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Cooking for communities, children and cows: Lessons learned from institutional cookstoves in Nepal

Benjamin L. Robinson [a],*, Mike J. Clifford [a], Joseph Hewitt [b], Sarah Jewitt [b]

[a] University of Nottingham, Faculty of Engineering, University Park, Nottingham NG7 2RD, UK
[b] University of Nottingham, School of Geography, University Park, Nottingham NG7 2RD, UK

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ABSTRACT

Despite a long history of Improved Cookstove (ICS) interventions by Non-Governmental Organizations, International Development partners and the Government of Nepal, the majority of rural Nepalese people cook on a traditional open fire for their large-scale cooking needs due to a significant lack of approved institutional-scale cooking solutions. Whilst 65.8% of rural Nepalese households cook with biomass as their primary fuel source to satisfy their personal energy needs, there is no information collected on institutional cooking use by the Government of Nepal. In this paper our main objective was to design, implement and evaluate a novel Institutional Improved Cookstove (IICS) to satisfy this gap and following its manufacturing and testing in a Government of Nepal approved test center, to identify the complex contextual factors that often override the technical capabilities of IICS. Our three-phase method combined qualitative and quantitative research approaches, as well as north-south collaborations involving a transdisciplinary research team to create an integrated systems approach taking into account the voices of all key energy stakeholders. Phase 1 included UK based co-design and testing at the University of Nottingham in 2017 to develop a novel IICS that could be used in rural Nepal. Phase 2 involved adapting the design to accommodate contextual factors highlighted by Nepalese partners and to meet testing requirements at a Government of Nepal approved testing center in late 2017. Phase 3 was conducted between December 2017 and April 2020 and focused on piloting the novel IICS in a range of locations, altitudes, socio-economic and cultural settings, monitoring sustained use and obtaining user feedback. We present our results through three case studies that highlight the highly contextualized nature of IICS adoption and sustained use, the importance of stacking, usability and cost savings, and a number of pathways to scale in an institutional setting.

Introduction

Irreversible respiratory health issues linked to air pollution from biomass fuels are responsible for up to 4 million deaths per year with 20% of these being children under the age of 5 (The World Bank, 2018). In the era of COVID-19, where underlying respiratory issues are one of the distinguishing factors between life and death, it is especially important to provide solutions to this global challenge. Across the globe, a long history of Improved Cookstove (ICS) programs have focused on reducing the number of people who rely on biomass as their primary cooking fuel (Hanna et al., 2016; Jagadish & Dwivedi, 2018; Johnson & Chiang, 2015; Kirch et al., 2016; Moses et al., 2019; Prapas et al., 2014). Most of these programs have focused on household-scale initiatives with little attention given to biomass stoves used by institutions, small businesses and even large households that contribute significantly to poor air quality and respiratory health issues (MECS, 2020). To achieve SDG7, Sustainable Energy for All (United Nations, 2016), the ICS sector requires largescale transitions to clean cooking systems in both household and institutional kitchens over the next 9 years. To fulfil this need, significant and targeted scaling effort is required (Quinn et al., 2018) to increase adoption and sustained use across these user groups. Existing solutions such as carbon finance (Freeman & Zerriffi, 2015) and results based financing (EnDev, 2020), amongst others, provide market based attempts at increasing both the supply capacity and end-user demand for ICS. As Ruiz-Mercado and Masera (2015) and Masera et al. (2000) point out, the adoption of ICS is a multi-dimensional issue based upon complex socio-cultural, environmental and financial contextual factors as well as the technical performance of the ICS - whilst financing is important as it remains one of a number of issues ICS end-users face; especially in relation to institutional-scale cookstoves (IICS). Government policy is also influential as biomass-fuelled ICS are supported by the Ministry of Population and Environment

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* Corresponding author.
E-mail address: benjamin.robinson@nottingham.ac.uk (B.L. Robinson).

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(2017) who focus on biomass short-and medium term energy planning scenarios whilst the (National Planning Commission, 2016) promotes forest enterprises. At the same time, significant financial support is available for biomass-fuelled ICS under the Renewable Energy Subsidy Policy whilst only limited support is available for LPG and regular load-shedding hinders cooking with electricity (Robinson, Jewitt, et al., 2021).

Traditionally the ICS sector has focused on improving the technical performance of ICS through the IWA Tier System[1] (International Organization for Standardization, 2012), rather than designing for context specific end-user preferences (Mobaraka et al., 2012). This is especially true for IICS as limited research has been undertaken on the technical development of cookstoves suitable for use in institutions, small business and large households. This gap has been identified by the Modern Services Energy Program (MECS, 2020) which is promoting the institutional cooking sector as an immediate research priority. Most IICS currently in use are large rocket stoves, as found by Habermehl (2008) rather than solutions specifically designed for institutional, business, farm and large family settings.

Currently, there are 47 household and institutional scale ICS approved by the Government of Nepal under its Renewable Energy Subsidy program (Ministry of Population and Environment, 2016) which can cover up to 50% of the cost of the cookstove dependent on the geographic location of implementation and the socio-economic status of end-users. Just two of these approved ICS are designed for institutional use (Renewable Energy Test Station, 2019); both of which are large rocket stove types as seen in Fig. 1. These solutions are often used for large scale cooking events such as festivals and celebrations as well as small business, educational institutions and livelihood purposes including cooking for cows. However, these IICS do not have the benefit of detailed engineering analysis, leaving them inefficient, smoke generating and exposing their users to the many detrimental pollution-related side effects (Rosenthal et al., 2018; World Health Organization, 2016).

More generally, energy consumption in Nepal is dominated by firewood and cylinder gas (LPG) as shown in the most recent national household survey (National Planning Commission, 2018). Unfortunately, there is no data on institutional firewood usage thus the household survey provides a rough guide to the IICS landscape. Whilst 91% of the population have access to electricity and 85% of total energy consumption is from renewables, only 28% of households, significantly under the global average of 59% (The World Bank, 2018), have access to clean energy even though the Himalayas have vast potential for hydropower (Ogino et al., 2019). This is due to 52.4% of households (65.8% of Rural Households) using firewood as their primary fuel source, a figure which does not take into account households who 'stack'[2] cooking technologies (of all scales) (Masera et al., 2000) and use firewood as their secondary or tertiary fuel source (National Planning Commission, 2018). A more realistic representation of fuel use can be seen if stove and fuel 'stacks' are considered together. Acharya and Marhold (2018) found that water heating and preparation of animal food accounted for over half of the fuel used for non-meal-related purposes in Nepal. When they looked at the area in which innovations are required to improve livelihoods, they noted a need for large stoves suitable for the preparation of food for livestock and for water heating as the current household solutions were not suited to the task. In addition, household-scale cooking solutions have found limited use amongst large families and institutions as explained by Lam et al. (2017). This encourages many ICS users to 'stack' "improved" and traditional technologies as well as household and institutional scale ICS to meet their cooking and livelihood needs. To add additional complexity, due to the diverse geography throughout Nepal there are significant spatial variations in the complex contextual factors that influence stacking regionally (Robinson, Clifford, & Jewitt, 2021; Robinson, Jewitt, et al., 2021).

In this paper, we report findings from a study involving the co-design of an IICS that balanced technical performance and social acceptability informed by preferences and priorities of end users in Nepal. The aim of the study was to test the capabilities of the IICS in real-world settings. Our Research Objectives (RO) were as follows:

1. To co-design & develop a novel Institutional Improved Cookstove (IICS) suitable for use by Nepalese institutions, small businesses or large households in collaboration with Live to Love International (Phase 1 and Designing the TLUD sections); a Kathmandu-based organization.
2. To integrate contextual factors in the design through manufacturing and testing the IICS in a Government of Nepal approved test centre (Phase 2 and Contextualization of TLUD design sections).
3. To test the capabilities of the IICS in real-world settings and determine complex contextual issues that act as barriers to adoption and sustained use (Phase 3 and Identifying the complex contextual barriers sections).

The study's novelty and main contribution is to bring together research on the technical performance of a novel natural draft Top-Lit Up-Draft (TLUD) with locally-informed understandings of how its adoption and sustained use is influenced by complex, contextual factors and end-user priorities. Our long-term engagement with end-users provides important data on sustained use of selected IICS which is vital for reductions in fuel use and emissions but studies of factors promoting this are almost completely absent from existing literature. These areas of novelty look to close the gap in knowledge regarding both technical performance and user priorities for IICS. The paper's significance lies in its relevance for IICS stove manufacturers, policy-makers, and practitioners seeking to reduce HAP-related health burdens through the promotion of clean cooking solutions beyond the household level.

The next sections outline the three-phase methodological approach that generated data for this paper. The results and discussion section sets out the quantitative and qualitative results in the context of three of the seven small scale study sites. The paper concludes by suggesting future work around a potential model for commercialization.

Methodology – a three phase approach

The methodology for this research was divided into three phases. Phase 1 included UK based design and testing at the University of Nottingham in 2017 to develop a novel IICS that could be used in rural Nepal (RO1). This phase involved a needs assessment conducted in collaboration with Live to Love International. Phase 2 involved adapting the design to accommodate contextual factors highlighted by Nepalese partners and to meet technical testing requirements at a Government of Nepal approved testing center (RO2) in late 2017. Phase 3 was conducted between December 2017 and April 2020 and focused on piloting the novel IICS in a range of locations, altitudes, socio-economic and cultural settings. The following section outlines the rationale for the mixed methods approach. This methodology sought to promote an integrated systems approach (Rosenberg-Jansen et al., 2018) to most

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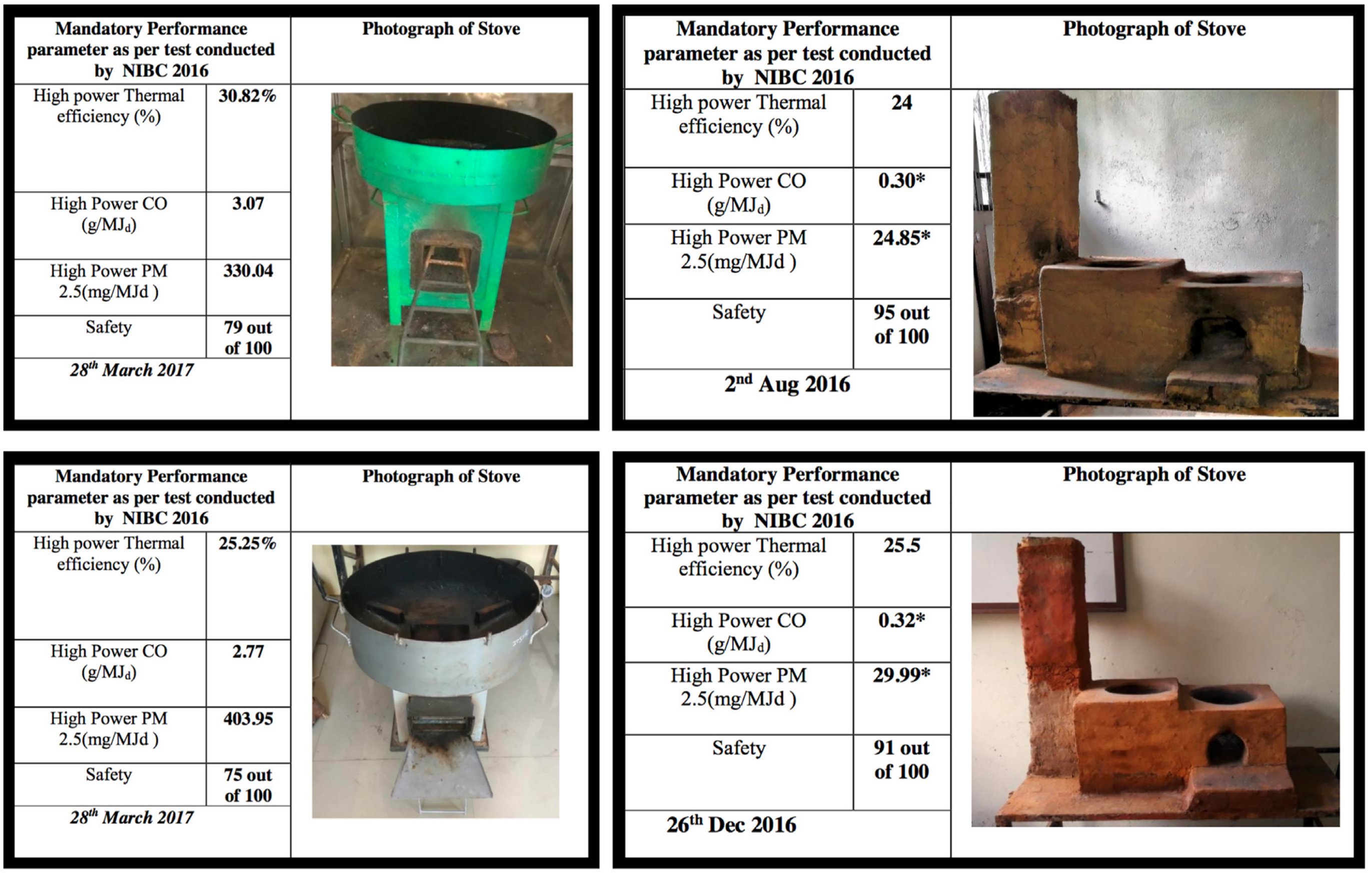
[1] The IWA Tier system assigns one of five performance tiers to emissions (high and low power CO and PM), efficiency (thermal efficiency and specific consumption), indoor emissions (CO & PM) and safety. Tier 0 represents an open fire and Tier 4 represents as aspirational cooking technology such as LPG or an electric hob. However, these testing methods have mixed reliability as discussed by Gallagher et al., 2016. An evaluation of a biomass stove safety protocol used for testing household cookstoves, in low and middle-income countries. *Energy for Sustainable Development*, 33, 14–25. due to the lack of field replicability. As a direct result of this focus on technical performance Moses et al., 2019. Development of a practical evaluation for cookstove usability, Ibid.48, 154–163, has recently developed a series of practical tests to better understand end-user needs and preferences. This system has been further confused by the introduction of a six tier system by the Clean Cooking Alliance, 2020. *Voluntary Performance Targets* [Online]. Available: https://www.cleancookingalliance.org/technology-and-fuels/standards/iwa-tiers-of-performance.html [Accessed 27th July, 2020]. In this research we shall use the standardized IWA Tier system.

[2] The use of multiple cooking technologies to suit end-user need.



Mandatory Performance parameter as per test conducted by NIBC 2016		Photograph of Stove
High power Thermal efficiency (%)	30.82%	
High Power CO (g/MJ_d)	3.07	
High Power PM 2.5(mg/MJd)	330.04	
Safety	79 out of 100	
28th March 2017		

Mandatory Performance parameter as per test conducted by NIBC 2016		Photograph of Stove
High power Thermal efficiency (%)	24	
High Power CO (g/MJ_d)	0.30*	
High Power PM 2.5(mg/MJd)	24.85*	
Safety	95 out of 100	
2nd Aug 2016		

Mandatory Performance parameter as per test conducted by NIBC 2016		Photograph of Stove
High power Thermal efficiency (%)	25.25%	
High Power CO (g/MJ_d)	2.77	
High Power PM 2.5(mg/MJd)	403.95	
Safety	75 out of 100	
28th March 2017		

Mandatory Performance parameter as per test conducted by NIBC 2016		Photograph of Stove
High power Thermal efficiency (%)	25.5	
High Power CO (g/MJ_d)	0.32*	
High Power PM 2.5(mg/MJd)	29.99*	
Safety	91 out of 100	
26th Dec 2016		

Fig. 1. Approved institutional cooking solutions, clockwise from top-left (a) green imported rocket stove, (b) & (c) brick and mud stoves, (d) local rocket stove. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

effectively utilize the skills of all key energy stakeholders in the design, manufacture and piloting of improved energy technologies.

Phase 1

Drawing on key principles established by the Appropriate Technology (AT) movement, which looks to utilize local materials and processes to create products that alleviate poverty (Patnaik & Bhowmick, 2018; Schumacher, 1973; Willoughby, 1990), and through collaboration with Live to Love (L2L) International[3] (who had previously identified the IICS gap in their earthquake response energy programs) we developed a novel ICS design based upon the emerging household-scale TLUD literature (Anderson, 2016; Desrosiers & Reed, 2006; Namagembe et al., 2015; Obi et al., 2016). We chose to first design the IICS in the UK due the importance of obtaining 'proof of concept' before applying for funding for phase 2 where we would consult further with Nepalese stakeholders. We therefore acknowledge that earlier engagement with end-users may have been beneficial but not possible due to a lack of funding at the UK design stage. We identified Top-Lit Up-Draft (TLUD) ICS as the most promising emerging household technology in terms of performance compared to other existing technologies (Still et al., 2014), the operation of which can be seen in Fig. 2. The benefit of the TLUD technology is the increased combustion efficiency through the creation of wood gas or syngas, leaving behind charcoal or bio-char which can then be repurposed for secondary uses such as water purification (Shimabuku et al., 2016), increased soil fertility (Whitman et al., 2011) or re-used for cooking or heating. However, this technology does highlight a weakness within the IWA tier system as the testing methodology does not account for the batch-fed nature of TLUD and inability to regulate the firepower.

Building upon the foundations of Kirch et al. (2016) we applied a number of established design mechanisms to the institutional scale, such as a pot skirt to increase the heat transfer to the pot (Bryden et al., 1997), chimney (Prapas et al., 2014) and existing knowledge on gasification such as the equivalence ratio (Roddy & Manson-Whitton, 2012) and the primary to secondary air flow ratio (Tryner et al., 2016). L2L also stipulated a number of design parameters such as being able to be used when there was no electricity, built and maintained using local materials and processes as well being under 50 kg in weight to enable easy transport over mountainous terrain. Additionally, we decided, with L2L, on a stove size based upon standard oil drums (which are commonly available in Nepal as a scrap metal source) and a common 50 L cook pot size. If the end users required additional cooking capacity, due to the low cost of the IICS, a modular approach was taken where another IICS could be added to the cooking stack. Additionally, we would only produce one size of IICS so as to not replicate the scaling issues seen when applying a household scale design to an institutional size as experienced by the existing IICS in Nepal. The result of this process was the design seen in Fig. 3 – a natural draft TLUD IICS.

In order to test the limits of the design and establish if the increased size of the IICS would affect performance, we designed a Partial Factorial Experiment (PFE) as a proof of concept before phase 2. The limits were established using a screening experiment giving the variance of levels for the designated factors. We reduced the number of factors by using one fuel type (Kiln Dried FSC Kindling), replicating the draw of a chimney through a pre-prescribed airflow from the extraction system and, as previous research has shown, estimating the ratio of primary to

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[3] https://www.livetolove.org/.

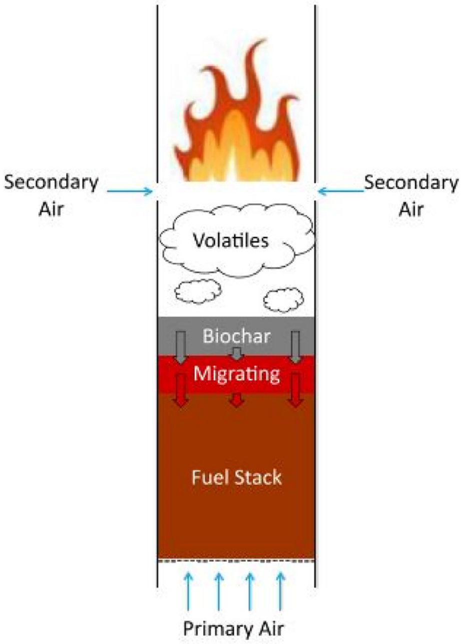

Fig. 2. Schematic diagram of TLUD ICS (Kirch et al., 2016).

secondary air is between 3 and 4:1 (Tryner et al., 2016). This resulted in 11 treatments (experiments) where we measured three temperatures linked to the reduction of harmful emissions such as CO, PM2.5, PM10 and CO2 and the temperature of the ICS as established by the International Organization for Standardization (2012). The results of this testing established the 'proof of concept' for the technical design of the natural draft TLUD IICS which we then took forwards to phase 2.

Phase 2

The AT principles (Schumacher, 1973) look to embed processes and practices utilized by end-user groups in an effort to overcome the low adoption rates that the ICS sector has suffered (Barrington et al., 2018; Devine, 2009; Dreibelbis et al., 2013). Therefore, we sought to further develop the TLUD design to accommodate the complex socio-cultural, economic and financial contextual factors by partnering with the Government of Nepal approved Centre for Rural Technology, Nepal (CRT/N). CRT/N was selected to manufacture and test cookstoves for field trials and contextual compatibility. As a government sponsored institution, CRT/N has access to the Renewable Energy Subsidy (Ministry of Population and Environment, 2016) for stoves used above 1500 m and 50% subsidies for institutional cookstoves as well as a number of government distribution schemes. After these contextualization modifications, CRT/N conducted a series of independent tests utilizing the standardized IWA Testing Method – Pot Boil Test, Continuous Simmer Test, Safely Test (International Organization for Standardization, 2012).

Phase 3

Ten cookstoves were distributed to a variety of institutions and small businesses across two regions in Nepal (Godavari & Helambu), including actors in the education and livestock farming sectors as well as in a number of religious institutions. The distribution of stoves took place in November and December 2017, with monitoring and evaluation conducted from February 2018 to April 2020. The evaluations were designed to provide an opportunity to discuss users' experiences of the new cookstove for the purpose of improving the design, understanding complex contextual factors as well identifying potential markets for commercialisation. The study selection criteria were designed to enable a wide variety of locations, altitudes, economic indicators, social status and geographies in order to test the limits of the TLUD both technically and socio-culturally. Child Research Nepal were selected as the implementation partner due to their existing relationship with the researchers and also a higher-risk appetite for projects that have the potential to create significant financial opportunities for low-income communities. The study sites for the TLUD IICS were identified from Child Reach Nepal's existing network and evaluated with an initial site visit before the small scale study began to explore suitability in terms of readiness for improved cooking technologies, influence of the institution on the surrounding community and past experiences of the participants with other technologies. Participants at each of the sites had to agree that at the end of the study the cookstove was either to be returned or purchased to discourage uptake of a "free" stove which may not have been valued. This resulted in P6 & P7 declining further involvement in the study. In practice, however, all participating institutions were allowed to keep the stoves.

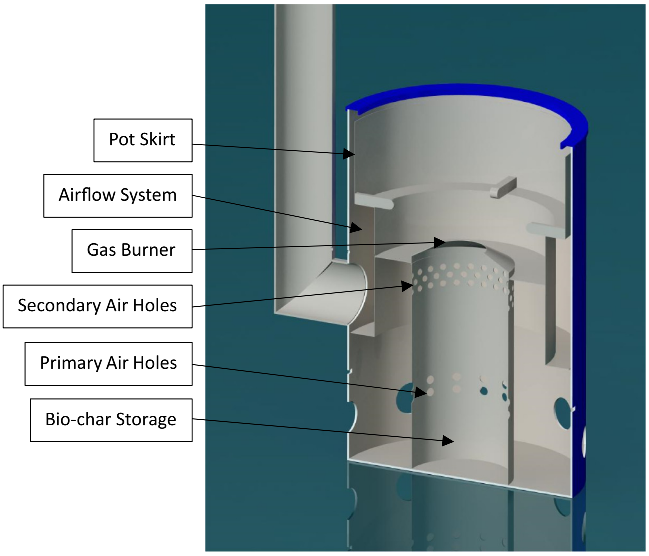

Fig. 3. The TLUD IICS design (colour).

The selected study sites can be seen in Table 1, where the same standardized cookstove was used at every site. As this technology was new to the Nepalese IICS Market and to the beneficiaries of the small scale study, a robust dissemination methodology was used to increase the possibility of success. This included training in which participants learnt how to effectively operate the IICS through a cooking demonstration, a semi-structured interview to ascertain their perceptions of the cookstove and how it would be used, the exchange of contact details for questions that arose during use, explanations of the Information Sheets and the signing of consent forms.[4]

As we were interested in the "lived experiences" of the IICS users and contextual factors which influence behavioral change, a phenomenological approach (Kielmann et al., 2012) formed the structure of the data collection through 24 semi-structured interviews plus informal discussions at each site as well as observations of the stove for evidence of use and adaptation for specific purposes. The observations were used to reinforce the claims made by participants in the semi-structured interviews, such as if the participant claimed to use the TLUD weekly, checks were made to see if there was carbon build up on the inside of the TLUD IICS, firewood and cooking pots located in close proximity and ash in the base of the TLUD IICS to confirm this. In addition, we observed the context in which the TLUD IICS was used; outside, inside, in

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[4] In accordance with the Ethical Approval which was obtained beforehand from the University of Nottingham UK.

Table 1
Study sites.

Code	Type of institution	Number of cookstoves	Altitude	Urban/peri-urban/rural	Why?
P1	School for vulnerable children (5–18 y/o)	1	1000 m	Peri-urban	To involve the local community, spread awareness, creating a local profile for the TLUD and reduce the school's reliance/costs on imported LPG.
P2	Briquette producer & plant nursery	1	900 m	Peri-urban	To test the bio-car element of the TLUD ICS.
P3	Small dairy farmer	2	900 m	Peri-urban	To explore the small-farmer and animal husbandry market though health benefits, the reduction of firewood used to cook for livestock and thus increases in revenue due to less fire tending time and more efficient use of wood.
P4	Community with three monasteries & one high school	4	2600 m	Rural	To work with an entire community across 3 monasteries and 1 high school for adults - 4 Institutional Sites. The location was chosen to test stove performance at 2600 m altitude.
P5	Teaching monastery and buddhist retreat centre	2	3000 m	Rural	To encourage education around responsible cooking whilst also providing valuable data for using the cookstove at extreme altitude.
P6	Community representative	0	1800 m	Rural	Failed project site
P7	Large national construction company	0	1000 m	Peri-urban	Failed project site
	Total number of cookstoves	10			

conjunction with other cooking technologies etc. For seven of the stoves, evaluations were completed at three months, one year and two years after the implementation period. The formal three-month evaluation of P5 was not undertaken due to snow blocking access, however an informal communication did occur stating that the TLUD IICS was being used. P4 did not have a 1-year and 2-year evaluation due to a lack of use and their TLUD IICS has now been repurposed to P1.

This phenomenological approach was chosen for its flexibility and capacity to “allow greater spontaneity and adaptation of the interaction between the researcher and the study participant” (Mack et al. (2005). A key limitation with this approach was the potential for bias linked to the lead author's involvement in all stages of the project cycle and the possible unwillingness of participants to report problems with the stove (Sovacool et al., 2018). All semi-structured interview data was transcribed and coded, using NVivo 12 (QSR International, 2019), into a series of nodes & cases. A combination of deductive and inductive approaches was used to create an Analysis Framework, Table 2, allowing for the identification of simple themes in the semi-structured interviews which were then related back to the research objectives.

Both before and after the interviews, participants were informed of how their data would fit into the larger body of research, whilst also ensuring that a full transcript was sent to the interviewee where possible. This was in accordance with the principles of AT where people's continued participation is key to the on-going research and development of cooking technologies. All data collected from participants was anonymized in accordance with the University of Nottingham's Data Protection Policy and the ethical approval that was granted for this study.

Results & discussion

Designing the TLUD

Testing at the University of Nottingham, UK produced a number of technical temperature data sets for each of the 11 experimental treatments. Fig. 4 shows the results from the most promising - treatment 1 (the lowest primary air flow setting, highest combustion temperature at 1026 °C). We chose to measure flame temperatures as there was no air monitoring equipment available for testing and flame temperature is directly linked to emissions (Kirch et al., 2016). There are four distinct responses that can be identified on Fig. 4, A B C D, that were reflected across all the treatments. Point A shows the maximum flame temperature at around 750 °C. The initial temperature peak (B) shows the temperature that the pyrolysis front passes through the thermocouple (~600 °C) whilst D shows the maximum combustion temperature (~1000 °C) of the remaining bio-char left over after the pyrolysis process. When compared with results from Kirch et al. (2016), who show

Table 2
Semi-structured interview analysis framework detailing key contextual influences by number of references to them.

Name	Description	References
Cooking practices	All references to general cooking practices both household and institutional. Sub-sections: briquettes, health problems, household cooking [alcohol production, cooking for animals, cooking for household, cooking frequency], institutional cooking, solar cooking, wood collection.	54
Cultural practices	Anything relating to culture; family structure, responsibilities, religion, perceptions, caste, geography	29
Earthquake & Indian fuel blockade	References to the impacts of the earthquake and fuel blockade	2
Entrepreneurship	Any reference to SMEs or entrepreneurship at any stage of the value chain, either as a bi-product or directly related to technologies.	1
Field visit observations	Observations from the feld	4
Intervention life cycle	Any information around the entire project value chain. Sub-sections: community needs, government subsidies, project design & community identification, project funding, project monitoring & evaluation, project training & promotion, technology development & manufacture, technology dissemination, technology maintenance	126
Intervention successes & barriers	Factors that have meant success and failure for interventions	23
Micro-finance	Programs relating to micro-finance	32
Other	Useful information but unrelated to this project. Sub-sections: alternative technologies, organizational background information, technology private section	32
Seasonality	How use changed with the seasons	3
Technology stacking	The use of multiple technologies interchangeably to fulfil the same job depending on situation	4
Technical TLUD	Sub-sections: benefits, bio-char production & use, fuel, ICS cost, life expectancy & warranty, market models, modifications, problems, safety, general use.	201

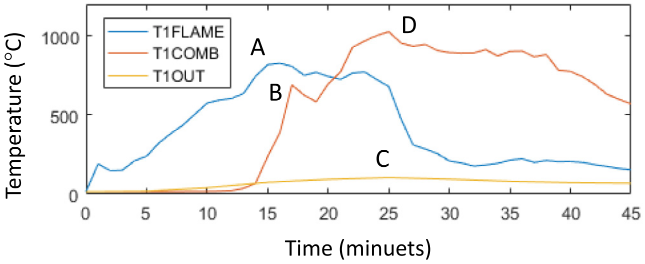

Fig. 4. Treatment 1 results – UK testing (colour).

flame temperature ~750 °C and pyrolysis temperature of ~500 °C on a household scale ICS, this shows a similar distribution however, the IICS achieved a significantly higher flame temperature due to the increased diameter of the fuel bed in the IICS. Lastly, C shows the maximum temperature of the outside surface of the stove which was measured due to the safely compliance elements of the IWA standards. Additionally, this experimental data reinforced research by Tryner et al. (2016) showing that a ratio of 3–4:1 secondary to primary air is optimal for reducing emissions both in the household and institutional scales.

Whilst these experiments showed 'proof of concept' further refinements of the design were needed in phase 2 in addition to the contextualization of the TLUD IICS design. For example, the experiment showed that the lowest primary air setting produced the lowest pyrolysis temperature front, 623 °C, however when compared to Kirch et al. (2016) this temperature needs to be further reduced below 600 °C to increase the combustibility of the resulting biochar. Secondly, the minimum stove wall temperature was 106 °C, which is greater than the IWA Standards. This temperature could be significantly reduced by insulating the heat transfer system and the inside of the IICS however, this addition would increase the cost of manufacture. Finally, the general trend of results showed that as the primary airflow increased, the bio-char combustion temperature decreased. This means that further limiting the primary airflow will increase the duration of usable heat from the IICS.

Contextualization of TLUD design

This 'proof of concept' was taken forwards by the design and testing team at CRT/N in Kathmandu, Nepal. It was important for the research team to share and develop the TLUD IICS design to suit the complex socio-cultural needs of the targeted user groups. The modification of the TLUD IICS design improved the usability and manufacturability of the ICS in the Nepalese context. North-South knowledge exchange occurred through the sharing of novel technical expertise from the University of Nottingham with detailed knowledge of end-user requirements from CRT/N. During the manufacture of the initial prototype there were a series of design changes which included:

- The modification of the combustion chamber –a hanging chamber was created to allow access from the bottom to more effectively remove charcoal.
- Introduction of a sliding door in the bottom of the combustion chamber to allow easy removal of charcoal as well as giving an extra control for airflow – key if the charcoal is to be burnt in the CC (which the Nepalese engineers assumed it would be)
- Introduction of stabilisers around the pot skirt to prevent warping and to add strength, as it was expected that end-users would heat cycle the IICS multiple times a day.
- Split ring at top to ease removal of pot, aid manufacture of lid and reduce the amount of material required for manufacture (local manufacturing process could not accurately make the ring on top of the pot size in one piece)

The ICS testers at CRT/N had limited training on the TLUD IICS hence the large standard deviation of results however as the repeats progressed, the knowledge of the testers also increased and the results improved. As suggested by Gallagher et al. (2016), we acknowledge the results of these tests are subject to interpretation even though there was full compliance with all Nepalese regulations (Ministry of Population and Environment, 2016; Ministry of Population & Environment and AEPC, 2016). Also, batch-fed TLUDs do not fit easily into the standardized lab-testing methodology and, as shown by Medina et al. (2017), there is often a discrepancy between lab testing and field use. The key results of this testing are presented in Table 3 and allow other IICS developers to benchmark their technical performance. This learning process produced mixed results for the TLUD IICS as, although it performed as expected in the high-power tests achieving tier 4 in the CO test, the PM result placed it at the tier 2/3 boundary and specific fuel consumption dropped to 84 g/l at the lowest consumption point in the fuel.

When comparing these results with the available existing solutions, the TLUD IICS outperforms or matches the Nepalese IICS. For example, the TLUD IICS average thermal efficiency is 43.3% compared to 30.82% (the closest competitor) and the High-Power PM is 260 compared to 330 or 404 mg/MJ. All stoves achieved the highest (tier 4) High-Power CO rating.

Identifying the complex contextual barriers

The results presented here are generated from the qualitative data collection and analysis conducted between November 2017 and April 2020 as part of the small scale study. The aims of this study were to test the capabilities of the IICS in real-world settings and investigate the complex contextual issues that act as barriers to adoption and sustained use of the IICS. The following section illustrates how the aims were achieved through three case studies (P1, P3, P5). These were selected in collaboration with key Nepalese stakeholders to represent three distinct elements of the institutional cooking sector: a school, a dairy farmer, and a monastery.

Case study one

The first case study (P1) focuses on a School for vulnerable children aged 5–18 years which provides meals for their residential students. The cookstove was used four to five times per week to cook food or boil water for drinking and saved significant costs on Liquid Petroleum Gas (LPG) which represented a major drain on school budgets. Prior to the installation of the TLUD, the school had used 7–8 cylinders of LPG per month to help prepare food that had a short cooking time, such as fried vegetables, but this fell to 5 cylinders per month afterwards. This reduction of LPG use continued as the school grew over the data collection period:

> "*we use 7 or 8 cylinders* [*of LPG*] *in a month, when we use this* [*cookstove*] *we only use 5 cylinders* […] *each cylinder is 1475Npr* (*15USD*) […] *it saves a lot of cost and time*"
>
> [– P1 (February 2018)]

Table 3
Key technical findings in Nepalese testing.

Number	Key finding
1	High power CO - 4.9 g/MJ – tier 4 (<8 g/MJ)
2	Low power thermal efficiency up to 59% (average 43.3%)
3	Burning rate 20–83 g/min throughout the test phases with firepower ranging from 12.0 to 25.5 kW
4	Specific fuel consumption 84–164 g/l
5	Turn down ratio reaching 2
6	High power pm 260 mg/MJ – tier 2/tier 3 boundary
7	Poor results in low power specific fuel consumption, low power CO & low power PM
8	Handles ≈50 °C at peak power output

Fig. 5. TLUD condition in 2019 after 1 year of use - school kitchen P1 (colour).

> "*We used to use 12* [*LPG*] *cylinders in a month, we use 8 now*"
> [– P1 (February 2019)]

Sold at approximately 15USD per cylinder, the new cookstove is capable of saving the school around 400USD per annum as a conservative estimate – a 22.5% reduction in LPG use. For a school which depends predominantly on external funding streams as it charges no attendance fees, such a saving constitutes a considerable benefit and enables more children to have access to education away from harmful home situations.

The school kitchen is shown in Fig. 5 where multiple cooking solutions are 'stacked' representative of most Nepalese kitchens, both household and institutional. The stacking of multiple cooking technologies has been identified at a household level by Ochieng et al. (2020) and Masera et al. (2000), just to name a few, but not yet in institutional kitchens. In this case the TLUD (right) is added to the existing cooking stack and used in preference to LPG for cooking large meals to reduce costs (firewood is collected from the forest free of cost) but when high heat or long cooking times are important, the mud stove (left) is favoured over the TLUD. The TLUD is used to make the curried elements, the mud stove for the rice and the LPG stove for the chutney that accompanies the food. Whilst this may be viewed as 'backsliding' (Jewitt et al., 2020) or stepping backwards on the energy ladder (Ruiz-Mercado & Masera, 2015), in the case of this school this addition to the existing cooking stack decreased reliance on unsustainably sourced LPG from India and increased the use of sustainably harvested wood from the adjacent community managed forest.

Cooks at the school were happy to leave the cookstove unattended once the fire had started for the full two and a half hours cooking time,[5] with confidence that the fire would not go out. They compared the TLUD favourably to the mud stove which requires tending every 5–10 min to ensure the fire remains constant as it allowed time for the kitchen staff to undertake other activities. The school context also provided an opportunity for teaching staff to engage with students in educational discussions about the environmental qualities of the cookstove and tentative plans were in place to utilize the TLUD's chimney for space heating.

> "*For us, since we are an educational institution, and most people in the community would be willing to use it, but for us its more beneficial to refer to other educational institutions because a lot of schools are going into sustainable energy and setting an example in front of the kids. For them this is a pretty big investment, not just in terms of using less wood but using it as an educational tool – that's huge*"
> [– P1 (February 2018)]

Building on the theme of the TLUD acting as an educational tool, the school has also received significant interest from the surrounding community in learning more about this novel technology. Other educational institutions as well as smallholding farmers have shown interest in buying the TLUD ICS to reduce cooking costs. The influence of this ICS goes beyond the local community as students from the school have suggested taking the design back to their own geographically distant communities:

> "*Also, it made a difference and taught kids. The kids are the ones who will invest in this in the future, for our kids a couple are saying – maybe I want to take this to my village*"
> [– P1 (February 2018)]

One issue highlighted by cooks at the school was that wood has to be cut into a certain shape or size and arranged in a specific manner to fit within the TLUD chamber, otherwise the fire takes a long period to initially light. It was noted that when suitably sized wood was stacked correctly in the chamber, the lighting time for the fire was approximately 10 min. Without the correct size and organization of wood, lighting time was between 30 and 45 min. Fuel is collected from nearby forests rather than purchased so the wood varies in size which creates additional labour and time requirements. Furthermore, in Nepal, fires are usually started from the bottom (rather from the top, as in the TLUD design) which was initially associated with some uncertainty about how best to light the fire.

> "*Even some of the villagers that have come here and seen it, we have asked if you would like* [*to light the fire*] *from top to down and they have been like* '*oh no you don't light a fire from top to down, you always have to light a fire from bottom to top*'"
> [– P1 (February 2018)]

A further issue highlighted was the challenge the cooks faced removing large, hot bowls from the cookstove once cooking was completed predominantly due to the size and the height of the cookstove[6] and the pot skirt.

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[5] The fire itself burned for around 90 min but, due to the residual heat, cooks were able to continue using the cookstove for around 150 min.

[6] The traditional cookstove also used in this kitchen is located at ground level reducing the need to lift pots in such a manner.

Fig. 6. TLUD condition in 2019 after 1 year of use - study site 1 - P3 - small dairy farmer (colour).

Case study two

This cookstove was used by a farmer in Godavari on the edge of Kathmandu Valley (P3). The farmer lives on a small landholding earning money raising livestock, predominantly cattle and cooks food for his livestock on a daily basis; an activity that is widely carried out on inefficient and polluting traditional three stone cookstoves by livestock farmers throughout Nepal. Overall, the farmer was very satisfied with the performance of the cookstove, using it twice each day in the morning and evening to prepare food[7] for his five cows and continued to use it through 2020 (Fig. 6). Additionally, he used the cookstove to boil water for activities on the landholding when necessary. The farmer reported that he could cook three times as much with the same amount of wood (which is acquired through a combination of collection and purchasing) when using the improved cookstove compared to his traditional three-stone fire. This represented a substantial reduction in the amount of wood he burned and money spent on firewood as well as reducing the time needed to boil 40 l of water from 1 h to 30–35 min.

> "*it has saved my time* […] *it has helped me save money as well like saving Rs 2-3000* [*20-30USD*] *a month is also a big thing. And in the context of a single year, it saves around Rs 36000* [*360USD*]"
>
> [– P3 (April 2020)]

In addition, the farmer reported being able to use the charcoal created by the TLUD gasifier for heating other things and this by-product was liked for the fact that it didn't produce smoke. Furthermore, unlike with his traditional stove and as seen in case study one, the farmer was able to leave the improved cookstove to burn without supervision, or the need to constantly add fuel, and was therefore able to carry out other tasks on the farm which he would not otherwise have been able to perform.

> "*I'm not required to stay there to look after the fire, I am able to do other chores like gathering fodder and other chores, I have time to do other activities*"
>
> [– P3 (April 2020)]

As a direct result of using the improved cookstove due to the combination of financial, fuel and time savings experienced by the farmer, in 2019 the farmer added additional cows to his stock. The impact of using the TLUD was not only on the farmer; surrounding livestock farmers also showed significant interest in purchasing a cookstove for their own use. This was in part due to the technical performance of the TLUD but primarily due to the social capital (Woolcock, 2002) and peer to peer relationships of the P3 farmer.

Despite the positive feedback from the farmer and the fact that he used the improved cookstove approximately 60 times per month, he did suggest some areas for improvement. Firstly, he requested that the cookstove and/or pot be made larger to enable him to cook greater quantities of food for the cows or boil more water in one cycle. Secondly, due to the design of the cookstove, the farmer found it a little awkward and time-consuming (around 15 min) to remove all the debris from the previous fire before adding wood for the subsequent burn. Similar usage issues were also reported by Gitau et al. (2019) with a household scale gasifier. Thirdly, related to this issue, the cookstove currently has no inlet to add additional wood to the ongoing fire to extend the length of the burn.[8] He therefore requested the addition of such an inlet towards the bottom of the cookstove to facilitate this.

Case study three

Case study three, a Teaching Monastery and Buddhist Retreat Centre (P5), reflects many of the same benefits and drawbacks of using the novel TLUD design as discussed in case study one and two. However, this example highlights the impact of high altitude (3000 m+) as transport access is restricted to 6 months of the year due to the snowfall and dangerous roads. This results in two distinct patterns of usage in accordance with seasonal changes: 6 months where warmth is prioritised (cold and dry season) and 6 months when building and farming are the priority (wet and hot season). Data collection showed a change in primary function between these two seasons as TLUD use shifted from cooking and boiling water in the summer to additionally being used to heat group spaces in the winter. Previously these functions were conducted using a traditional three stone fire or, in the case of heating group spaces, not conducted at all due to the inefficiency of a three stone fire heating a group space. In addition to its primary functions, in the rainy season the users also dry firewood in the base of the ICS for the first batch and then use the wet, harder-to-burn wood in subsequent batches. The changing of primary function resulted in the cookstove being used 365 days per year.

> "*Up there in winter it is very easy, the environment is very dry and the wood is very dry and the wind is coming very nicely. But summer, because of the wood a little bit of smoke is coming, the wood is not totally dry. At that time our wood is almost fireproof* […] *But for that stove can be used any kind of woods because after heating the iron, even the wet fireproof wood will burn very nicely.*"
>
> [– P4 (February 2019)]

The ICS users in P5 did also suggest modifying the cookstove so that it was no longer batch fed and creating an easier way to remove the pot from inside the pot skirt – all recurring themes throughout the study.

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[7] A maize-based powder is mixed with hot water to create a high-starch soup to support cow growth and fattening.

[8] Currently, the entire burn cycle must finish before more wood is added and a new fire begins rather than being able to simply add more fuel to extend the burn.

Fig. 7. TLUD condition in 2020 after 2 years of use - Buddhist Retreat Centre P5 (colour).

However, the soot on the chimney and wall in Fig. 7 also indicates that the stove was being used ineffectively with the pot balanced on steel bars on top of the cookstove. Although this significantly reduces the heat transfer, Nepalese cooks like to see a big flame so the adaptations may have been made to enable the fire to be seen, monitored and added to from the top. The final learning from this religious study site was the association of the TLUD stove with local religious leaders and festivals as members of the surrounding communities all associated the cookstove and its use with their religious centres. Whilst it is difficult to assess whether this association impacts the use of ICS at the household level, many community members did aspire to own a cookstove like the TLUD.

These three examples contribute to knowledge on the capabilities of the TLUD IICS in real-world settings and contextual factors that have influenced sustained use as well as providing insights into the balance of positive and negative impacts that the IICS had and continue to have on the everyday lives of users. Feedback from end users has contributed to the TLUD IICS co-development process as suggestions from end-users regarding how it could be improved will be valuable for addressing the technical and social barriers to sustained and exclusive IICS use. Clearly there is a need to reflect on the outcomes of these evaluations when deciding the ways in which the product can be altered to create the most user-friendly experience, however a willingness to pay for this TLUD IICS was seen across the study sites. Modifications to its design may be necessary in order to tailor its specifications to the needs of those working with the device on a day-to-day basis.

1. co-design & develop a novel Institutional Improved Cookstove (IICS) suitable for use by Nepalese, institutions, small businesses or large households in collaboration with Live to Love International (Phase 1 and Designing the TLUD sections); a Kathmandu-based organization (Phase 1 and Designing the TLUD sections)
2. To integrate contextual factors in the design through manufacturing and testing the IICS in a Government of Nepal approved Nepalese test centre (Phase 2 and Contextualization of TLUD design sections).
3. To test the capabilities of the IICS in real-world settings and determine complex contextual issues that act as barriers to adoption and sustained use (Phase 3 and Identifying the complex contextual barriers sections).

Conclusion

This paper presents a novel natural draft TLUD IICS, in accordance with research objective one, to co-design & develop a novel IICS for use in institutional and small business contexts, and two, to integrate contextual factors in the design through manufacturing and testing in a Government of Nepal approved test center. We achieved this through a North-South collaborative partnership by utilizing technical knowledge of the novel TLUD technology developed by the lead author and knowledge of the complex contextual environment in Nepal from Live to Love International and CRT/N echoing the integrated systems approach championed by Rosenberg-Jansen et al. (2018). Testing by CRT/N showed thermal efficiencies of up to 59%, a maximum firepower of 25.5 kW, tier 4 high power CO emissions and a burn rate of 20-83 g/min as summarized in Table 3. The thermal efficiency shows a large increase on the existing approved institutional solutions which range from 24 to 30.82% in Fig. 1. These results show the technical capabilities of the novel TLUD, as well as the potential to be included in the Government of Nepal's renewable energy subsidy scheme. This partnership has created a cooking technology that has seen sustained use of nine out of ten TLUD IICS between November 2017 and April 2020.

The third research objective contained two parts. The first - to conduct a small scale study to test the capabilities of the IICS in a real-world setting - was achieved through collaborating with a local partner to identify and implement 10 TLUDs across 5 geographic regions and monitoring their use in the implementation period. Our long-term approach to data collection differs significantly from the evaluative snapshot presented in Robinson, Clifford, and Jewitt (2021) which allows for insights into patterns of sustained use rather than focusing solely on initial adoption. The results show significant savings on fuel investment and the redistribution of this saving to expanding resources throughout the majority of study sites. This included investing in new livestock, providing education opportunities for at-risk children and increasing the opportunity for educational practices aimed at surrounding communities. The second part, to identify complex contextual issues that act as barriers to adoption and sustained use, required long-term feedback on the TLUD IICS. Many of the social and technical barriers that we identified are seen throughout the household scale literature but are yet to be associated with IICS use. The dairy farmer's primary need was cooking for cattle with the minimum weight of firewood whilst the school required the use of multiple cooking technologies to accommodate a wide variety of dishes at minimum cost. The primary use varied in P5 due to the changing seasons between heating water, cooking for large groups and space heating. Our research highlights the importance of IICS solutions as part of an emphasis on ‘cleaner stacks’ (Jewitt et al., 2020), that recognises the limitations of linear energy models in institutional and small business as well as household settings. However, in the Nepal context there are policy constraints as discussed in Robinson, Jewitt, et al. (2021). Finance, which is often seen as a central barrier to the adoption and sustained use of household scale ICS, was not apparent here as all sites were willing to invest in new cooking technologies which would result in future cost savings.

Whilst contextual needs varied between the farmer, school and religious centers the barriers to use revolved around the same issue; the useability of the TLUD IICS. Due to its batch filled nature, pot skirt and non-traditional lighting method the TLUD technology requires a willingness by the user to stick with these new methods. There is still significant technical development required to mitigate these user preference issues. The influence of north-south collaboration in meeting these needs should not be underestimated. In this case, it greatly improved the socio-cultural acceptability of the ICS as well as the simplicity of its manufacture and design which allows easy maintenance whilst providing user-focused information on how further refinements will enable it to more fully satisfy the socio-cultural needs of users.

Looking forwards to future research pathways, traditionally routes for scaling in the ICS sector have been limited (Rehfuess et al., 2014) and institutional settings may offer novel opportunities for both supply and demand side growth. From the data collected in this study, we would suggest marketing or promotion through the capitalization of social networks (Shell Foundation, 2018) by embedding a "cookstove champion" in each community institution, looking to involve local artisans in the production of the cookstoves, as suggested by Robinson, Jewitt, et al. (2021). Furthermore by integrating the existing Government of Nepal Institutional subsidy program, the retail cost could be subsidized by up to 50% (Ministry of Population and Environment, 2016) further increasing the accessibility and affordability of the TLUD ICS to under 80USD, the price of a Tier 4 household ICS (Clean Cookstove Alliance, 2019). However, this would not be possible for an institution that has already claimed the subsidy on another improved cooking technology because only one subsidized stove is permitted per household.

This paper contributes to a broader discussion around the role of institutions in promoting improved cooking technologies which is an under-researched area that could hold the key to unlocking the vast potential of improved cooking technologies as either a developmental stepping-stone or educational tool. We also recognize the importance of trans-disciplinary research (Brennan & Rondón-Sulbarán, 2019) in achieving these aims through the opportunity to collaborate with other sectors outside of technical engineering, broadening the scope of research and challenging the traditional methods utilized by existing International Development Organizations.

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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