fuels; (3) use pellets to displace only clean fuels while maintaining other baseline dirty fuels; (4) use pellets, displacing all fuels equally (i.e., maintaining their original stacking ratio); (5) use only LPG. The most affordable option for the median household is to displace LPG with pellets (4.6 % [Q1: 6.4 %, Q3: 3.0 %]) (Fig. 2). Exclusive use of biomass pellets is the second most affordable; median households have a conventional affordability ratio of 5.0 % [Q1:7.0 %, Q3:3.3 %]. Using pellets to displace dirty fuels while retaining other clean options (e.g., LPG) produces a median conventional affordability ratio of 6.0 % [Q1: 8.3 %, Q3: 3.9 %].

4.2.1. *Post pellet scenarios accounting for consumption adjustment*

Next, we explore affordability if households adjust their total cooking energy consumption with the introduction of biomass pellets, displacing certain fuels while increasing aggregate consumption. Recent research reveals that, in practice, users mainly displace charcoal but also

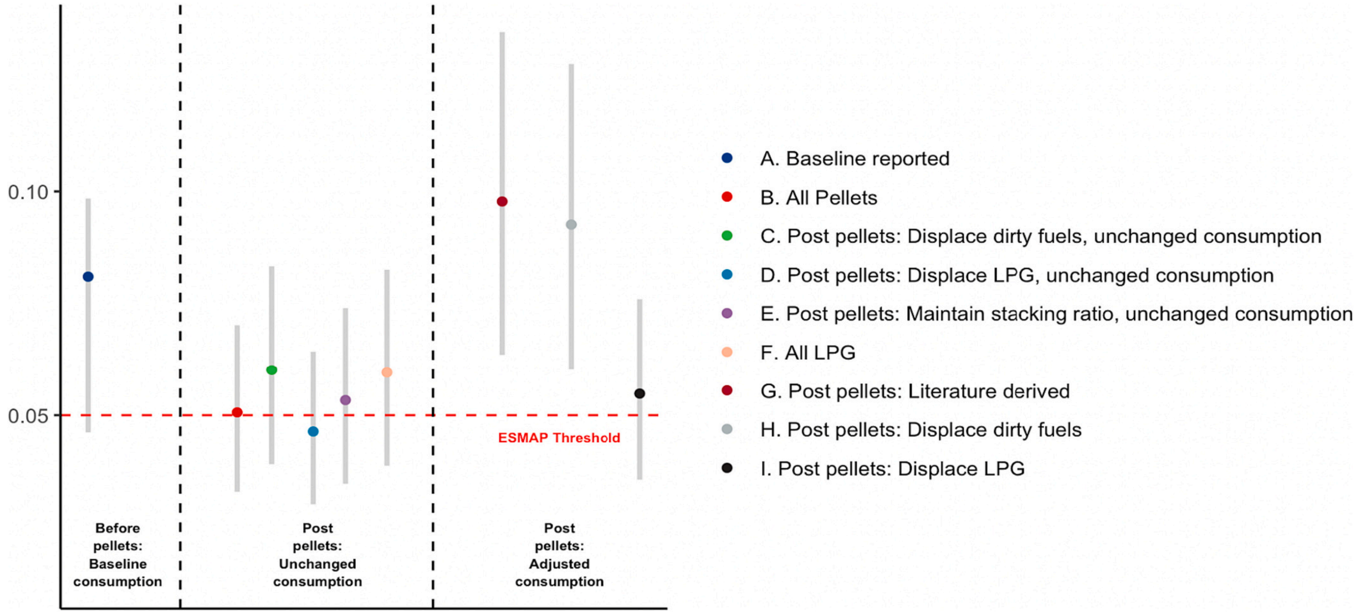

Fig. 2. Conventional affordability ratios (CAR) under baseline (left panel) and pellet adoption scenarios in which aggregate cooking energy remains at the baseline (middle panel) or adjusts upwards with biomass pellets (right panel). Data from EcoSafi customers in Nairobi. CAR is median cooking fuel expenditure as percentage of median Nairobi household expenditure, for households with ≥4 members (2016 Kenyan Household Budget Survey). Range bars depict the ratio for 25th and 75th percentile of household expenditure.

increase energy consumption with access to biomass pellets [32,33]. Therefore, we model three affordability scenarios as if the user adjusted their cooking energy consumption while (1) following trends from emerging literature, (2) using pellets to displace only dirty fuels, and (3) using pellets to displace only LPG. If users increase consumption in line with literature-derived estimates, their conventional affordability ratio is 9.8 % [Q1: 13.6 %, Q3: 6.4 %] (Fig. 2) at median household monthly expenditure. If the pellets displace only charcoal, the conventional affordability ratio is 9.3 % [Q1: 12.8 %, Q3: 6.0 %]. We also model affordability with pellets displacing only LPG. The median conventional affordability ratio is then 5.7 % [Q1:7.6 %, Q3: 3.6 %]. This is the most affordable option while allowing for upward cooking fuel adjustment, though the data suggest that users are not resorting to this.

4.2.2. *Affordability of cooking fuel before and after essential purchases*

For all scenarios, we also investigate the residual income affordability ratio, for which we subtract food and housing from the median 2016 Nairobi household expenditure. The most affordable option for the median household is still to displace LPG with pellets, without increasing aggregate cooking energy (10.6 % [Q1: 18.2 %, Q3: 6.4 %]) (Fig. 3).

In practical terms, considering these hypothetical clean stack scenarios, accounting for all combinations of pellets and LPG, a median household in Nairobi, after paying for rent and food, would have

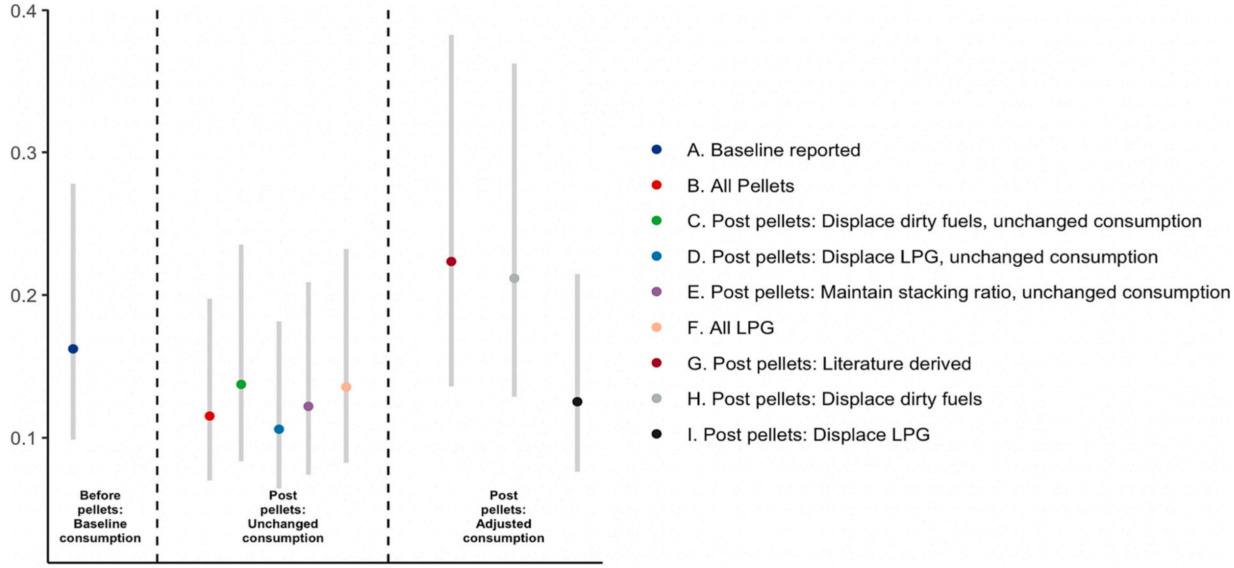

Fig. 3. Residual income affordability ratios (RIAR) under baseline (left panel) and pellet adoption scenarios in which aggregate cooking energy remains unchanged at baseline levels (middle panel) or adjusts with the introduction of biomass pellets (right panel). Data from EcoSafi biomass pellet users in Nairobi. RIAR is cooking fuel expenditure as a percentage of median household income in Nairobi after subtracting out food and housing (from 2016 Kenyan Household Budget Survey), for households with ≥4 members. Range bars depict ratio for the 25th and 75th percentile of household expenditure.

109–129 USD per month for every other household expense. For a 25th percentile household, paying for a clean stack leaves 49–69 USD per month for everything other than food, fuel, and rent.

These scenarios and ratios have vastly different implications for different economic percentiles. To stay below ESMAP's threshold, a median household's only option is to displace LPG with pellets while maintaining consumption (Fig. 2). The 25th percentile have no clean stack option that is at or below the ESMAP threshold for affordability. The residual income affordability ratio for the 25th percentile represents a 2.8 times worse fuel affordability ratio than their conventional affordability ratio.

4.2.3. Potential affordability of cooking fuel

We evaluate the (conservative) potential affordability ratio under scenarios of clean stacks, and exclusive use of pellets and LPG. We find that, at the (conservative) essential-needs level of 2 MJ per person per day, the median potential affordability ratio for exclusive pellet use and 75 % pellet use with 25 % LPG are the only two scenarios barely under the ESMAP threshold of 5 % (4.7 % [Q1: 6.5 %, Q3: 3.3 %] and 4.9 % [Q1: 6.8 %, Q3: 3.2 %]). Exclusive LPG use is unaffordable (Fig. 4), even when the stove has an imputed cost of zero.

Across all scenarios each median potential affordability ratio is roughly equal to or higher than ESMAP's 5 % threshold. Exceptions to this include (i) the conventional affordability ratio if median households displace LPG while not changing consumption and (ii) the potential affordability ratio if median households exclusively use pellets or use 75 % pellets with 25 % LPG. However, even these are very close to the 5 % threshold (4.6 %, 4.7 % and 4.9 % respectively). We find that LPG would need to be subsidized by 0.5 USD/kg for a 25th percentile household of five to reach a potential affordability ratio that meets ESMAP's threshold for clean fuels alone.

5. Discussion and conclusions

Our study indicates that almost all clean stack scenarios using pellet stoves in Nairobi's households face barriers to affordability, however it is measured. Decades of empirical evidence suggest that households will stack [15–17]. Thus, the search for a perfect, exclusively used, clean fuel is unrealistic. Instead, the sector needs to offer households a suite of clean, affordable fuels to ensure that a clean stack is economically feasible.

A clean cooking transition, necessary for health benefits and modern energy for all, is currently inconceivable for the lower- or even median-expenditure brackets. Unaffordable cooking fuel exacerbates income inequality; our results confirm previous literature in which lower-income households spend relatively more on fuel [26,42]. It should be unacceptable for vulnerable households to spend upwards of 10 % of their income on clean fuel or suffer the health consequences of a (even partially) dirty stack. Our results corroborate that clean fuels are the least affordable options [5,21,43]; thus, within and beyond Kenya, policy makers must consider how to increase the affordability of multiple clean options. For the Nairobi case, governments and donors could (1) promote the distribution of clean fuels in small quantities, while not increasing the unaffordability, (2) support a clean-fuel subsidy for the lowest income quartiles of at least 0.5USD/kg, and (3) consider broadly subsiding clean fuels because reducing air pollution is a public good.

With respect to the first recommendation: The inability to purchase clean fuels in smaller quantities on shorter timescales is a well-documented barrier to clean cooking affordability [21]. However, when clean fuels are sold in smaller quantities, the per unit cost of clean energy increases (e.g., the per unit cost of LPG in the 1 kg cylinder is higher than in the 13 kg cylinder). Pay-as-you-go models have been suggested where users can pay little by little through a meter on the stove; however, this additional hardware as opposed to traditional LPG has not scaled and further adds to cost of the fuel [44]. Despite this tradeoff between total fuel cost and purchase quantities, small-quantity purchases are more consistent with many low-income households' cash flows. Our results support this conclusion as the majority of EcoSafi customers purchased pellets and other fuels in the smaller quantities of those offered.

With respect to the other two recommendations: We fully recognize the many priorities that low-income countries must balance, and

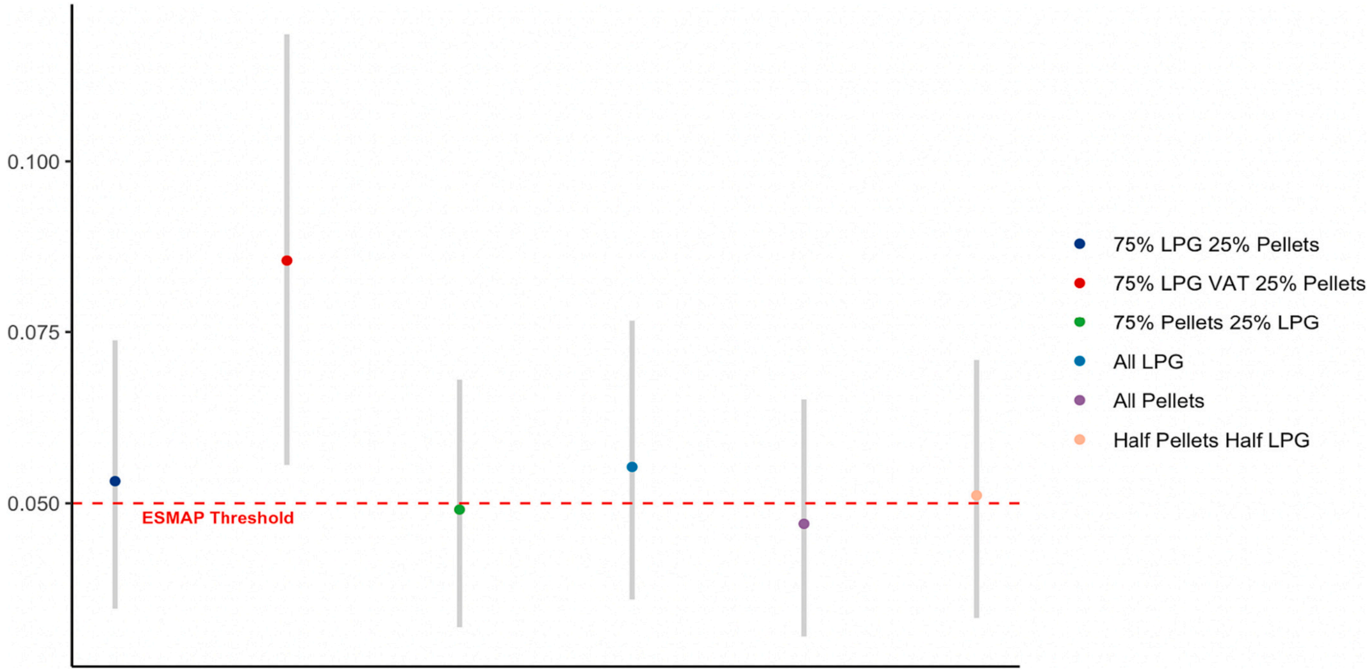

Fig. 4. Potential affordability ratios (PAR) for EcoSafi biomass pellet users in Nairobi under exclusive clean fuel scenarios. Median cooking fuel expenditure for 2 Megajoules (MJs)/capita/day as percentage of median household expenditure, for households with ≥4 members. Range bars depict ratio for 25th and 75th percentile of household expenditure. The median PAR of exclusive pellet use and 75 % pellet use with 25 % LPG use are the only two scenarios under ESMAP's threshold of 5 % of income.

therefore clean fuel subsidies may not be immediately forthcoming. We note, however, that Kenya has pursued subsidies for energy access (other than clean cooking fuels) [45]. Further, the clean cooking policy landscape is dynamic in Kenya. Kenya removed the Value-Add Tax (VAT) on LPG between 2016 until 2020, but reinstated it as of July 2021 [46]. This has since been reduced to 8 %, and as of June 2023, the president has suggested returning to a full exemption [47]. While the Kenyan government has numerous pressing needs, a clean cooking subsidy is not unprecedented as other low-income countries have pursued national LPG subsidies with varying degrees of success. While policies cannot ensure that the stack will be clean in practice due to the other factors driving stacking, they can ensure that the technologically viable clean options are made affordable.

Our study has limitations that must moderate our conclusions. We evaluate affordability at a monthly time scale when many customers purchase biomass or charcoal per day or per week [21]. However, nationally representative surveys report only monthly expenditures. We present many different stacking scenarios as we do not know how the average consumer may actually alter their post-pellet stacking behavior. To account for heterogeneity in stacking behavior, our analysis presents realistic scenarios based on recent data from peri-urban Kenya [32,33].

Despite these limitations, our work has direct implications for recent and ongoing efforts to track energy access. Simple adjustments to routine data collection practices could increase the understanding of cooking affordability, as many surveys already collect the necessary data to construct the conventional affordability ratio. For example, the standard Demographic and Health Surveys could amend two questions [48] to collect stacking data for other researchers and stakeholders to estimate affordability. The WHO's guide for measuring energy access could add to their single question on cooking expenditure and require (not suggest) that surveyors consider the context of expenditure or income. Our work indicates that future surveys, (e.g., ESMAP's developing standardized survey), should collect the (minimum) data necessary to construct metrics to fully evaluate the affordability of (potential) clean stacks. Critical metrics to collect are overall monthly household expenditure as well as monthly expenditure on every cooking fuel used by the household (not just the primary or the cleanest fuel).

Policy makers should at least ensure that the minimum, although debated, energy consumption within the potential affordability ratio is within an acceptable threshold relative to total household expenditure. The potential affordability ratio should be used as an essential-needs benchmark, and not a prescribed affordability ratio. All measures of affordability should include all household cooking fuels, not just the primary or cleanest. The most robust cooking affordability metrics could also collect expenditure on essential items such as rent and food.

Future affordability work should also account for households adjusting their consumption with cleaner fuels becoming available. Although a few clean cooking studies incorporate dynamic demand scenarios [49,50], the majority do not [30,51]. Accounting for adjustment can reveal a more accurate range of affordability implications.

Finally, the extreme unaffordability of cooking fuel that we find undermines efforts to meet several Sustainable Development Goals (SDGs). The global community cannot expect the lowest income households to live with the equivalent of 49 USD after rent, food, and cooking fuel in return for using clean options. This unaffordability directly contradicts SDG 7. The cost of clean fuels disproportionately burdens lower-income groups and female-headed households [26], compromising the ability to achieve global goals related to poverty (SDG1), inequality (SDG 10), and gender equality (SDG 5). The achievement of SDG 7 must not come at the cost of these other SDGs, which makes measuring, tracking, and subsequently ensuring the affordability of an entire clean stack a development imperative.

CRediT authorship contribution statement

AGW and IR designed the research. AGW analyzed the data. AGW and IR wrote the paper.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Annelise Gill-Wiehl reports financial support was provided by National Science Foundation. Annelise Gill-Wiehl reports a relationship with Better Cooking Company Ltd. that includes: funding grants, but unrelated to this work.

Data availability

The data that support the findings of this study are available from EcoSafi but are not publicly available.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.erss.2023.103275.

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