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Reinventing boiling: A rapid ethnographic and engineering evaluation of a high-efficiency thermal water treatment technology in Uganda

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ABSTRACT

Often in engineering for global development, product designers do not have the time or resources to conduct long-term technology adoption studies with large sample sizes for every iteration of their design and therefore must rely on shorter, targeted studies that measure both the technical and user acceptance parameters. This work presents a combination of experimental engineering and rapid anthropological methods to provide a mixed-methods approach to evaluate and improve the design of a novel water treatment technology, the InStove Water Purifier. This product uses the principles of pasteurization and heat recuperation to theoretically reduce energy consumption for water purification by 97% in a continuous process, producing enough water for 1400 people each day. The case study in Mbale, Uganda, used rapid ethnographic methods that included participant observation, focal follow, and time allocation; and engineering performance experiments that included fuel efficiency tests, water bacteria measurements, and data collection of temperature and flow rates. Data from all methods were synthesized in a Diffusion of Innovations (DoI) framework to gain insight into potential barriers and benefits of adoption of the technology within this specific context. As defined in a DoI framework, potential benefits to adoption include decreased overall time and labor to purify water, decrease in use of biomass resources, increase in overall water throughput, and low learning curve for the product operator. Similarly, potential barriers to user acceptance include the trust required by users towards product efficacy, lack of customization, and potentially undesirable changes in time allocation and fuel wood preparation.

1. Introduction

According to the World Health Organization (WHO), of the 2.1 billion people worldwide who lack access to safely managed water, 263 million spend over 30 min per trip outside of the home collecting water [1]. Additionally, over 2.6 billion people rely on the traditional use of biomass for their daily energy needs with 1.2 billion people boiling their drinking water daily over inefficient open fires [2,3]. Over the past few decades, the United Nations (UN) has promoted the Sustainable Development Goals (SDGs) and the antecedent Millennium Development Goals (MDGs) which included strategies to reduce the number of people without safe access to clean water and energy resources [4]. However, the recent history of water treatment and energy projects to address the MDGs and SDGs has raised significant concerns regarding longevity; hundreds of millions of dollars are spent by donors annually on initiatives that fail to have long-term impact because the projects don't match the needs and preferences of households and communities [5,6]. Within the technology for development sector, low adoption and poor dissemination rates of water treatment and renewable energy technologies are a common cause of reduced longevity. Reasons for low adoption may include inadequate understanding of user needs and/or technology barriers [2,7], neglecting to take a socio-technical approach during design and implementation [8], lack of required information transfer to the users [9], deficient supply chain [10], and insufficient relations with local partners [6,11], among others.

Researchers are calling for implementation-based studies to use cross-disciplinary mixed-method approaches to investigate the dissemination of water treatment and energy technologies [12,13]. For example, Stern [14] proposes an integrated, trans-disciplinary science of human-energy interactions to better understand the complex relationships between people and technologies. In a similar vein, Jepson et al. [15] proposes that researchers approach household water provision by assessing how social and political factors establish benefits and barriers to water access, rather than simply assessing the functionality of access to water itself. The integration of social scientific research,

Abbreviations: DoI, Diffusion of Innovations; SDG, Sustainable Development Goals; MDG, Millennium Development Goals; WHO, World Health Organization

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both theory and method, helps understand determinants of individual and societal behavior which leads to more comprehensive analysis of technology adoption [16]. Because social research of new technologies can be expensive, is less easily reproduced, and is less quantifiable, it is often ignored – with the regrettable result that investment decisions are often made based only on technical performance [7].

The objective of this study was to apply a rapid cross-sectional mixed-method approach within a DoI framework to evaluate the feasibility of the InStove Water Purifier (the water pasteurizer), a biomass-powered water treatment technology within the specific context of a hostel in Mbale, Uganda and ultimately provide the manufacturer with design recommendations for their product. To do so, we examined the usability and user acceptance of the technology using focal follow, an ethnographic tool, during the intervention of the water pasteurizer to observe qualitative characteristics of user actions. We used a time allocation method to quantify the distribution of time that the operator devoted to specific tasks. These methods were used to observe participants both before and after the intervention of the new technology, as it is recommended that boiling water be used as a benchmark to assess any alternative disinfection methods [17]. Simultaneously, we conducted performance experiments, including fuel efficiency tests and data collection of temperature and flow rates.

2. Background

This study used a Diffusion of Innovation framework to evaluate the benefits and barriers (as defined in the DoI context) of a water treatment technology at a hostel in Mbale, Uganda. Background on the theoretical approach, technology, and location of the case study is presented in this section.

2.1. Diffusion of innovation framework

Scholars are advocating for increased assessment of factors relating to adoption of energy technologies [18]. Diffusion of Innovations (DoI) is a theoretical framework that examines society's adoption of a new technology or behavior by analyzing stakeholders' perspectives to determine risks and barriers associated with the technology or behavior in a specific context [19,20]. Perceived risk, cost, equipment complexity, and lack of sociopolitical acceptance can all inhibit technology adoption [9,21,22]. The DoI framework has been applied to predict adoption behavior of solar-water disinfection technology in Bolivia [23], determine barriers related to solar PV pumps in India [24], and analyze the lack of investment in renewable energy technologies in Chile [25]. A review of diffusion of renewable energy systems by Negro et al. [2] determined that potential barriers to adopting a new technology include economic constraints, gaps in knowledge, competing substitutes, and lack of resources available to support the new technology. A study by Ojomo et al. [26], which used DoI to identify enablers and barriers to household water treatment systems, determined that free distribution of technology was a barrier to sustained adoption compared to financing programs, which encouraged long-term use.

There are many reasons why a an adoption of behavior or technology spreads through a society. Commonly, individuals in society learn and imitate the majoritarian behaviors, a theory known as conformist transmission [27]. Prestige-based cultural transmission occurs when the behavior of individuals with more skill, success, and status is imitated [28]. These, and other theories of transmission and diffusion, offer frameworks for evaluating the spread of culturally acquired values and behaviors. However, we might not be able to fully apply transmission and diffusion frameworks to projects in international development, because projects are often funded from external resources, rather than from within a community. When households have agency in the selection of their energy and water technologies, diffusion and transmission can be readily examined. However, in the case of community-based implementation projects, donors or organizations often administer decisions regarding which technologies and solutions will be disseminated.

Herein, we used the DoI framework to examine the so-called benefits and barriers of adopting a new water treatment technology in a specific context to determine potential design and implementation changes. Benefits include product attributes that lead to user adoption and, ultimately, diffusion of a technology within a specific society. While barriers refer to attributes that are either undesirable or inaccessible to users, ultimately leading to product neglect or rejection.

2.2. Technology description: The InStove Water Purifier

Grounded in a DoI framework, this mixed-method approach to engineering design research, combining applied anthropology and engineering methods, is presented through the case study of a pilot test of a water pasteurizer heated externally by a biomass-powered cookstove in Mbale, Uganda.

The cookstove sector can be described in two categories: (1) local production by individuals or co-operatives (with varying formality) typically with support from international NGOs and (2) hi-tech stoves, which are mass produced and imported by small to medium sized international organizations [29]. Extensive research and testing on improved cookstoves (ICS), for example wood-burning rocket-type stoves and charcoal stoves, has been conducted worldwide. Rocket-type stoves have been shown to have efficiencies between 25–35% and reduce levels of emission from 50 to 90%, all while reducing the amount of fuel required by 30–60% [30]. Meanwhile, charcoal stoves have been found to reduce CO emissions factors by 60% compared to traditional stoves, with efficiencies between 38.7–47.5% [31]. However, there has been varying levels of ICS adoption particularly among African countries, with explicit differences between rural and urban populations [32].

Pasteurizing water over a biomass-burning cookstove can be a simple and sustainable water disinfection method, however, current practices are time consuming and environmentally costly [33]. Although significant reduction of microorganisms are observed well below the boiling point of water [34], over 1.2 billion people around the world still disinfect their drinking water by raising it to boiling (100 °C) because boiling generally provides a visual indicator of temperature [3]. Drinking water is traditionally boiled over a three-stone biomass fire that requires the procurement and combustion of solid fuels and introduces a variety of health and environmental hazards. Boiling drinking water in this way is an extremely inefficient process, wasting time and local biomass resources, producing significant amounts of emissions that are harmful to both health and climate, and creating scalding water that must then be substantially cooled before use, increasing the risk of injury and wasting valuable energy [33]. Because pasteurization is a culturally appropriate solution to disinfect water, taking advantage of the vast potential for improvements in the use of local renewable energy in this process could lead to significant benefits.

To address this opportunity, Institutional Stove Solutions (InStove), a stove manufacturer in Cottage Grove, Oregon, USA, designed the InStove Water Purifier (Fig. 1) – a self-regulating biomass-powered system designed to heat water to the pasteurization temperature then recuperate heat by cooling it down to a safe handling temperature. The pasteurization unit sits in a 60-L pot on a single-burner institutional-sized cookstove. Cold untreated water enters the system from a pressurized source and is first preheated as it passes through a heat exchanger before flowing through a metal coil and collecting additional heat from a reservoir of hot water in a large stockpot that is heated externally by the biomass cookstove. Next, water flows through an automatic mechanical thermostatic valve that remains closed when the water temperature is below 71 °C, ensuring that only water at or above the pasteurization temperature passes through the system. The heated water then flows through a pipe with increased diameter, labeled as the "kill chamber" before re-entering the hot side of the heat exchanger

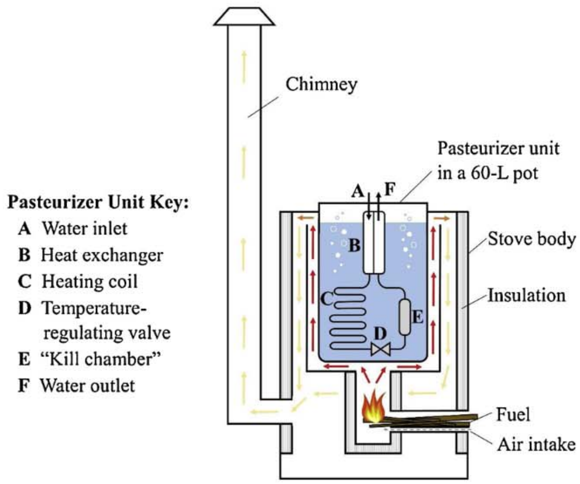

Fig. 1. The InStove 60-L biomass cookstove with the pasteurization unit inserted [40].

where it will effectively release waste heat that is used to initiate the heating of the cold inlet stream in the cold side of the heat exchanger. After exiting the "hot" side of the heat exchanger, water exits the system at a safe handling temperature ready for storage or consumption.

Water boiling tests over a traditional open fire found that 1 L of water required about 200 g of wood to reach boiling from room temperature [35]. In comparison, initial tests of the InStove Water Purifier's performance determined the consumption rate for steady-state operation was 5.5 g of equivalent dry wood to pasteurize each liter of water, representing a 97% savings in fuel [36]. The clean combustion of the InStove resulted in emissions of only 0.11 g of CO and 0.72 mg of particulate matter per liter of pasteurized water at steady-state operation, resulting in a respective 98.9% and 99.7% decrease compared to traditional open fire boiling [36,37]. Most importantly, bacteria removal testing showed a 99.9999% (6 log) reduction in both *E. coli* and bacteriophage MS2 (a viral indicator) concentration [38], meeting the WHO guidelines for drinking water treatment technologies [39].

2.3. Field evaluation

Oregon State University and InStove partnered with MAPLE Microdevelopment to implement and evaluate the InStove Water Purifier in the Mbale District of Eastern Uganda. Grace Burleson, one of the field researchers in this study, previously worked with MAPLE in Mbale and connected the organization with InStove to perform this pilot study. Uganda is considered one of four African countries to be regarded as a 'potential' developmental state based on the country's growing capacity in their economic and political spheres, as well as the industrial oil and gas industries [41]. However, domestically, an estimated 72.7% of Ugandans use traditional cookstoves for cooking and/or boiling water, greatly stressing the local bioenergy resources [42]. Despite over three decades of ICS initiatives, current importation and domestic production quantities are well below the nation's potential demand [43]. ICS adoption in Uganda is attributed to key barriers and enablers including stove quality, design, financing, government support, local skills, community engagement, and marketing [44].

MAPLE, a non-governmental organization, has worked in Eastern Uganda since 2009, where they form community-managed savings and loan groups, provide access to financial services, and teach financial literacy, entrepreneurship, and business development. The partnership with MAPLE, and their entirely Ugandan-educated and dedicated staff, supplied the research team with the necessary resources to complete work such as accommodation, transportation, translation, and local mentors and experts. InStove supplied MAPLE a proposal for implementation, which included requirements for a site with 100–500 beneficiaries, current cooking/boiling practices over inefficient fires, and proximity to town, among others. Through one of the Ugandan employees' personal connections, MAPLE identified an appropriate hostel in Mbale willing to participate in the field study. In the Mbale District, it is common for families, from small surrounding villages, to send their children to secondary school in Mbale or Kampala. Due to the demand for safe and affordable accommodation, there are many privately-owned hostels that house students during the school year. For a monthly fee, these hostels provide students with meals, drinking water, and other typical accommodations. One such example was Diana's Hostel, which became the location for the implementation study of the water pasteurizer. At the hostel, the manager was responsible for decision-making regarding household policies, technology purchases, budgeting and staff affairs. All other employees at the hostel reported directly to the manager. At the time of the study in August 2017, Diana's Hostel housed 104 teenage girls and had five employees (manager, guard, matron, cook, and cleaner). Throughout the study, the researchers worked closely with the hostel staff, who were very welcoming and excited to participate in the study. Each staff member at the hostel was compensated with a bag of groceries in a fair amount, recommended and approved by Oregon State University's Institutional Review Board. Ultimately, we selected this location for the pilot study because the MAPLE staff personally knew and trusted the manager and the hostel cook used large amounts of firewood daily to cook and boil water.

Although much of Mbale has access to piped water, the water is commonly boiled before drinking because waterborne illness, such as typhoid and dysentery, are common due to poor infrastructure in the city water system [45]. Diana's Hostel has reliable access to city water, which is pumped daily into their privately managed elevated water tank. From the tank, water is gravity fed to a variety of taps throughout the hostel. This elevated tank served as the water source for the pasteurizer during the implementation study.

3. Methodology

Researchers are calling for implementation-based studies to use robust mixed-method protocols to investigate household water treatment and energy solutions and use ethnographic methods to understand wood fuel, charcoal, and other household forms of bioenergy [12,46,47]. While there are a range of methods to evaluate the impact of technology and development initiatives, recent trends favor interdisciplinary mixed-method approaches for humanitarian technologies such as improved cookstoves [13,48,49]. Mixed-method research is a methodology for conducting research that involves collecting, analyzing, and integrating quantitative and qualitative data in a single study [50], resulting in more comprehensive and holistic research compared to a single-disciplinary approach [51]. Specifically, the addition of an ethnographic perspective in applied engineering work offers a unique understanding of energy usage within specific contexts [52]. Using anthropologic methods, including historical, ethnographic, critical, and triangulating evidence, is especially important in the assessment of technologies since they directly expand human capabilities and are thus highly subjective [53,54]. Ethnographic methods, such as participant observation, provide a narrative of the user and assist designers in identifying factors that influence technology use and impact [55]. Other qualitative methods, including interviews and open-ended surveys, can be incorporated into engineering research to increase the value of observations and evaluations of user-technology-interface. When appropriately used, these methods can replace structured and/or quantitative surveys, which can only provide insights to predetermined inquiries [56,57]. A study of cookstove design in Peru utilized qualitative interview data to analyze the usability of improved cookstoves and propose design changes that improve user adoption rates [58]. Another study of improved cookstove adoption in a rural village in Mali incorporated participant observation to understand the role of cooking within the larger context of a day of work for women. This observation, coupled with a minute-by-minute time-series account of cooking tasks, generated valuable information regarding user technology needs. In the end, researchers determined that improved cookstoves did not meet all the needs of households and did not significantly influence cooking energy use [55]. This information illustrates the limitations of using a solely technological approach, which could have led to inaccurate findings, and is therefore invaluable to design engineers who aim to create significant impact for their users.

3.1. Ethnographic methods and the Rapid Assessment Process (RAP) technique

Ethnographic methods are community-based research methods designed to collect information through intensive, iterative contact between the researcher and study participants [59]. While central and highly regarded by anthropologists, systematic ethnographic research is a rather new method for engineers and some development practitioners. In the field of international development, ethnographic methods can be used to conduct needs assessments or to evaluate whether a given intervention has had the intended effect [60,61]. These qualitative methods are derived from anthropology's "ethnography," which traditionally requires lengthy fieldwork and very open-ended research to gain the utmost information regarding a specific culture. Practitioners often do not have the time or financial resources to engage in a traditional, lengthy ethnography but can gain valuable insights regarding their design by using ethnographic methods. The Rapid Assessment Process (RAP) is often used to quickly learn insightful information from the perspective of the beneficiary. Although this technique shares many similarities with traditional ethnography, RAP relies more heavily on data triangulation by multiple researchers, including a mix of insiders and outsiders. Semi-structured interviews are a key component to using RAP as they provide a guideline of topics to discuss but allow for open-ended responses [62]. While a rapid assessment may be the most appropriate approach for some projects, it is important to recognize and mitigate shortcomings, which are summarized thoroughly by Shah [57]. First, researchers are at risk of misrepresentation due to over-generalizing, effects of changing seasons, and unseen long-term trends. Second, accuracy may be compromised due to lack of iteration, depth, understanding of relevancy, or triangulation. Lastly, the validity of the work may be diminished by several mistakes and shortcomings common among researchers: culture-shock, behaving ethnocentrically, lacking rapport, or unintentionally influencing informants' behavior [57]. In our two-week study, we borrowed techniques from RAP and aimed to mitigate shortcomings by working with a partner organization with long-term ties to the study community, using researchers with previous field experience in the region, setting specific boundaries on the study to prevent overgeneralization of findings, and triangulating multiple qualitative methods from a team of both U.S and Ugandan researchers.

For this study, participant observation, focal follow and time allocation were used to better understand the implementation context of the water pasteurizer and learn potential barriers and benefits of technology adoption. The Oregon State University Institutional Review Board under study number 7257 oversaw all research with human subjects.

3.1.1. Participant observation

The field research team consisted of two students from Oregon State University and two Ugandan MAPLE staff members. Throughout this study, the student researchers spent time and gained the trust of the employees and teenage girls at the hostel with help from the MAPLE staff who had rapport and facilitated any colloquialism and cultural translations. Informants were bilingual, and researchers interviewed them in both English and Lugisu. Although the U.S researchers only spoke English, any information communicated in Lugisu was translated by MAPLE staff into English and all final notes were written in English. Water treatment was observed before and after the implementation of the water pasteurizer to better understand and evaluate the context surrounding the users. Participant observation is an important step in the ethnographic process because strategic observation allows for untold assumptions, underlying rules of thumb, local intuitions, shared world views, and conflicts of interest that may not be gathered in simple interviews or surveys [52]. Student researchers jotted down notes regarding the environment, people's actions and words, and general observations in a field notebook. At the end of each day, notes were copied onto a computer and additional reflections were added.

3.1.2. Focal follow and time allocation

Focal follow is a method in which the researcher spends time with the subject, the "Focal," during their day to examine their tasks and gain an understanding of their experiences, perspectives, and priorities by recording events and actions over a specified duration [63,64]. Throughout focal follow, informal interviewing and participant ethnography took place to gain insight to the Focal's tasks and view of their responsibilities. For this study, the Focal was a 30-year-old cook from Bududa, a nearby village in the Mbale District. The Focal lived at the hostel and earned an income cooking meals and preparing drinking water each day. During focal follow, the time allocation of the Focal's actions related to water treatment were documented. Time allocation is a method to understand an individual's behavior based on the tasks they spend time doing and has been used to plan and evaluate the impact of development projects in the Global South [65]. People in every society allocate time as a resource, choosing to divide their day between various responsibilities and leisure. It is important to note that much of the world has not commoditized time the way Western society has [66], where it can be saved, spent, wasted, and bought – emphasizing the importance of qualitative work to corroborate any time allocation findings. While there are cultural differences in perceptions of time, the time allocation technique is worthwhile because of the inherent fact that performing one task means you cannot do another. Thus, this method is an indirect way of measuring human behavior which, when coupled with supplemental ethnography, can lead to further insights of an individual's values, priorities, and daily routine.

Student researchers used a simplified method of time allocation to study the operator's behavior before and after the intervention of the water pasteurizer by studying the Focal's time spent while preparing water, rather than evaluating his whole day. Following and participating in conversation with the Focal inevitably changes their behavior, however, it was assumed that tasks related to preparing food and clean water were of priority and would still be accomplished in a similar manner regardless if a researcher was present or not. The null hypothesis ($H_{0,t}$) is the time allocated to performing water preparation tasks before the intervention over the baseline fire (t_{BF}) equal to the time allocated to those same tasks after the intervention of the water pasteurizer (t_{WP}). Here, time (t), measured in minutes, is equal to the sum of time spent collecting water and firewood, preparing/maintaining a heating source (baseline fire or cookstove), cooking, water disinfection, and other tasks that may be discovered in the field that relate to these. The alternative hypothesis ($H_{1,t}$) is that the time for these tasks before intervention will be different from the time after.

$$H_{0,t}\colon\ t_{BF} = t_{WP}$$

$$H_{1,t}\colon\ t_{BF} \neq t_{WP}$$

During the study, time, separated by different tasks, was measured by student researchers using a wristwatch, recorded in a field notebook, and categorized during data analysis after the field study. Three trials of each process (baseline stove and water pasteurizer) disinfecting 50 L of water were observed. Researchers conducted daily ethnography with the Focal and other individuals at the hostel to triangulate data and gain insights. On the fifth day, during implementation of the pasteurizer, the Focal and the hostel manager received a brief, hands-on, step-by-step training from the student research team. Using the pasteurizer involves connecting a hose to a tap and maintaining and tending a small fire – which the Focal quickly mastered within minutes due to his extensive experience cooking over wood-burning fires. After implementing the pasteurizer, the same focal follow and time allocation methods were applied for four days, and again, ethnography and informal interviews triangulated the data.

3.2. Technical methods

Concurrently, to evaluate the technical performance of the water pasteurizer, the student researchers monitored the system temperatures, flow rate, and fuel usage. Each technical method is described briefly below.

3.2.1. Temperature

The disinfection mechanism of the water pasteurizer is heat. For the pasteurizer to reduce microorganism concentrations to a safe level, the temperature of the water must be held at 71 °C or higher for 15–20 s before cooling down and exiting the system. During field tests, key temperatures in the pasteurizer were measured with thermocouples. These included the temperature of the water at the inlet, thermostatic valve, and in the stockpot. The inlet temperature was only measured once and was expected to remain mostly constant. The temperatures of the stockpot and thermostatic valve were measured and recorded every minute during operation (which lasted between 35 and 55 min). However, during the first use of the pasteurizer at the hostel, the thermocouple attached to the inside of the connection directly before the valve failed. This thermocouple was attached with silicone through a hole drilled into the connection. Efforts were made to replace the thermocouple but the glue would not set in time for the subsequent tests. To avoid the risk of leakage, a new pipe connection without a thermocouple was inserted into the system. During initial testing in January of 2017, the temperature difference between the thermostatic valve and the stockpot averaged at 0.32 °C with a standard deviation of 2.1 °C. Researchers in the field assumed that the temperature of the pot was a reliable estimation of the temperature of the water flowing through the valve and would be sufficient for the field study despite the failed thermocouple.

3.2.2. Flow rate

The flow rate of the InStove Water Purifier was monitored with an electronic flowmeter and microcontroller. Flow rates were measured in liters per minute and recorded during testing to evaluate the throughput of the system.

3.2.3. Fuel usage

Experimental testing of the efficiency of the water pasteurizer within this context focused on quantifying the difference in fuel usage between the pasteurizer and the hostel's baseline stove. Wood usage was measured before and after the implementation of the pasteurizer using a FUEL sensor. The Fuel, Usage and Emissions Logger (FUEL) is an autonomous sensor-based monitoring system that quantifies the usage rates and fuel consumption for biomass cookstoves [67]. FUEL provides a log of weight readings to determine the amount of wood used over time during cooking and water disinfection events. These data were used to compare change in biomass fuel usage before and after the implementation of the pasteurizer. Because only relative change in fuel use was determined, field measurements of the fuel moisture content and higher heating value were not required. The null hypothesis ($H_{0,w}$) is that the weight of the wood used to perform water and cooking tasks before the intervention over the baseline fire (w_{BF}) is equal to the weight of the wood used for those same tasks after the intervention of the water pasteurizer (w_{WP}). Here, weight (w) is measured in kilograms (kg). The alternative hypothesis ($H_{1,w}$) is that the weight of wood used before the intervention will be different than after.

$$H_{0,w}\colon\ w_{BF} = w_{WP}$$

$$H_{1,w}\colon\ w_{BF} \neq w_{WP}$$

The FUEL sensor monitored the baseline cooking and water disinfecting method in the institution for three consecutive days. Then, after the installation of the water pasteurizer and training and practice for the operator, the FUEL was used to monitor the usage of the pasteurizer for three consecutive days.

3.2.4. Bacterial contamination

During the implementation of the pasteurizer, three samples of the hostel's water source were collected and counted for bacteria at 100 mL and 1 mL volumes and using Petrifilm™ *E.coli*/Coliform count plates by the 3 M Corporation. A total of three samples were collected from the outflowing water when (1) the flow initially started, (2) after 10 min of continuous flow, and (3) just before the flow stopped. Each sample was plated at 1 mL and 100 mL concentrations and plates were incubated for roughly 20 h in a lunch thermos with an internal temperature maintained between 35–39 °C monitored by a thermocouple. Temperature in the incubating thermos was controlled by adding or removing hot water in a sealed container.

4. Results

4.1. Participant observation

The hostel purchased firewood, which was delivered bi-monthly and stored in a pile near the garden in the back of the compound. Each morning, the Focal woke up around 3:30 AM. The first task of the day was starting the fire in one of the two semi-improved cookstoves in the kitchen. While the fire was becoming established, the Focal washed a 60-L aluminum cooking pot using soap, water, and a sponge in a sink adjacent to the kitchen. Next, a 20-L jerrycan was filled from a water tap in the kitchen and the empty, clean pot was placed on the stove. Once filled with water, the jerrycan was poured into the pot on the stove. Another full jerrycan and a quarter jerrycan of water were added subsequently. Together, the researchers and the Focal concluded that roughly 45 L of water was heated each morning over the stove. Student researchers observed this process for four mornings (three weekdays and one Sunday). On average, water was heated over the fire for 46 min (beginning around 4:10 AM).

During this time, the Focal mostly relaxed in front of the stove with occasional tending or maneuvering of the fire (sometimes for practical reasons and sometimes out of boredom). After about an hour, once small bubbles began to form in the pot, the Focal sounded an alarm from the kitchen to notify the residents of the hostel that hot water was prepared. The Focal aimed to sound it at 5:00 AM each school day. Within minutes, girls lined up outside of the kitchen holding thermoses and 5-L jerrycans. Water collected in thermoses (0.5–1 L) was used for morning tea and water collected in small jerrycans (5 L) was left to cool down for drinking at lunchtime. Roughly 20 girls collected water each morning – each filling between 1 and 5 containers for themselves and their roommates. The thermoses were typically used by individuals; however, jerrycans were shared among 5–10 girls each.

The girls placed their empty containers on a small serving table in the kitchen and the Focal dipped a handheld water pitcher into the pot and poured the hot water into the containers. One student researcher participated in this task one morning and found it extremely difficult to fill the pitcher with hot water while smoke from the cookstove stung their eyes and impaired their vision. The Focal acknowledged that the smoke was difficult to handle but said that he was used to it. Each morning, a small amount of hot water remained in the pot and was used to begin cooking beans for lunch.

During the implementation of the pasteurizer, three hostel employees were involved: the cook (Focal), manager, and security guard. They all seemed excited but also hesitant to use the new product. The research team deferred to their preference of location and selection of a water source during set-up, which was a tap near the kitchen. With the assistance of a translator, researchers explained the system in detail – ensuring that each employee understood how the water flowed and how it was purified. Once he understood how the pasteurizer worked, the Focal was eager to try it out.

Once the system was in place, without significant coaching, the Focal started the fire in the InStove and quickly mastered tending it. He was most surprised by how much smaller the pieces of wood needed to be to fit into the fuel entrance of the stove and spent extra time chopping wood, which he had not prepared for. The pasteurizer required 35 min to heat up enough to begin the flow and disinfection of water. It then ran for 14 min, filling every 5-L clean water container at the hostel and generating roughly 100 L of clean water with minimal tending of the fire. The Focal and others watching seemed impressed by the system but were skeptical that it was really cleaning the water due to the inability to see the water passing through the interior of the system. After seeing the incredulous reactions of the staff, the researchers arranged a time to explain the pasteurizer to gain their trust.

After the excitement and initial reactions died down, the Focal commented that he wished the pasteurizer could generate hot water for tea as well, as the clean water exiting the system was close to ambient temperature. Additionally, researchers noted that the leftover water heated for drinking each morning over their semi-improved cookstove was also used to begin cooking beans – something that the pasteurizer could not provide. Otherwise, the Focal commented that there was no smoke in his eyes and that it required minimal firewood. The manager even claimed "[the firewood] we use in a week could last [the pasteurizer] a whole year." Student researchers observed that, although the Focal did not boil water for drinking after the implementation of the pasteurizer, he continued to heat water each day for tea and other cooking needs over his semi-improved stove.

4.2. Focal follow and time allocation

After the field study, where field notes were taken for both Focal Follow and Time Allocation methods, data were coded based on thematic task categories. During water treatment processes at Diana's Hostel, the Focal's tasks were broken into the following categories: (1) tending the fire, (2) resting or chatting with others, (3) fuel collection or preparation, (4) performing other chores (such as cleaning the pot), and (5) serving water to the girls. Both the total time to purify 50 L of water and the time allocated across tasks in the two processes varied. Fig. 2 [68] shows the differences in time allocation between the baseline boiling method and the water pasteurizer for trial 3 of each process. Table 1 shows the total time for boiling 50 L of water from each trial. Most notably, the time spent resting during the water disinfection process decreased from 34 to 6 min in trial 3. Resting accounted for 60% of the total time to disinfect 50 L of water over the baseline fire and 18% of the total time to disinfect 50 L of water on the water pasteurizer. Additionally, time spent tending the fire increased from 9 to 14 min when using the pasteurizer, increasing the relative percentage of time spent tending from 16% to 42%.

Table 1
Statistical analysis of the total time to purify 50 L of water (min).

Trial #	Baseline fire	InStove Water Purifier
1	76	42
2	48	145*
3	57	33
μ	60.33	37.50
σ	14.29	6.36

* Data point removed due to weather interference.

In the middle of the second trial for the pasteurizer, a rainstorm hit Mbale and caused a significant delay. Due to this delay, researchers removed this data point from the analysis. While these results do not show a statistically significant difference between the time required to purify water on the baseline fire verses the water pasteurizer ($p = 0.1335$ for a two-tailed t-test), likely because of the small number of trials conducted, the difference in mean values is still noteworthy at 22.8 min.

4.3. Temperature

Of three test trials, the average temperature of the pot at the time the thermostatic valve opened was 80.0 °C for both a "cold-start" and a "warm-start". A "cold-start" represents operation of the system starting from ambient temperature. A "warm-start" represents operation starting from much warmer than ambient temperature due to the system retaining its heat from a previous test the day before. Even with the approximation of the valve temperature being 0.32 °C cooler than the stockpot on average, due to the broken thermocouple, this is well above the pasteurization requirement of 71 °C.

4.4. Flow rate

During testing, the measured flow rates of the water pasteurizer ranged between 6.8 and 8.3 L/min with an average flow rate of 8.0 L/min, equivalent to 480 L/h. All water containers at the hostel were filled in a matter of minutes once the flow began.

4.5. Fuel usage

The FUEL sensor monitored the baseline cooking and water disinfecting solution at the hostel for three consecutive days. During this time, the FUEL sensor determined that 104 kg of wood was used. Researchers observed that during these three days, the hostel's baseline stoves were used for roughly 37 h to prepare food and 6 h to prepare clean water. From time-stamped data obtained by the FUEL sensor, we can estimate that an average of 4.9 kg of wood was used each day to prepare clean water, or, roughly 49 g of wood per liter of water disinfected (estimating 50 L of water boiled twice each day).

Then, after the installation of the InStove and training and practice for the operator, the FUEL sensor was used to monitor the usage of the

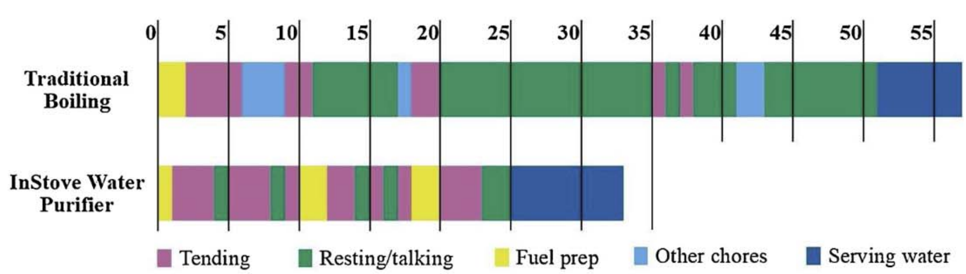

Fig. 2. Time allocation for disinfecting 50 L of water over baseline fire vs the InStove Water Purifier [68].

Fig. 3. Biomass fuel size differences between the semi-improved boiling method (left) and the InStove Water Purifier (right).

water pasteurizer. However, the Focal declined to use the sensor because from his perspective, "the weight of the wood was nothing" compared to their semi-improved baseline stove. The wood used for the institution's semi-improved cookstove had diameters up to 30 cm while the InStove requires much smaller pieces of wood with diameters less than 6 cm (Fig. 3).

To measure fuel usage of the pasteurizer, student researchers in Uganda performed experimental testing with staff members from MAPLE after the pilot study at the hostel. During 45 min of running the water pasteurizer, the FUEL sensor reported that 1.2 kg of fuel was used. Accounting for a "cold" start-up time of 35 min and a flowrate of 8 L/min, researchers concluded that the pasteurizer required roughly 15.6 g of fuel per liter of water produced, accounting for start-up time. Because this accounts for startup time, the longer the pasteurizer is allowed to run, the lower this figure will be since it is a continuous flow-through system as opposed to the batch process of the boiling pot method.

Although the fuel consumption results are not statistically significant, they potentially represent a reduction of biomass fuel use of 68%. Concurrently, ethnographic data highlighted the user's high perception of fuel savings using the pasteurizer compared to boiling water.

4.6. Bacterial contamination

The count plates showed zero presence of bacteria in the hostel's water source and, inherently, zero presence of bacteria in the Purifier's effluent water. This finding does not negate the need for water disinfection as the water source's reliability is inconsistent in Mbale [45].

5. Discussion

The results show multiple tradeoffs associated with adopting the water pasteurizer. Applying the DoI framework, themes in data include both benefits and barriers to adoption, which are described below and summarized in Table 2. Additionally, this study highlights the importance of method triangulation and the value of in-depth and short-term ethnography, even if results are not statistically significant due to a small sample size.

5.1. Benefits of adoption

As described in the DoI framework, benefits include product attributes that lead to user adoption and, ultimately, diffusion of a technology within a specific society. Potential benefits of adopting the water pasteurizer, identified by this study, include decreased overall time and labor to purify water, decrease in biomass resources required, increase in overall water output, and low learning curve for the product operator. Informal interviewing and observation combined with time allocation and fuel usage data show a high potential for user acceptance due to the pasteurizer's time and fuel savings. While our results for neither time or fuel savings are statistically significant due to limited sample size and duration of the study, ethnographic data indicate that users perceived noteworthy savings in these categories. Temperature and flow rate measurements support the known required temperatures and time to kill harmful microorganisms as data showed that water spent over 15 s at temperatures ranging from 78 to 87 °C, well surpassing pasteurization requirements.

The results from qualitative data show that the learning curve for the technology is low for a user with previous experience tending fires. This implies that operation of the system is culturally acceptable as it mimics the baseline water treatment solution, boiling over an open fire.

5.2. Barriers to adoption

Barriers, as defined in the DoI framework, refer to attributes that are either undesirable or inaccessible to users, ultimately leading to product neglect or rejection. Potential barriers to user acceptance of the water pasteurizer, identified by this study, include the trust required by users, lack of outlet temperature control, change in time allocation, and change in fuel wood preparation. The Manager and other users noted that the product did not show the water flowing through the interior of the stove. Because users are familiar with boiling water and visually seeing bubbles or steam to indicate purification has occurred, it is important that implementers of this system learn an adequate means of proving the product's efficacy to users, which will inevitably vary from user to user. Otherwise, some individuals may lose trust and refrain from using the product.

Users expressed interest in using the pasteurizer for other water needs such as tea and warm water for bathing. The manager and the Focal mentioned that a valve to control the outlet temperature would be a preferred design change. This feedback is especially valuable for design engineers who aim to reduce user reliance on traditional cookstoves. Although the Focal did not boil water for drinking after the implementation of the pasteurizer, he continued to heat water each day for tea and other cooking needs over his semi-improved fire. In this situation, the pasteurizer could not completely replace current methods. This feedback led engineers at InStove to design a hot outlet for the discharged water which may also serve to illustrate the efficacy concern noted above. Without this feedback from users, the InStove Water Purifier would never replace reliance on traditional fires to meet the institution's drinking water needs and would simply be a supplemental technology. Data such as these, from ethnographic methods, is

Table 2
Benefits and barriers of the InStove Water Purifier.

Benefits	Barriers
Decreased time to purify water	Lack of trust from new users (cannot visually see water flowing through the internal pasteurization unit)
Decreased biomass resources required	Little "feedback" during system start up; i.e. no bubbles or steam showing pasteurization
Increased water capacity	No water outlet temperature control
Low user learning curve	Cannot directly see the flame
Water is safe to handle immediately	Loss of leisure and/or multitasking time
	Increased labor during fuel preparation

Table 3
Proposed design changes from ethnographic methods.

Design/implementation proposed	Reason	Method
Change the angle of the fuel feed entrance	Improve usability, require less time for tending	Focal follow, Time allocation
Add manual temperature adjustment	For users to generate hot water	Participant observation
Increase the size of the fuel feed entrance	Improve usability, reduce labor during fuel preparation	Focal follow, Time allocation
Incorporate simple thermometer	To improve user experience	Focal follow
Incorporate a training and user guide	To improve initial trust of the system	Participant observation

necessary for reporting more accurate impact of technologies in the field. While it can be correctly reported that the water pasteurizer increased the institution's water capacity and saved significant time and fuel during the production of clean drinking water, it is incorrect to claim that users will see an overall decrease in fuel usage because they will continue to rely on their traditional technologies for the other applications that involved heating water.

Additionally, the water pasteurizer requires a different fuel size than traditional fires. The wood purchased and used for the institution's semi-improved cookstove had diameters up to 30 cm while the pasteurizer required much smaller pieces of wood with diameters less than 6 cm. Although the pasteurizer required significantly less wood than boiling over a traditional fire, any required behavior change (such as sourcing smaller wood or spending more time chopping) must be assessed during in the long term. Researchers suggest that future work involve evaluating the user's willingness to modify their fuel preparations or sources due to a risk that they may be averse to this form of additional labor or cost.

Results from the focal follow also showed barriers with usability of the product. First, while the stove is heating up to operation temperature (71 °C), there is minimal user-feedback to know how close the system is to beginning the flow of water. The Focal asked if a thermometer could be attached so that he could observe the gradual increase of temperature. Additionally, the fuel feed entrance made the system difficult to use because of the limited visibility of the wood and fire. The Focal bent over frequently to check the flame and tend the fire.

Time allocation results exposed that benefits associated with the water pasteurizer include increased efficiency and reduced time. However, they also identified costs such as potential loss of leisure time and, although minimal, increased time required for preparing fuel and tending the fire, and consequently reduced multi-tasking capabilities. This suggests that people who adopt the technology may have to actively tend it, rather than resting or multi-tasking as they may have done with their previous method. In future implementations, these barriers and benefits are product attributes that will be weighed by the user as he or she continues to use the pasteurizer. These attributes must be observed during long-term monitoring and evaluation to understand user preferences and values over the long-run.

5.3. Study strengths and shortcomings

This study highlights the importance of a mixed-method research approach to energy and water treatment technology evaluation. However, project implementers may not have the time or resources to conduct long-term studies with large sample sizes. In these cases, it is important to design rapid assessments, such as RAP, with a trusted and vetted local partner to examine benefits and barriers of the technology. The use of multiple methods is essential to examine both the technical performance of the technology and the social and cultural perceptions in the context. While much of the technical data was not statistically significant due to short timeline and small sample size, the findings from ethnographic methods are invaluable in the product design and learning phases, especially for engineers working outside of their culture. Additionally, we must recognize that solutions to global issues, such as access to renewable energy and clean water, cannot be solved with a solely technological approach. While this study focused on evaluating the design of a water treatment product, the authors recognize that access to reliable clean water in Eastern Uganda is a systemic concern, rooted in political and historical matters, and not a problem that will be solved with a single product. Therefore, it is essential that social science methods be incorporated into research concerning access to clean technology, which is inherently multifaceted.

5.4. Recommendations for product design and future long-term assessment

This study did not assess performance and user acceptance over long-term use, which is crucial to understanding adoption rates. Rather, by focusing on a single case-study, researchers were able to determine potential barriers and benefits of the new technology in a short amount of time. Additionally, since the paying customer of technologies, such as the pasteurizer, is often not the end-user (particularly in development projects with donors), the DoI framework cannot be fully used to predict diffusion in this context. Instead, the framework led to insights that can inform designers and practitioners about the potential impacts and risks associated with their product. This information could be used for design changes, planning implementation strategies, and understanding target user markets; among others. After these impact and risk factors are identified, future long-term monitoring should focus on observing these factors on user behavior and technology uptake. Table 3 presents a summary of design and implementation proposed to the product manufacturer for consideration to improve the system.

6. Conclusion

For institutions in Uganda with access to a water source and firewood, the InStove Water Purifier could serve as a reliable and economical water treatment method, however, long-term uptake of the current design may face certain barriers. Through a Diffusion of Innovation framework, benefits of adoption identified by the study include time and fuel savings, reduction of smoke, increased water disinfection capacity, and a low learning curve. Barriers of adoption and potential reasons for abandonment may include lack of user trust, increased labor for fuel preparation and tending time, inadequate technology-user-feedback while using the system, and lack of hot water output capability. Many of these user concerns can be address with simple design changes that could lead to more sustainable uses of the product.

Future work for evaluation of this product includes implementation in higher-demand contexts. In a situation with greater scarcity or cost of biomass resources and more demand for water, the water pasteurizer has the potential to significantly reduce the fuel use per liter of water produced and potentially meet an unmet demand for clean water.

Broadly, this study highlights the feasibility of a modified ethnographic approach grounded in the Rapid Assessment Process and the importance of method triangulation including ethnographic evaluation methods for engineering solutions in their intended context. Triangulation of data from multiple methods is extremely useful to corroborate results and gain better understanding of both the technology and users within a specific context. While two methods on their own concluded statistically insignificant results (time allocation and fuel usage) due to limited sample size and duration of the study, ethnographic data indicate that users experienced noteworthy savings in these categories while also providing valuable conclusions regarding the usability of the product's design. This study emphasizes the value that comes from working closely with end-users in an uncontrolled experimental environment, as multiple design recommendations were produced from these insights. Applying rapid ethnographic methods and analyzing qualitative data can lead to improved evaluations of engineering projects in the field and therefore increase the impact of water and energy technology interventions.

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