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Agile Development of an Affordable mHealth Technology for Point-of-Use Water Quality Testing and Education in Guatemala

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An abstract of

a thesis submitted to the Faculty of Emory College of Arts and Sciences

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Abstract

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BACKGROUND: Uptake of point-of-use water filters manufactured by the local, Guatemalan social enterprise EcoFiltro in rural indigenous regions is suboptimal, as previous studies have identified a gap in awareness about water contamination that is undetectable by sight. Edutainment and mobile health technologies have been shown to promote water, sanitation, and hygiene (WaSH) recommendations, and microscopy along with non-mobile image recognition analyses have been used to detect enteric pathogens. However, the intersection between handheld technologies and microscopy-based point-of-use water quality testing has not been explored.

STUDY OBJECTIVES: To 1) explore a possible innovative method for point-of-use water quality testing using the Foldscope and an AI-based algorithm for real-time *E. coli* detection, 2) co-design an application with this water testing capability and WaSH edutainment by interviewing relevant stakeholders in the EcoFiltro company, and 3) from their perspectives assess how the application can promote their filter's uptake and consistent use.

METHODS: In partnership with the Universidad del Valle de Guatemala (UVG) Microbiology Department, UVG computer science students, and image recognition experts at the Department of Biomedical Informatics in the Emory University School of Medicine, the application described above has started taking shape. Furthermore, the agile co-design and evaluation of the application development was carried out starting in October 2020 through two rounds of semi-structured interviews (n = 17) with EcoFiltro leadership and employees, including field staff. The qualitative data was transcribed and coded using a grounded-theory approach.

FINDINGS: The co-designed EcoFiltro application has high compatibility and acceptability within the company. The edutainment content coincides with field workers' routine tasks, and there was a high level of agile engagement. Interviewees recognize that the content and in-development water testing capability can address the lack of community awareness on water contamination, and EcoFiltro's poor customer service and community engagement. This can result in increased confidence in EcoFiltro and increased filter uptake. Therefore, the wider use of and adherence to the EcoFiltro (which already has a nationwide distribution chain) has the potential to reduce the burden of diarrheal disease in the country. The novel method of water quality testing has other potential implications for global WaSH.

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List of Important Acronyms and Abbreviations (in Alphabetical Order)

Acronym/Abbreviation	Meaning	Page Where it is First Introduced
AI	Artificial intelligence	1
API	Application programming interface	35
APK	Android Package	35
CEH	Guatemala's Comission for Historical Clarification (La Comisión para el Esclarecimiento Histórico)	6
CLTS	Community-led total sanitation	19
COCODES	Community development councils in Guatemala	73
CV	Computer vision	40
DHS	Demographic and health survey program	12
DIBaS	Digital Images of Bacterial Species database	21
EED	Environmental enteric dysfunction	18
EMPAGUA	Municipal Water Company (Empresa Municipal de Agua)	13
ENCOVI	National Survey of Living Conditions (Encuesta Nacional de Condiciones de Vida)	8
ENSMI	National Maternal and Child Health Survey (Encuesta Nacional de Salud Materno Infantil)	9
FAQs	Frequently asked questions	37
GOe	WHO’s Global Observatory for eHealth	26
IGSS	Guatemalan Institute of Social Security (Instituto Guatemalteco de Seguridad Social)	11
INCAN	National Cancer Institute (Instituto Nacional de Cancerología)	11
IR	Image recognition	21

JMP	WHO/UNICEF’s Joint Monitoring Programme for Water Supply and Sanitation	13
MARN	Ministry of Environmental and Natural Resources (Ministerio de Ambiente y Recursos Naturales)	13
MDG	Millennium Development Goals	9
mHealth	Mobile health	1
MINEDUC	Ministry of Education (Ministerio de Educación)	24
ML	Machine learning	40
MMR	Maternal mortality ratio	9
MSPAS	Ministry of Public Health and Social Welfare (Ministerio de Salud Pública y Asistencia Social)	10
NGO	Non-governmental organization	7
ORT	Oral rehydration therapy	17
PAHO	PanAmerican Health Organization	6
QR code	Quick response code	52
SDG	Sustainable Development Goals	15
STMMs	Short-term medical missions	12
UN DESA	United Nations Department of Economic and Social Affairs	3
UVG	Universidad del Valle de Guatemala	35
WaSH	Water, sanitation, and hygiene	1

I. INTRODUCTION

This thesis explores the potential role of affordable, health technologies in rural Guatemala in addressing a complex web of socioeconomic inequities which are deeply rooted in the country's history. This research develops an innovative approach to addressing the region's deficit of safe water–and the resulting repercussions on the health of marginalized populations–through low-cost water quality testing and community education. The project was conducted in partnership with local social enterprise EcoFiltro, which manufactures and distributes ceramic pot water filters at subsidized, accessible prices in rural areas. As with other attempts to scale up several water purification strategies in rural Guatemala, the company's efforts to promote long-term use of the EcoFiltro have been hindered by a lack of community understanding surrounding water contamination and the benefits of filtration in reducing transmission of diarrheal pathogens. This formative, quality improvement study outlines the agile co-design of a mobile application for point-of-use water quality testing and water, sanitation, and hygiene (WaSH) community education.

The thesis first engages with relevant literature on the region's political background, historical oppression of indigenous Mayan communities, and how both are reflected in the country's current development indicators and healthcare infrastructure. I will also present data on Guatemala's progress on the global WaSH agenda and the burden of diarrheal disease in the country. Different water quality testing methods, including microscopy and artificial intelligence (AI) techniques for image recognition, are explored along with the potential to scale up water purification technologies at the national level. I then elucidate EcoFiltro's role within this broader sociopolitical and developmental context, exploring the potential benefits from a mobile health (mHealth) technology tool to increase uptake and adherence to filter use. Lastly, previous work done with mobile technologies in the field of WaSH, the efficacy of entertainment education or "edutainment," and evaluation outcomes for smartphone-based interventions are reviewed. This information creates a multi-pronged foundation from which to build an EcoFiltro-specific mHealth application with water testing capabilities and community-facing edutainment content.

This agile co-design study is a part of an ongoing research program to enable low-cost, point-of-use water quality testing and increase use of household water filters. This program encompasses the ongoing development of the technology, including the programming of the application, microbiological water sampling protocols for lay fieldworkers, and an image recognition algorithm to leverage artificial intelligence for real-time detection of *E. coli*. This thesis project is embedded within this larger research program and focuses on the co-design of the application with EcoFiltro staff. It included two rounds of interviews with company employees and leadership, inquiring about their perspectives on the application and, more specifically, its water testing capability as it is being designed. The objectives of this study are: 1) to present this novel approach to water quality testing within the context of global health WaSH and 2) to co-design the app technology with EcoFiltro stakeholders and assess from interview data whether the app technology can work to further EcoFiltro's mission and goals. I will present the results of the interviews, grounding them in findings from relevant fields, identifying limitations, and defining next steps for the project.

II. BACKGROUND

2.1 The Two Guatemalas

Guatemala is a small Central American, democratic republic bordered by the Pacific Ocean to the south, El Salvador to the southeast, Honduras to the east, Belize and the Caribbean to the northeast, and Mexico to the north and west. 2018 population estimates placed Guatemala first in Central America, and eleventh in the Americas overall, with a national population of 17.2 million (UN DESA Population Division, 2019). Its largest and most populous city is the country's capital, Guatemala City–officially named Nueva Guatemala de la Asunción–near the territory's southeastern coast. The ancient Mayan civilization, which extended throughout Mesoamerica, was historically concentrated in what we call Guatemala today, with the famous ruins of Tikal in the large northern state of Petén having been the capital of the empire (Coe & Houston, 2015). The country has a long history of volcanic and seismic activity, with a contrast between the two major mountain ranges that cross over its southern half–Sierra Madre and Sierra de los Cuchumatanes–and the warm, humid lowlands (see Figure 1). Around one-third of the population lives in these mountainous regions known as the highlands. The official language is Spanish and the national currency is the *quetzal* (Central Intelligence Agency, 2020).

Guatemala today suffers from a limited reach of government services outside of urban centers, and a growing divide between what has been referred to as the *two Guatemalas*: the rural, indigenous Maya communities and the predominantly *ladino* (or mestizo) metropolitan areas. A lengthy history of political turmoil, poverty, and crime that disproportionately affected the indigenous population has set the stage for the country's modern-day inequalities.

Figure 1. *Topographical map of Guatemala. Large red squares indicate capital cities of countries, while small red dots indicate Guatemala's state capitals. The list of colors from lower to higher altitude are the following: green, yellow, orange, and grey* (Ezilon Maps, 2009).

2.1.1 Historical Background

At the end of the 15th century, Spaniards arrived in and conquered Caribbean and Latin American land, with most of the Guatemalan territory coming under the full control of Spain during the 16th century. Their arrival devastated local Maya populations from the start through violent invasion and the spread of disease, eventually exploiting them as forced labor under the dominion of the Viceroyalty (Jonas, 1991). Spanish rule attempted to forcibly impose its own cultural practices and Catholic beliefs while also replacing the pre-Hispanic economic order with European technology, livestock, and large-scale cash crops--notably coffee and sugarcane, which became and continue to be important areas of production and exportation (Coe & Houston, 2015). Plantations were sites of considerable economic--and often brutal--exploitation of native labor, a system which remains in place long after Guatemala attained independence from Spain in 1821. The Spanish elite's expropriation of indigenous land laid the groundwork for the country's continuous struggle with unequal land distribution (Jonas, 1991).

The new economic order introduced by the Spaniards also organized Guatemalan society into a class system with indigenous laborers at the bottom, followed by *ladino* salaried workers and bureaucrats, and the elite *criollos* of pure European lineage at the top (Smith, 1995). This class system, although not overtly a part of political structures, is largely maintained today via societal discrimination and governmental negligence (Cabrera et al. 2015; Barrett 1997). In the 20th century, intervention by the United States government and the United Fruit Company supported a series of Guatemalan dictators that limited land distribution (Dosal, 2005). Beginning in 1944, President Jorge Ubico introduced a decade-long revolution of social, economic, and most importantly, agrarian reform–a period often referred to as the "Guatemalan spring." Ubico's reforms were sustained by democratically-elected President Jacobo Árbenz. At odds with the United Fruit Company's economic interests in maintaining Guatemalan landholdings, Árbenz was overthrown by a United States-backed coup and replaced by yet another dictatorship (Gleijeses, 1991). In 1960, heightened tensions between indigenous populations and the military government erupted in a 36-year long civil war between the US-backed Guatemalan military and the predominantly indigenous leftist rebellion (often called *guerrillas*).

About a decade before the signing of the Peace Accords in 1996, Guatemala began to hold relatively successful democratic elections and subsequently a recovery from its economic recession. However, mismanagement of its largely centralized infrastructure continues to impede democratic (particularly judicial) processes, and there continues to be low penetration of social services (McCleary, 1997; World Bank, 2005; PAHO, 2017). Weak democratic structures and distribution of social goods across society are in part due to the lack of a formal post-war reconciliation and accountability for the government's actions during the war, which continues to fuel a collective distrust of the judiciary (World Bank, 2005). Distrust has also locked indigenous populations into a state of near-isolation in hopes of protecting their traditions and culture, affecting their integration into society–seen in their disenfranchisement from the country's education and healthcare systems (Bellino, 2016; Glei et al., 2003). The combination of weak government structures and socioeconomic disarray following the war has somewhat propelled drug trade and organized crime and allowed them to operate with impunity (Brands, 2010). Exploitation and discrimination of indigenous peoples, such as land disputes and brutal plantation labor, continue to go unaddressed.

The international community accepts that concurrent genocidal massacres of the Mayan population during the armed conflict, in which tens of thousands of indigenous people were slaughtered, were largely carried out by the military and government-backed paramilitary groups, and only a small percentage of deaths were attributable to the rebels (CEH, 1999). Despite sufficient evidence to support these conclusions and ongoing work to uncover and identify remains in mass graves, the genocide continues to be a highly contested topic within the country (Nelson, 2015). In fact, the Guatemalan Congress approved a non-binding resolution in 2014 which states that "it is legally impossible ... that genocide could have occurred in our country's territory during the armed conflict," and yet still calls for "national reconciliation" (Perez, 2014). The call for reconciliation is ultimately meaningless unless the government makes an effort to recognize the atrocities committed by the military in the decades-long conflict, and how it is reflected in the current state of indigenous populations. This speaks to why post-war sentiments in Guatemala are still relevant today, and how there continues to be a lack of will, both in the government and among urban elites, to extend services to the rural Maya populations. It provides important context for understanding how this violent history of inequalities and negligence is reflected in Guatemala's contemporary human development indicators.

2.1.2 Resulting Human Development Indicators

The years following the armed conflict saw an immense post-war influx of aid in part by foreign governments, multinational organizations, and other non-governmental organizations (NGOs). Despite this rapid and overwhelming growth of the NGO sector in Guatemala and additional, numerous efforts to bring humanitarian aid to the country, there has been little progress with regards to closing gaps and creating sustainable social impacts (as will be demonstrated in the following data). Rohloff et al. attributed this to how the efforts often function "as proxy agents for the government," competing for "limited funds" and ignoring "service duplication," which together have "restricted the sector's flexibility and capacity for local engagement" while "creat[ing] community burnout and fuel[ing] resource shopping" (Rohloff et al., 2011).

A Systematic Country Diagnostic performed by the World Bank in 2016, the CIA Factbook, and data from the Pan American Health Organization all summarize developmental challenges in Guatemala. Poverty increased from 55% in 2000 to nearly 60% in 2014, according to a poverty line equivalent to $4 per day. This increase is likely due to the continuous exclusion of the lower socioeconomic classes from the country's economic growth, which is concentrated almost solely in urban centers. The exclusion originates from a lack of human capital seen in a large portion of the population that does not have adequate access to quality healthcare and education (Sánchez et al., 2016). According to the 2014 National Survey of Living Conditions (ENCOVI), the total literacy rate for citizens aged 15 years and older was 79.1%. The survey reports the following disparities in literacy across the population: 86.1% in urban dwellers, 71.4% in rural dwellers, 84.8% in men, and 74.0% in women. The most educationally disadvantaged groups are rural women and indigenous women, with a literacy rate of 64.7% and 57.6%, respectively (PAHO, 2017). The lack of outreach from public services is also indicative of weak structures of governance, still unable to employ effective political representation, justice, and equity. The government's tendency toward impunity for high-ranking officials often allows the judiciary to dismiss their unlawful acts. This, in turn, feeds a cycle of bureaucratic mismanagement that continuously siphons governmental resources from their intended destination. Frequent natural disasters and criminal activity that disproportionately affect the poor also play an important role in maintaining, if not worsening inequalities (Sánchez et al., 2016).

Furthermore, the Guatemalan economy has not reached the desired potential, despite increased foreign investment and recent mercantile policies. Guatemala is the fifth poorest economy in terms of per capita income in the Latin American region, a decrease of five places from its location in 1960 (Sánchez et al., 2016). Its private sector does not have the capacity to generate enough employment for a largely incompetent population, fueling the informal economy, and depriving the formal one of growth (Sánchez et al., 2016). Urbanization is highly centralized and growing at the heart of the country as migration to existing centers continues. As of 2014, nearly half of the entire Guatemalan population lived in metropolitan areas found in Guatemala, Escuintla, Quetzaltenango, and other departmental capitals. Hence, urban centers also struggle increasingly to extend services to periurban settlements and vulnerable areas (PAHO, 2017). Electrification levels are remarkably high nationwide, with 91.8% of the population having access to electricity. However, disparities still exist between urban and rural regions, with 96.8% and 86.4% access, respectively (Central Intelligence Agency, 2020).

Beyond the socioeconomic struggles are the health repercussions, notably malnutrition stemming from unequal access to produce and reliance on unhealthy diets. Guatemala has the highest levels of undernutrition than any other country in the Americas, with 47 percent of its children demonstrating stunted growth due to chronic malnutrition (and, shockingly, increases in prevalence within even the most economically-advantaged area surrounding Guatemala City). Undernutrition again demonstrates ethnic disparities, with 61.2 percent of indigenous children suffering from undernutrition in comparison to 34.5 percent of non-indigenous children (Sánchez et al., 2016). Rates of overweight and obesity are also an increasing issue. The 2008-2009 National Maternal and Child Health Survey (ENSMI) revealed that 36% of men and nearly half of women of reproductive age were either overweight or obese (PAHO, 2017). Despite endemic malnutrition, several other health indicators in Guatemala have improved in recent years, notably infant mortality, the percentage of pregnant women who receive prenatal, natal, and whose children receive postnatal care, life expectancy, and some infectious disease rates (Sánchez et al., 2016). The 2014-2015 ENSMI reported that the average mortality rate for children under the age of five was 35 deaths per 1,000 live births. This met the Millennium Development Goal (MDG) target of 37 deaths per 1,000 livebirths for the year 2015 (PAHO, 2017).

The maternal mortality ratio (MMR) has decreased rather steadily since 2009, from 131 deaths per 100,000 live births to a 2017 estimate of 95 deaths per 100,000 live births (World Bank, 2019). This decrease, however, failed to achieve the MDG target of reducing maternal mortality by three-quarters from the 2000 estimate of 240 deaths per 100,000 live births. Historically, there have also been drastic inequalities regarding this indicator. In 2000, indigenous women had an MMR that was three times that of the non-indigenous demographic–211 deaths per 100,000 live births and 70 deaths per 100,000 live births, respectively. According to the 1998-1999 ENSMI, whereas 55% of *ladina* women had births attended by doctors or nurses, only 17% of indigenous women fulfilled these criteria (Population Reference Bureau, 2003).

2.1.3 The Guatemalan Healthcare Landscape

In theory, the health system in Guatemala is stratified in order to permeate society at each level. However, political corruption often prevents public services from making a significant difference in rural communities, facilitating the provision of these services by other parties. Guatemalan health services are therefore composed of a landscape of different sources, rather than one consolidated healthcare system. The actual Guatemalan healthcare system, funded by Ministerio de Salud Pública y Asistencia Social (MSPAS), is organized into large national hospitals within urban centers of each department, and health centers or health posts located at a more rural level (Bowser & Mahal, 2011; MSPAS, 2017). Even though the health system has an assigned coverage of 70% of the population, access indicators indicate otherwise and have remained fairly unchanged since 2000, particularly disfavoring indigenous populations (PAHO, 2017). Taking a closer look at the structure of MSPAS and the presence of other sources of healthcare in Guatemala can outline why there is a need for sustainable interventions in rural, indigenous communities.

The countrywide physician density as of 2018 was 3.6 per 10,000 population (Central Intelligence Agency, 2020). However, analyzing specific subsets of the Ministry of Public

Health and Social Welfare's (MSPAS) outreach reveals further disparities within the healthcare system. Within the Department of Guatemala, home to the capital city, the physician density of the MSPAS system in 2014 was 8.1 per 10,000 population. In contrast, the MSPAS network within larger and denser rural departments like Alta Verapaz and Huehuetenango had a physician density of 1.5 and 1.6 per 10,000 population, respectively (PAHO, 2017).

It is not out of the ordinary for national hospitals to experience shortages in medications or equipment and to have extensive, months-long waitlists for a procedure or consult (which in some hospitals are carried out by primary-care doctors rather than specialists) (Knowlton et al., 2017). A parallel health system available in Guatemala is the Guatemalan Institute of Social Security (IGSS). However, the healthcare offered in the IGSS facilities is limited to citizens employed in the formal economy, which is concentrated in the urban areas, covering only around 18% of the population (PAHO, 2017). Another example of poor coverage in the national healthcare system is the fact that there is only one oncology hospital serving people without private insurance or social security in the public sector for the entire country–the National Cancer Institute (INCAN). INCAN, along with the two other primary cancer referral hospitals in the country–San Juan de Dios and Roosevelt–are also located in Guatemala City. The care-seeking process has many barriers, including transport, lodging, loss of income, all of which are "direct costs incurred by patients [which] still can be significant" (Flood et al., 2018).

In the private sector, there are many healthcare providers that offer services, albeit concentrated in the metropolitan areas. These private services come at a relatively high, inaccessible cost, and a mere 8% of the population accesses private health insurance (PAHO, 2017). Perceptions of quality from private providers that also work in the government system indicate that they often prefer the quality of care in their private practices over public MSPAS or

IGSS services (Roche et al. 2018). Therefore, whereas care offered via the MSPAS system is uniquely poor in quality and reliability, the IGSS and private sources are without a doubt inaccessible to most of the country. Without many accessible options to choose from, impoverished communities often turn to short-term medical missions (STMMs, called *jornadas* locally) of visiting medical teams that occur throughout the year in a span of usually one to two weeks all over the country (Esquivel et. al., 2017). Facilities used to set up a temporary clinic include military hospitals or rentable buildings, while some are integrated into the work of local hospitals. The missions have a reputation of offering, for the most part, better quality care than that of the public hospitals, and at little or no cost. It is understandable why these STMMs have risen dramatically in popularity and demand (Esquivel et. al., 2017). Other NGOs provide mostly non-surgical services and treatments that are often used in rural Guatemala. An example of these is WINGS Guatemala, advocating for reproductive rights and providing several reproductive health services through local community health workers (WINGS Guatemala, 2020).

Diarrheal diseases present a considerable burden within the Guatemalan healthcare landscape (Arvelo et al., 2019). The 2014-2015 ENSMI found that 19.2% of children under five suffered from diarrhea in the two weeks preceding the survey, with 2% experienced diarrhea with blood (DHS, 2017). This burden can most likely be attributed to the use of unclean drinking water sources (Clasen et al., 2015), but more accurately to a lack of effective sanitation which is often the source of fecal contamination that imbues drinking water in rural communities (Jarquin et al., 2016). Furthermore, the frequent co-morbidity of undernutrition and diarrheal disease shows the importance of the malnutrition and infection cycle, further discussed below. It would be helpful to carry out an assessment to comprehensively evaluate how young children are being exposed to fecal contamination. However, with data that is currently available, drinking water certainly seems as the dominant exposure route. A deeper look into the quality of water sources and the presence or absence of sanitation systems in the country can further inform our understanding of the systemic challenges and why innovative WaSH interventions are necessary.

2.2 Water Quality and Sanitation Systems in Guatemala

2.2.1 Water Supply

According to the WHO and UNICEF's Joint Monitoring Programme (JMP) for Water Supply and Sanitation, 5% of the Guatemalan population still consumed surface water or water from unimproved sources in 2017 (JMP, 2019). The Ministry of Environmental and Natural Resources (MARN) reported that 90% of all surface water in Guatemalan rivers, lakes, and springs were contaminated to different degrees. Of approximately 24,000 controlled water systems and mechanical wells in the country, only one-third have the appropriate residue levels of chlorination (the adopted water purification method), while the remaining two-thirds presented at least some degree of unsanitary bacterial contamination (Sánchez et al., 2016). Therefore, despite some apparent successes during the Millennium Development Goal (MDG) period, the data above shows the reality that households continue to face significant challenges in obtaining drinking water of adequate quality and why household filtration remains essential.

According to the Constitution of the Republic of Guatemala, the provision of basic water services falls upon the individual municipalities, or the subdivisions of the Guatemalan departmental states. Whereas Guatemala City residents can often rely on municipal water companies such as Empresa Municipal de Agua (EMPAGUA) to provide them with water, rural Guatemalan citizens must rely on any basic services provided by their local government or the use of surface water or small-scale wells. In theory, both the Ministry of Health and MARN should be regularly monitoring water sources all over the country, which routinely lapses. The mismanagement of federal funds that are allocated to tackle water contamination essentially leaves most municipalities to fend for themselves. This is seen in how the infrastructure needed to pump water into households is largely absent in most rural municipalities. Some municipal governments do manage to provide their communities with water treatment options, particularly chlorination. There are also cases where the local MSPAS monitors water quality. For example, the local authorities in the municipality of Santiago, Atitlán handle chlorine treatment of water that is collected from Lake Atitlán, and water quality is assessed by the local *Centro de Salud*, or health post (Nagata et al., 2011). In practice, varied systems and implementation of water purification methods at the municipal level lead to unequal access to clean water across the country.

Poor water quality from unimproved sources in Guatemalan communities is a regular origin of water-borne pathogens that often leads to an endemic prevalence of diarrheal disease. According to World Bank assessments, around 40% of the rural Guatemalan population in 2014 did not obtain water from within their homes (World Bank, 2018). Further, previous studies have shown that up to 98% of water sources in Guatemala are polluted with *Escherichia coli*, the most common indicator of fecal contamination (Chiller et al., 2006). Data on the MDGs suggests that between 2000 and 2014, accessibility to an improved drinking water source within the entire Guatemalan population increased from 87% to 91%, surpassing the country's 2015 objective of 88.5% (World Bank, 2018). Despite these improvements, there is ambiguity surrounding what is considered to be an "improved" water source in Guatemala and if such a source fulfills the drinking water guidelines set by the WHO. Despite conflicting opinions on the status of water quality in Guatemala, it is also clear that increases in agrochemical use and untreated wastewater leakages have led to considerable water contamination throughout the country. Large basins such as Lake Atitlan and other types of surface water function as vital sources for consumption and agriculture but have contributed to eutrophication and bacterial contamination detrimental to health (Sánchez et al., 2016).

Furthermore, according to the WHO/UNICEF Joint Monitoring Programme (JMP), there is a degree of disparity between the rural and urban areas, as well as when comparing the wealthiest and poorest quintiles of the population–the poorest primarily being the rural, indigenous demographic. Urban areas have near-total coverage of at least basic water services, (though this figure likely excludes urban informal settlements), whereas rural areas have coverage of around 90%. The wealthiest quintile of the Guatemalan population again has near-total coverage of at least basic water services, and the poorest quintile has coverage of under 80% (JMP, 2019). While an improved drinking water source, as described by the MDGs, can potentially be outside of an individual home and shared within the community, the Sustainable Development Goal (SDG) marker that is a safely managed water source must be on the premises, free of contamination, and available when needed (UN MDGs, 2000; UN General Assembly, 2015). The proportion of the Guatemalan population that had a source of water that fit these guidelines as of 2017 is merely 56%. This figure is 46% in rural areas and 66% in urban areas (JMP, 2019). As mentioned previously, the root cause of water pollution is most commonly a lack of proper sanitation infrastructure, the disparities around which will now be described.

2.2.2 Sanitation Coverage and Handwashing

The worst-case scenario for the sanitation infrastructure of a community is the practice of open defecation. According to the JMP, 6% of Guatemalan households continue to practice open defecation, while 46% of Guatemalan communities have at least one household that practices open defecation (JMP, 2019). These measures are unfavorably high and essentially point to the fact that nearly half of all communal water sources in Guatemala are at risk of some degree of fecal contamination, unless they are improved sources that protect against pathogen influx. As of 2017, the proportion of the rural population that practiced open defecation was 8% (a marked improvement from the 2000 rate of 22%), while it was only 1% prevalent in the urban populations (JMP, 2019). A study in Kenya revealed that open defecation free (ODF) villages had significantly lower levels of bacteriological contamination of drinking water sources when compared to open defecation not free (ODNF) villages (Okullo et al., 2017). While it depends on population density and context, even apparently small rates of open defecation can result in greater fecal contamination of groundwater and subsequently communal water sources.

Evaluation of the Millenium Development Goals revealed that between 2000 and 2014, the rates of the use of an improved sanitation system in Guatemala increased from 39% to 53% but did not reach the 2015 MDG target of 65.5% (World Bank, 2018). The same ambiguity applies here, particularly if an improved sanitation facility does not necessarily protect against the diarrheal pathogens that are of concern. Nevertheless, the disparity between rural and urban regions is most apparent in terms of sanitation facilities, with 51% and 79%, respectively, using at least basic services (JMP, 2019). There is no data on safely managed sanitation facilities in Guatemala–excluding those that are shared. There are, however, some indications that sanitation infrastructure continues to improve in urban areas but not necessarily in rural communities. For example, between 2000 and 2017, the prevalence of sewer connections in urban areas increased from 68% to 73% but decreased from 11% to 10% in rural areas. Even though open defecation is relatively low when compared to countries like India, many latrines may not properly contain waste, which can lead to run-off and contamination of groundwater (JMP, 2019).

Handwashing practices and facilities often mitigate human-to-human transmission of enteric pathogens. In Guatemala, 2017 data shows that 77% of the population had access to basic handwashing facilities at home. When stratified between urban and rural areas, the rates were around 83% and 70% respectively (JMP, 2019). The presence or absence of sanitation infrastructure and handwashing facilities, including the ability to pay for consumables such as soap, play a key role in determining community and household risk of exposure to enteric pathogens. In rural Guatemala, the greater lack of sanitation facilities and handwashing practices allow for greater exposure, resulting in a considerable burden on the Guatemalan health landscape: diarrheal disease.

2.2.3 Diarrheal Disease

Diarrhea is one of the leading causes of under-five deaths both in Guatemala and around the world (DHS, 2017). Oral rehydration therapy (ORT) along with zinc supplementation are WHO essential medicines used to avoid morbidity and mortality, though the MSPAS supply chain of zinc experiences frequent stockouts (Hall-Clifford & Amerson, 2017). A facility-based surveillance system in the departments of Quetzaltenango and Santa Rosa detected a total of 5331 diarrhea cases between November 2008 and December 2012. They identified an average incidence of 659 diarrhea cases per 10,000 persons per year (which is adjusted based on healthcare-seeking behaviors from a household survey in the area), with a much greater adjusted incidence in children under the age of five: 1584 cases per 10,000 children per year. The system managed to obtain specimen samples from 1381 (26%) of the total 5331 cases, which included specimens from 827 (60%) of the total cases in children. They found that nearly half (47%) of all specimens had bacterial, viral, or parasitic etiology (or multiple etiologies), and 55% for children under five (Arvelo et al., 2019).

The low nutritional status of indigenous communities can often be exacerbated by the illness, particularly zinc deficiencies. This sets off a cycle that dampens the immune response that would normally meet diarrheal microbes in the first place (Mazumder et al., 2010). If the exposure to enteric pathogens is frequent enough, then long-term adverse effects in the gut, commonly referred to environmental enteric dysfunction (EED), can develop. A 2018 study in rural Uganda found that unsafe drinking water was associated with EED and the related poor growth outcomes in children (Lauer et al, 2018). Growth stunting is frequently used as a proxy for understanding the developmental impacts of frequent diarrheal disease in children, during which there is a two-fold loss of nutrients: 1) loss of calories due to poor intestinal absorption during the bout of diarrhea; 2) expenditure of calories through the immune system to fight the infection. Frequent bouts of diarrhea exacerbate underlying undernutrition.

In Guatemala from 1969 to 1997, the nutritional supplement *atole*, a cornmeal gruel containing high-quality protein, energy and micronutrients, was provided to pregnant women and children under the age of seven in two treatment villages, which was compared to two control villages who were provided with a low-energy drink called Fresco. *Atole* villages saw improved nutrient intake and reduced stunting in children under three years of age, as well as improved schooling, reading, and intelligence in those who received *atole* before the age of three. Furthermore, the wages of men who were provided with *atole* through the age of two years were increased by 46%. Martorell concluded that the studies compiled showed a “substantial improvement in adult human capital and economic productivity result[ing] from the nutrition intervention,” which “provides a powerful argument for promoting improvements in nutrition in pregnant women and young children in low income countries” (Martorell, 2017).

Diarrhea is often stigmatized within the rural Guatemalan populace due to the high penetration of public health recommendations for sanitation, and consequently the association of diarrhea with an overall lack of hygiene (Hall-Clifford, 2019). These messages have placed the blame for diarrhea at the household level rather than at the water systems level. Arvelo and colleagues suggested that laboratory capacity should henceforth be improved in order to detect and control outbreaks of enteric disease, while also promoting public health interventions to address the root cause (Arvelo et al., 2019). Introducing systemic improvements in sanitation infrastructure could potentially address the contamination of drinking water sources in Guatemala. While an implementation of community-led total sanitation (CLTS) in Mali found no decrease in the rates of diarrhea, it did see improvement in growth outcomes of children, particularly those under the age of two. The authors argued that CLTS could have impacted child growth via pathways other than reducing diarrhea rates (Pickering et al., 2015). Such a comprehensive approach at the community level may have merit in the Guatemalan context. In addition to improving sanitation systems, the study by Arvelo et al. points towards a broader need for efficient and accessible water quality testing methods in Guatemala.

2.2.4 Water Quality Testing Methods

Common laboratory methods for the evaluation of the microbiological quality of water include the IDEXX Colilert QuantiTray and membrane filtration (MF) colony counts. Both of these water quality testing strategies measure the total amount of coliforms present in a given volume of sample (Rijal, 2019; IDEXX, n.d.). The IDEXX Colilert assessment specifically detects fecal, or thermo-tolerant, coliforms in wells that taint yellow, while wells that fluoresce under ultraviolet light indicate the presence of *E. coli* specifically (IDEXX, n.d.). There are also emerging techniques to assess not just one individual source of water but an entire community's exposure risk. The urban and periurban contexts have at their disposal the SaniPath Exposure Assessment Tool, which evaluates exposure to fecal contamination via multiple different pathways (i.e., municipal drinking water, produce, bathing water, drain water, latrine water, etc.) (Raj et al., 2020). The central issue with these testing methods is the reliance on a laboratory or stable setting to be able to quantify the results, meaning that it would not be feasible to carry out any of these tests exclusively in a resource-constrained environment. One type of coliform exposure assessment that could be feasible in such a setting would testing kits such as the LaMotte Coliform Test Kit, which measures total coliforms and only requires compliance with protocols that ensure that the water sample is collected properly (LaMotte, 2021). However, two drawbacks that also pertain to coliform test kits include the overwhelming cost that would involve using these technologies regularly for detection purposes, and the time they take to deliver results.

More recently, microscopy is being applied to the growing need for financially accessible water testing strategies that can provide results relatively quickly, making them feasible for implementation in low-resource settings. By taking advantage of low-cost microscopy devices, such as the Foldscope and Cellscope (priced at around 1$ and $6 each, respectively), and coupling them with the cameras of smartphone devices, a cheap, novel microbiological detection method was created. A 2015 study by Ephraim and colleagues compared the sensitivities and specificities of the Foldscope and Cellscope in detecting the presence or absence of *Schistosoma haematobium* ova from participant urine samples obtained in Ghana. They found that the Foldscope and Cellscope had sensitivities of 55.9% and 67.6%, and specificities of 93.3% and 100.0%, respectively, when compared to traditional light microscopy (Ephraim et al., 2015). Other variations of the technology are emerging, including ones that exclude the smartphone component and instead couple a digital microscope with an image analysis scanner, which are currently too costly and require complex training when focusing on rural fieldwork (Holmström et al., 2017). Another variation used a smartphone coupled with the microscopy piece but added the ability to take brightfield and fluorescent images (which would later undergo image analysis using ImageJ), which could also prove to be unnecessarily expense for the intents and purposes of rural water testing (Breslauer et al., 2009).

There has not, however, been much research around the possibilities that image recognition (IR) software can bring to point-of-use water quality testing. While some of the studies above explored the possibility of using a smartphone coupled with a microscopy device, none attempted to integrate the image analysis software directly into an application in the phone itself. Furthermore, few studies have taken advantage of image databases for pathogens of interest, such as the Digital Images of Bacterial Species (DIBaS) created by Zieliński and colleagues (Zieliński et al., 2017). Doing so while also incorporating the resulting IR software into mobile devices could allow users to detect enteric pathogens as the microscopic images are taken. However, a current challenge with this approach is the difficulty in differentiating most enteric bacterial pathogens from environmental bacteria on the basis of size and morphology. Light microscopes themselves are not able to visualize viruses, but it may be possible to detect and identify protozoa in water. These considerations are at the forefront of what is being explored as part of the broader project, but they are not explored within the data for this thesis.

2.2.5 Water Purification Scalability

Point-source chlorination has been successfully implemented and scaled up within only a select few Guatemalan municipalities. However, implementation of such purification initiatives on a national scale has proved challenging. The 2006 study by Chiller and peers attempted to scale up the purchase of flocculant-disinfectant as the main point-of-use water purification method in underprivileged communities in Guatemala (Chiller et al., 2006). A subsequent study published by the same team evaluated the long-term success of the intervention by assessing the rates of flocculant-disinfectant purchases sixth months after the initial study. They found that "[e]ven after efficacy was demonstrated within their community and an aggressive sophisticated marketing approach," merely 5% of the original households purchased the flocculant-disinfectant for point-of-use water purification during the 2 weeks prior and used it within the last week (Luby et al., 2008). Effects on the taste of the water, which has high cultural value in Guatemala, may explain these outcomes.

In Guatemala, the social enterprise called EcoFiltro sells clay, point-of-use mechanical filters that have virtually become the most accessible water purification option for rural, indigenous families. Despite the filter's popularity, it has encountered similar issues in comprehensibly reaching most of rural Guatemala with its technology, and hence, the scalability of their sales. Given how the government's efforts to scale up chlorination, researchers' efforts to introduce flocculant-disinfectant, and even a local company's efforts to deliver mechanical filtration have all, for the most part, failed, attempts to scale up other purification technologies (i.e. Aquatabs, sand/rock filters, etc.) are likely to meet similar failures. One could even go as far as to say that in most circumstances, the technology that is introduced rarely matters. What weighs more heavily is the mechanism by which long-term behavior change–in this case utilizing the technology consistently–is achieved. With a vacuum of sustainable purification programs currently in place, Guatemalan households must resort to boiling their water, which is costly in terms of firewood, labor, and often increases exposure to indoor air pollution. EcoFiltro's technology, however, is unique in that it is low-cost, can be controlled at the household level, is similar in style to clay pots used traditionally for water storage, and does not change the taste of the water. Furthermore, their outreach strategies are novel, and when combined with sustainable, educational techniques to promote long-term behavior change, they could yield promising results.

2.3 EcoFiltro: A Social Enterprise for Water

2.3.1 The Filter and the Company

EcoFiltro is a local Guatemalan social business based in Antigua, Guatemala that produces ceramic water filters integrated with activated carbon, sawdust, and colloidal silver in the interior as neutralizing agents in order to produce drinkable water without an unpleasant taste or smell (EcoFiltro, 2020; Erickson et al., 2014). The clay base of the filter must be replaced every two years, while the dispensing container is durable. EcoFiltro works in all 22 departments of Guatemala and also operates throughout Central America (with the exception of Belize), Mexico, Peru, Venezuela, the United States, and the European Union (Barrera, 2019; EcoFiltro, 2020). The technology of the filter and production procedures are open-source, and EcoFiltro has trained teams from more than 60 countries to establish their own factories operated under their own local branding. It was originally designed by Fernando Mazariegos in 1981 as a family-run nonprofit, which received the World Bank's Marketplace Award for Sustainable Technology both in 2003 and 2004 (Revue Magazine, 2011). Mazariegos later partnered with entrepreneur Philip Wilson, who became CEO in 2009 and transformed the nonprofit into a thriving social business with a solidified, national distribution chain (*info*Dev, 2012). EcoFiltro was subsequently named one of the Top 50 Small and Medium Enterprises by *info*Dev in 2011, an international association that is sponsored by the World Bank, and was invited to participate in the 4th Global Forum on Innovation and Technology Entrepreneurship (Revue Magazine, 2011).

At the forum, EcoFiltro earned a spot as one of the Top 20 winners, being the only representative of Central America in both the Top 50 and Top 20 lists (*info*Dev, 2012).

Given the enterprise's deep market penetration in Guatemala and international success, it is a technology that has strong prospects for scaling. In Guatemala, EcoFiltro generates most of its profits by appealing to wealthy groups in urban areas by selling fashionable containers for the filters at higher prices. It reinvests all profits into the social arm of the business. This enables lower pricing of the basic filters for underprivileged communities and supports the network of local community workers as promoters (Figueredo & Chowdhury, 2019). The company has maintained a partnership with the Ministry of Education (MINEDUC), which facilitates the provision of EcoFiltro to schools throughout the country. Official statistics from the EcoFiltro website report that 5,473 schools have been reached through this program, corresponding to a total of 31,409 filters delivered to schools and 925,125 children impacted, all between 2014 and 2019 (EcoFiltro, 2020). Lean data field surveys conducted by the EcoFiltro Research Program have gathered information from 180 clients about the filter. For example, the main benefits that customers described from using the product include the taste of the water after being filtered and the economic gain of not having to buy bottled water or to collect or buy firewood to boil fetched water with. The surveys also showed an 80% overall satisfaction rate, including satisfaction with the taste of the filtered water ("Lean Data Field Surveys," 2018).

2.3.2 Issues with Community Outreach

In a technical report for EcoFiltro based on survey work completed by the 2015 NAPA-OT Field School in Antigua, Guatemala, researchers found that 87% of filter users in the sample self-reported both a reduction in the incidence of diarrhea and in household expenses–particularly with regards to purchasing water jugs and bottled water–due to the filter (Handojo et al., 2015). It is important to disclose that this self-reported data could have been affected by courtesy bias. However, it does not change the fact that the EcoFiltro has been found to remove 99.99% of *E. coli* through laboratory tests (EcoFiltro, 2020). Despite these findings, there are not enough community members trying the filter, and in low-income households that do adopt it, long-term retention rates are suboptimal. This could potentially be happening because the rural populations have a difficulty understanding the water purification benefits of a filter (Figueredo & Chowdhury, 2019). The lean data field surveys reported that 83% of the customers surveyed reported drinking water exclusively from the EcoFiltro, and 75% reported to be satisfied with the product overall. This means that beyond the suboptimal adoption rates, there are also minor issues with the consistency surrounding filter use and the overall acceptance of the filter.

The surveys also found several other potential reasons for why this trend is prevalent, even though the surveys did not include a specific instrument for directly assessing long-term filter retention. Product failure was reported by 11% of the clients who were interviewed, which explains why the filter was abandoned in those cases but may not explain the broader trend. One piece of data that could potentially make sense of these tendencies is the fact that 65% of clients who needed to replace the filter did not know where to purchase the new filtering unit. This taps into one of the major flaws currently affecting the company, which is the lack of an efficient system to quickly address broken pieces and remind customers how they can go about replacing their filtrating unit. Building from this finding, the surveys also found that most answers to open-ended questions revolved around a need for better customer service and a greater presence of EcoFiltro in their communities (“Lean Data Field Surveys,” 2018). The need to increase community engagement and improve customer service–particularly in cases of damaged product or filters than need replacements–is, therefore, a significant obstacle to EcoFiltro's efforts to introduce sustainable behavior change.

Many technologies that are introduced to rural Guatemalan communities are often met with a degree of distrust. From their perspective, many public health recommendations seem to disrupt their indigenous way of life--stemming from the long history of oppression towards indigenous communities. The CEO of EcoFiltro has often described how some rural households have even transitioned over time from using the filter to purify water to using the filter base as a trashcan. These observations have ultimately revealed that the enterprise needs to support its technology with: (1) education on the health impacts of contaminated water (which by itself is usually not sufficient to change behavior), (2) a more convincing format for demonstrating to communities the microbiological contamination that they need to address, and (3) mechanisms to strengthen EcoFiltro's presence in communities. Given that EcoFiltro community vendors all utilize a smartphone or tablet, there is an opportunity to capitalize on the device through a mHealth intervention that can help promote the use of the filter in the long-term.

2.4 Mobile Health (mHealth) Interventions in WaSH

2.4.1 mHealth Overview

Telemedicine and mobile health strategies have revolutionized the health sciences and provided innovative ways to collect data, promote healthy behaviors, and conduct follow-up. These strategies often function outside the context of a healthcare facility, building on the already popular eHealth services. The WHO's Global Observatory for eHealth (GOe) collected information on prominent mHealth strategies practiced in its 114 Member States, the most popular of 14 categories being health call centers (59%), emergency toll-free telephone services (55%), managing emergencies and disasters (54%), and mobile telemedicine (49%). When excluding the first three and considering the remaining 11 categories of interventions, the data has shown that around two-thirds of these programs are in the pilot or formative stage. While this may make it seem that these mHealth programs all undergo an evaluation process, only 12% of Member States reported carrying out results-based evaluations for their mHealth implementations (WHO, 2011).

As of today, there are many considerations for ensuring that mobile health technologies achieve their desired impacts. The implementation of frameworks such as the agile design-thinking approach could ensure that all mHealth programs undergo the strict evaluation process that is suggested above. Furthermore, the GOe also recommends that all interventions pay close attention to the handling of confidential client information, given that it is one of the main concerns that policymakers have when reviewing mobile health technologies (WHO, 2011). There is also discourse within the field of mHealth which suggest that interventions always frame their approaches with the long-term reliability of their end-users in mind, as well as the durability of the supply chains needed to sustain these technologies over time.

Within the field of WaSH, interventions utilizing mHealth aspects have become more common, particularly in the promotion of healthy water, sanitation, and hygiene practices. This entails that most mHealth programs in the field of WaSH fall under the classes of community mobilization and health promotion and raising public health awareness–according to the WHO's GOe data categories (WHO, 2011). This shift in approach can frame interventions as community-led behavior change instead of merely a set of recommendations along with the introduction of infrastructure, which does not necessarily guarantee long-term adoption or indicate meaningful community engagement. Exposure to media and electronic information can introduce recommendations more consistently while also making them easier to grasp and can henceforth be an active driver of behavior change and awareness. A 2019 study in Tanzania found that access to media, including mobile phones, radio, but particularly television, was positively associated with knowledge indicators around favorable water, sanitation, and hygiene practices. For example, the quantity of media exposure had a positive linear association with self-reported frequency of handwashing (Alexander et al., 2019). Future studies may need to rigorously evaluate whether media exposure changes handwashing behaviors in real life among other WaSH recommendations. Many of the educational interventions that happen in the field of WaSH may also benefit from capitalizing on technologies that have inevitably become more widely used, even in underprivileged communities.

A study that may point towards an affirmative answer was conducted by Markle and colleagues in Zambia, where community-led total sanitation (CLTS) programs and the local leaders conducting them were introduced to an mHealth delivery and monitoring system called CLTS M2W. The implementation allowed communities to assess their progress towards sanitation goals more comprehensibly and resulted in 1,500,000 new users registering for the sanitation program in only 18 months (Markle et al., 2017). An analog of this intervention could potentially be applied to the situation with EcoFiltro, with filter production creating demand for a water purification technology, but other components still needed to drive long-term behavior change.

2.4.2 Edutainment

Mobile health interventions are becoming increasingly reliant on edutainment techniques, a combination of education and entertainment, to capture the end-user’s attention and make the information presented more accessible. Edutainment has a lengthy history through traditional mass media like plays, radio, television, and film among others (Němec & Trna, 2007). The medium has historically offered education somewhat indirectly but has now come into the forefront of how educational interventions in global health are designed. An example of this is a randomized controlled trial called Project Accept, which was designed to test the efficacy of community mobilization, mobile voluntary counseling and testing, and post-test support services in reducing HIV incidence in three African countries and Thailand. The researchers introduced the community mobilization strategy mid-study, HIV/AIDS edutainment, which led to a considerable increase in the number of participants, particularly younger people (Kawichai et al., 2012). Another study in South Africa found similar results, in which edutainment techniques used by the Shout-It-Now (S-N) program were found to contribute to an increase in HIV counseling and testing rates over an 18-month period (Daniels et al., 2016).

2.4.3 Smartphone Applications

As more communities around the world obtain access to smartphones and similar devices, the use of these tools to improve health outcomes in those communities has embellished the mHealth field. For example, a systematic review conducted by Free et al. (2013) discovered that text-messaging interventions increased adherence to antiretroviral therapy in a low-income setting and smoking cessation in high-income environments. The authors suggested a stricter, randomized controlled trial (RCT) design with measured, objective primary outcomes in order to be able to establish a relationship between the mHealth program and the health of the beneficiaries. An important conclusion from this systematic review discusses how most mHealth interventions are one-dimensional (only using text-messaging or voice-messaging capabilities and no inclusion of other, potentially beneficial components). By making mHealth interventions multi-faceted, their effects on health behaviors, and the self-management of disease can be further elucidated. Most importantly, however, the authors even suggested the use of application software, which could result in a considerably interactive platform that is available on one's device at any time and could also have significant implications for health behaviors and disease management (Free et al., 2013).

Other more recent studies in the field of mHealth have built on the observations of Free et al., implementing more interventions in low and middle-income countries, "particularly in view of the high coverage of mobile technologies in these settings" (Free et al., 2013). For example, a study conducted in Bangladesh evaluated the process through which a mHealth approach was proposed for the delivery of a phone-based, cholera prevention WaSH program called CHoBI7--Cholera-Hospital-Based-Intervention-for-7-Days. They conducted interviews with government stakeholders to determine scalability and discovered support for the mHealth delivery format among diarrhea patients and their families. To fine-tune the text and voice messages delivered through the program, workshops were held to determine stakeholder preferences. Finally, a pilot implementation of the mHealth program revealed high user acceptability and how feasible it was to deliver the mHealth program to diarrhea patients arriving at a health facility in Bangladesh. Most of the trials evaluated in the Free et al. 2013 meta-analysis were involving text-messaging or voice-messaging technologies, but not the use of both concurrently. This echoes the need for more multi-faceted mHealth programs as suggested by Free and peers but also argues how mHealth programs should investigate the preferences of the communities they will be implemented--something that would be accounted for through an agile design-thinking framework (George et al., 2019) The agile development of an intervention essentially means that it is iteratively designed through end-user feedback and a user-centered approach.

An example of a multi-faceted mHealth intervention in Guatemala that applies an agile design-thinking framework of repeated evaluation is one in which Guatemalan midwives were introduced to a smartphone application that allowed them to conduct perinatal monitoring when connected to a 1-D Doppler. The goal of the intervention was to increase midwife referrals to a healthcare facility, and therefore increase births carried out in a facility. Through the agile design evaluation process, the application was designed to be understood by an illiterate population and employed vocal instructions, visual diagrams, a connection to a cloud of perinatal monitoring data, and the ability to contact a local ambulatory team. If the application cloud recognized any issues with the fetal heartbeat, it automatically contacted the ambulatory team so that the pregnant woman could be taken to the nearest hospital (Martinez et al., 2017). The bold use of a smartphone application's limitless potential as demonstrated by Martinez and colleagues could prove useful in relation to the situation with EcoFiltro. By creating a multi-faceted application through an agile design framework that could promote the use of the EcoFiltro in the long-term through various approaches (including real-time microscopy using the aforementioned Foldscope), one could address one aspect of the lack of sustainable health behaviors in Guatemala: the eventual abandonment of water purification technologies.

III. METHODS

To reiterate, the objectives of this study's quality improvement methods are: 1) to present a novel approach to water quality testing and 2) to co-design an application with EcoFiltro stakeholders and assess how it can or cannot further EcoFiltro's mission and goals. Since successful mHealth interventions require a rigorous, culturally sensitive development process, an iterative agile design process has been posed as an effective tool in creating such technologies through frequent rounds of evaluation by the benefactors and end-users (Wilson et al., 2018). The reasoning behind this user-centered design is explained in how "consumers often do not return to applications that do not immediately engage them, therefore undermining the intervention's potential effectiveness" (McCurdie et al., 2012). This is also seen in how around one quarter of all downloaded apps in 2010 were used only once (Localytics, 2011). Furthermore, healthcare technologies intended for the developing world carry with them additional considerations (Malkin, 2007).

The means by which agile design methodologies are created and analyzed have also been established in the past (Matthews et al., 2006). The pregnancy monitoring project by Martinez et al. is an example of agile development that was successfully implemented with a rural Maya population following a similar co-design process as this study (Martinez et al., 2017). The agile evaluation of the in-progress EcoFiltro application will be covered last in Section 3.3, while Section 3.2 will first detail the development of the various components that make up this application. My responsibilities within the project were to create the initial framework of the EcoFiltro application, pulling and creating content, communicating between the image recognition and microbiology experts, and communicating between the app programmer and EcoFiltro branding representatives.

3.1 Ethics

The proposal for this research was submitted to the Emory University Institutional Review Board (IRB) as a quality improvement study and, therefore, was exempt from IRB review (Grady, 2007). The study is considered quality improvement because the need for the technology was first identified by EcoFiltro to improve their community-based work. The only human subjects involved in the project were EcoFiltro staff and data collected from them was exclusively used to make revisions to the technology and protocols. No community members were involved in the project, though EcoFiltro field staff drew on their deep experience and knowledge of Guatemalan communities and culture to provide input on the prototypes.

3.2 Technology Development

The methods through which a mobile health technology intended to improve long-term adherence to the EcoFiltro is developed go far beyond what is captured within this dissertation (See Figure 2). Here I detail the formative phase of the technology's development up until the feedback received from the second round of interviews. This includes the structural application development, current microbiology protocols for the collection of water samples, and current image recognition processes to detect the presence or absence of enteric pathogens. Each of these components are in-progress due to how intertwined they are. Microbiology protocols and image recognition code must ultimately be finalized and integrated into the application in order for the technology to be truly complete. The application's educational content is also being reviewed by a design team from a company currently employed by EcoFiltro which handles the social enterprise's branding. In order to respect social distancing recommendations due to the COVID-19 pandemic, all work was conducted remotely with the exception of the microbiology and image recognition experts who regained access to their respective laboratories at the start of 2021.

Figure 2. *Phase chart showing the completed and ongoing components of this agile co-design endeavor.*

3.2.1 Application Development

The application that was co-designed with EcoFiltro staff is meant to provide communities with edutainment on water contamination, videos explaining the social enterprise and the filter, and additional features to support the company's customer service and community engagement. The development process yielded two separate applications: the version for EcoFiltro staff which included guidelines for water quality testing, and the community version which excluded this capability. While internet access is required in order to initially download the applications, all content is henceforth available when needed with the exception of external links. I created the overall structure of the application and, at the request of EcoFiltro, pulled visual content from the EcoFiltro website and official YouTube account.

In July 2020, one computer science student from the Universidad del Valle de Guatemala (UVG) was recruited to help build the educational and practical application for EcoFiltro and created the foundation for it using the React Native open-source mobile application framework. For the purposes of the initial, agile development of the technology, the information on the application was considered static or wire-framed. This entails that no application programming interface (API) is needed to store data on changes made to the foundation. Instead, the student employed an organization using consecutive sprints, or a sequence of targeted updates, on a Google spreadsheet with a corresponding Android Package (APK) of the application outputted to be used during interviews. This concept of sprints has been well-established as a methodology, particularly in the design of mobile applications (Knapp et al., 2016; Alrabaiah & Medina-Medina, 2021). For every new APK, the developer ran continuous integration (CI) tests using a shared Git repository from GitHub, which allowed for the errors to be identified quickly. During the agile design process for the app, I communicated all additions or changes to the UVG student through a Google document. While another student took over the original's work in December 2020, this process for communicating feedback from interviews and updating the application accordingly has been maintained.

Before the start of the alpha-tester interviews, the application consisted of a Home Page with four principal buttons a user could select (See Figure 3). The "Evaluate your water" button (on the top left) was a placeholder for the water testing capability that will only be part of the application's version made available to EcoFiltro staff, rather than community members. (Note: all titles and content appear in Spanish in the actual application.) The water quality testing technology was still in the early stages of development. The other principal buttons included an educational section on water contamination titled "Contaminated water and your health" (on the bottom left), an educational section on the EcoFiltro social enterprise and filter titled "About EcoFiltro" (on the top right), and a "Contact Us" page (on the bottom right) through which users can send queries and comments directly to the company and access EcoFiltro's Google Map of filter distribution points throughout Guatemala.

Through the "Contact Us" menu, users are asked to provide their name, phone number, email, and can optionally include their own EcoFiltro's code as well when they submit a message. This option is particularly important given that it creates the opportunity for EcoFiltro staff to send reminders on maintenance and unit replacements to clients with filter codes that were delivered after a certain amount of time. If users registered their information in the application settings, then messages sent through the "Contact Us" page would automatically include that data on the sender in the corresponding fields. Finally, the Home Page also incorporated a "User Settings" configuration page in the top right-hand corner, where users would be able to register their personal and filter information and change the language of the application. Although the application is currently only available in Spanish, we anticipate providing language functionality in the indigenous Mayan languages of Guatemala.

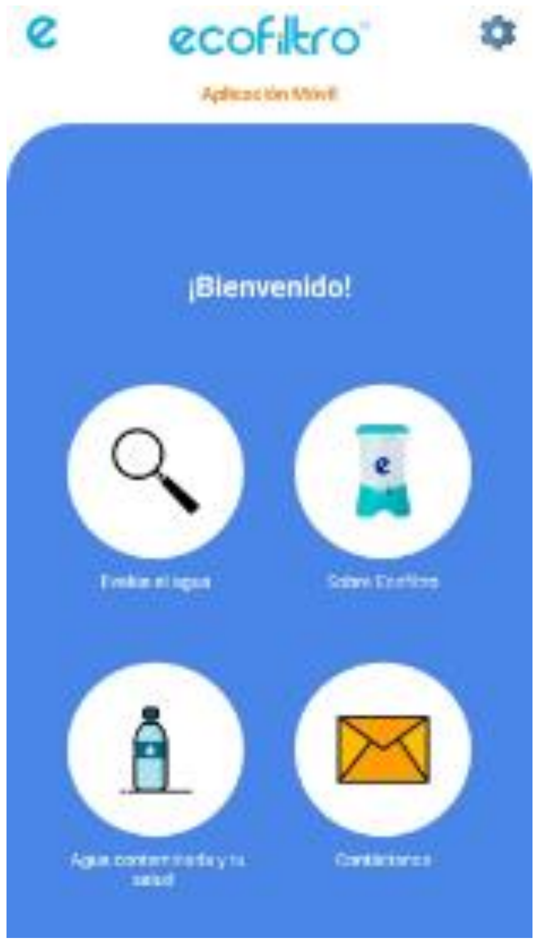

Figure 3. *The original Home Page of the EcoFiltro application*

The "Contaminated water and your health" section was comprised of three infographics that I created through the design software Canva and were each accompanied by their own audio narrative (which I also recorded) that could be activated by selecting on a megaphone icon in the top righthand corner of the infographic. The topics explored in these infographics were "Bacteria in the water," "Water and your health," and "Other contaminants." The "About EcoFiltro" section mainly consisted of official EcoFiltro videos, including one on filter installation, use, and maintenance, two family testimonials, one on the mechanisms behind the EcoFiltro's purification, and one on the workings of the social enterprise. The only non-videocentric subsection within "About EcoFiltro" was the all-important Frequently Asked Questions (FAQs), which also incorporated the megaphone icon and the corresponding recording for each question and answer. With the basic app layout described, I hope to make it clear how each round of interviews resulted in commensurate changes to the application as part of the agile co-design process.

3.2.2 Microbiology

In July 2020, one biochemistry student and two biochemistry faculty members from the Center of Studies in Biotechnology at UVG were recruited to create the water sample collection protocols that will, in the future, be followed by EcoFiltro field staff to implement the water quality testing portion of the app. The smartphone-compatible microscopy device that was initially used to take images of purified water and water contaminated with *E. coli* was the MagicZoom USB Microscope with adjustable magnification up to 1600X. After initial field and lab-based trials, the team decided to transition to the Foldscope due to its considerably lower cost and interference from the MagicZoom light's plastic rim in resulting images. This origami-based paper microscope and its resulting images have been validated in earlier studies (Cybulski et al., 2014). The Foldscope has a fixed magnification of 140X, a resolution of 2 microns, and unlike the MagicZoom camera, its lens is attached magnetically onto a smartphone's camera (Cybulski et al., 2014). The slight lack of robustness in the Foldscope is simply outweighed by its overwhelming inexpensiveness. If it is well taken care of, one can certainly be used in the long-term. As this transition between microscopy devices occurred, images of water samples continued to be compiled and the protocols for collecting those samples refined.

The refining of the protocols continues to evolve around the type of consumable supplies that would be necessary to collect, prepare, and analyze water samples in a resource-constrained environment (i.e. pipettes, glass slides, staining dyes, heat sources, etc.). The preliminary protocols-in Spanish–used during the second round of interviews are included (see Appendix). Initial test images using the MagicZoom revealed that crystal violet dye created microscopic images with greater texture than blue India ink; yet, India ink is more widely available in shops in Guatemala. Furthermore, as the Foldscope came into play, calibration images were taken using yeast samples, which in turn allowed the UVG student to determine that heat fixation (HF) resulted in higher-quality images than air-drying (AD) as the method of fixation. The degree of light exposure at the moment of image-capture also affected the texture and clarity of the bacteria in Foldscope images of diluted *E. coli*. Darkfield images were determined to have a clearer texture of the bacteria than brightfield images. Given that the protocols for obtaining quality microscopic images are still in the development phase, disposal protocols for a low-resource setting have not yet been determined. The team is committed to ensuring the protocol is as simple as possible for EcoFiltro field staff while yielding the highest possible quality of images.

While the microscopic images have informed the modifications to the protocols for preparing and photographing water samples, they have not yet directly fed into the training of an image recognition software that can identify bacterial contamination. This is where the microbiology team's focus has shifted. Images are now being taken from a variety of water sources, including Guatemala City tap water, bottled water, surface water, and water contaminated with *E. coli* cultures. Samples from these sources are now being photographed before and after passing through the EcoFiltro, which will help image recognition experts create a gradient of detection. Furthermore, all images of water samples taken using the Foldscope are replicated using a traditional light microscope to be able to compare the quality of images as well as the detection level between microscopy methods. Images of random materials and objects are also being compiled using the Foldscope, MagicZoom camera, and an optical microscope in order to offer an additional layer of comparison between microscopy devices. My task within this rigorous work was to compile and share images taken, coordinating the communication between the Guatemala City-based microbiology team and Atlanta-based image recognition experts.

3.2.3 Image Recognition

A feedback loop has essentially been in place in which image recognition experts communicate feedback to the microbiology team on the types of images they need in order to produce an image recognition software specific for EcoFiltro. All images that were taken and uploaded to a shared Emory University Box (and subsequently OneDrive) folder were later accessed by two faculty members from the Departments of Biomedical Informatics and Radiology at the Emory University School of Medicine. In order to develop a coded algorithm that can identify bacterial contamination of water samples, these image recognition experts used the aforementioned database by Zieliński and colleagues: DIBaS. The database contains a total of 660 images of 33 different species of bacteria, including 20 images for *E. coli* specifically (Zieliński et al., 2017). It allows experts to classify bacteria based on an image's texture, which is analyzed through machine learning (ML) and computer vision (CV) modules. When images go through a CV module, they are pre-processed and segmented, or divided into small pixels. These pixels produce a specific texture signature that is analyzed by an ML model which ultimately determines if a given pathogen is present or absent in the image by comparing it to images from the DIBaS database, which was similarly explored by Qu et al. (Tariq & Foroosh, 2016; Qu et al., 2019). This spectral analysis will be used on all images taken as part of the microbiology team's most recent endeavor.

As described previously, these image recognition strategies and microbiology procedures may experience difficulties in identifying specific bacterial pathogens based on morphology and size–especially given the fact that pathogenic and non-pathogenic *E. coli* look essentially identical. However, it definitely can still function to demonstrate visual evidence of microbiological contamination and a reduction in overall bacterial load before and after filtration. These challenges will be further explored as part of the ongoing, broader project, but are not evaluated in the groundwork laid out in this thesis.

3.3 Agile Design-Thinking Research Process

In order to iteratively co-design the app with end-users at EcoFiltro, 17 semi-structured interviews in total–divided between six in an alpha-tester phase in October/November 2020, and eleven in a beta-tester phase in January 2021–were conducted with different stakeholders at EcoFiltro, from community workers to the leadership team. The interviews focused on the end-user experience by introducing the content of the developed application to participants and exploring its potential effectiveness, accuracy, and feasibility to be integrated into EcoFiltro's mission and workflow. The two interview phases occurred as the technology began to take shape: 1) the alpha-tester participants were presented with only a community application (excluding the water quality testing capability); and 2) the beta-tester interviewees were able to see the staff application, focusing on a prototype of the water quality testing capability. As expected from an agile development and co-design process, having two rounds of interviews to explore and provide feedback on the technology prototypes allowed for important information about the end-user experience and preferences to be collected and acted upon in the technology development process.

3.3.1 Alpha- and Beta-tester Sample Characteristics

The sample of participants for the alpha-tester interviews included the CEO of the EcoFiltro, the former head of the company's education program, the leader of the company's rural field staff, and three rural field workers. The sample of participants for the beta-tester interviews included five other EcoFiltro rural field workers, two urban and periurban field workers, a representative from the design company Indigo currently employed by EcoFiltro, the company's commercial and administrative manager, the company's NGO sales supervisor, and a company accountant (See Table 1).

Table 1. Interview participant demographics per sample.

Demographics (n)	**Alpha-tester sample (n = 6)**	**Beta-tester sample (n = 11)**	**Complete sample (n = 17)**
Female, n (%)	2 (33)	3 (27)	5 (29)
Age, median (IQR)	34.5 (14)	31 (6)	31 (7)
Role, n (%)			
Management staff	2 (33)	3 (27)	5 (29)
Rural field workers	4 (67)	5 (45)	9 (53)
Urban field workers	0 (0)	2 (18)	2 (12)
Other key informants	0 (0)	1 (10)	1 (6)
Years at EcoFiltro, median (IQR)	7.5 (3)	5 (4)	5 (4.5)

3.3.2 Data Collection

Semi-structured, hour-long interviews formulated as a kind of tour of the application's version at the time were conducted individually via Zoom, with questions embedded at every point in the guide of the app. Alpha-tester interviewees were asked questions about each of the configurational and educational components of the community application, and how applicable they were to the sales and promotion of EcoFiltro. The participants provided feedback on the visual and audible content as well as its overall structure. Conversely, the beta-tester interviewees were asked questions more specifically about the water quality testing protocols and their feasibility since most of EcoFiltro's work happens in rural, low-resource settings. The educational content that was presented to the alpha-tester interviewees was introduced to the beta-tester participants as more of a supporting aspect to the water quality testing capability. The Zoom sessions were recorded to facilitate data capture and transcription.

3.3.3 Data Storage and Analysis

All Zoom interviews were recorded with the participant's verbal consent and stored securely in a single computer. Only the audio files that were outputted by Zoom were uploaded to the Google Drive folder already shared between members of the team. These audio files were transcribed. The de-identified transcripts replaced the audio files in the Google Drive folder as to further protect the confidentiality of the data. I reviewed the transcripts myself along with the Zoom video recordings to provide context of what was being discussed and developed codes of recurring themes in the data. Codes were independently verified by a review of selected transcripts by my project advisor. In accordance with the grounded theory approach, codes were based on the themes that emerged from the data without any bias towards desirable results or points (Corbin & Strauss, 1990). Representative and illustrative quotes from each code were extracted and are accompanied by screenshots of the corresponding change made to the application, if applicable. The results below are divided between the alpha-tester interviews and the beta-tester interviews.

IV. ALPHA-TESTER INTERVIEW RESULTS

The alpha-tester interviews focused on the overall structure, function, and supporting content of the application. While the water testing capability was mentioned during these interviews, there were no protocols or content related to this capability ready for review at the time. The feedback that emerged from the qualitative data was coded into the following categories: application revisions (including language norming suggestions, suggestions for adding or modifying existing content, and structural changes), long-term possibilities (including future additions, increased sales and community reach, and the water testing capability), and finally the culturally-appropriate design (including end-user engagement, the educational content, and engagement with the agile design process).

4.1 Application Revisions and Edits

4.1.1 Language Norming

Four of the alpha-tester participants provided suggestions for changing written terms or phrases at some point during the interview, particularly in the educational content. Two participants recognized problems with titling the testimonial video subsection of “About EcoFiltro” as “Experiences” (See Figure 4). Both suggested that this title be replaced with the word “Testimonials” (A1; A3). Three interviewees pointed out that noun articles should always be used in sentences and titles in Spanish (A2; A3; A5). One of them explained that “there are some little words that are eaten, right? So, articles like ‘los’ and ‘las,’ which are also important so that it [the noun] has a much more proper, stronger feeling” (A3). A participant also suggested that the word “EcoFiltro(s)” replace “filter(s)” wherever it is used in the application (A2). One interview resulted in the adding of the word “vomiting” along with “nausea” in the “Water and your health” infographic. The same interviewee also suggested that the same infographic “needs a correction at the top where it says 'Drinking or using dirty water [agua ensuciada].' The term 'ensuciada' is not correct. It can be ‘contaminated water’ or it can be ‘dirty water [agua sucia] with bacteria that can cause…’ either term but not ‘ensuciada’” (A3). This concern was echoed in another interview (A5). Discussion in one interview also led to the changing of the word “bacteria” to “microbes” wherever it was used in the application (A1).

Figure 4. *The altering of the testimonial video subsection title from “Experiences” to “Testimonials.”*

4.1.2 Additional Content and Tools

Five of the alpha-tester interviewees proposed the addition of new content or functions to the application. The clearest example of this was the suggestion to add a link to the digital EcoFiltro product catalog to the "About EcoFiltro" page (See Figure 6), "where people can see the different styles of EcoFiltro, their presentations, and the price" (A4). Another interviewee suggested that the "Contact Us" page should include fields for the "query date" and one "to measure location," to see "what kind of geographic space is most interested in [EcoFiltro]" (A3). Two other interviews also provided further feedback on the "Testimonials" page, one proposing that more videos be added, explaining that "people respect 'maestros', you know teachers or school directors, a lot here. So we would probably put a lot of them" (A1). The other participant suggested that a text entry option be added to the page in order to have new families provide their own written testimonials:

> "I'm not sure if there [in the Testimonials page] one could add maybe a written form for the family… Because it would also help us to collect information from the families that are introducing themselves to the use of the EcoFiltro… Asking the family like, 'Tell us your testimonial,' so that when I'm a user of EcoFiltro and have the application, I can have the experience of sharing how it went with my filter. Since these testimonials help us to have more support, right? Knowing that families are happy with it" (A5).

This same interviewee suggested that an image or phrase be added to the "Bacteria in the water" infographic as to indicate how "cesspools" and groundwater contamination can also affect wells that are commonly used as a source of water in Guatemala, especially given that "when the people from the [government] Health Center carry out water tests, they indeed show that the wells also have *E. coli*" (A5). Finally, another notable suggestion was the inclusion of an option to voice record a message within the "Contact Us" page (See Figure 5):

"Yeah I mean that would be ideal. The more ways that people can contact us and it's easy, the better. That's how we communicate with our rural team, it's mostly voice… [inaudible] A lot of times they're driving or on their motorcycles or… you know I get a lot of voice notes, that seems to be the *modus operandi* in rural Guatemala" (A1).

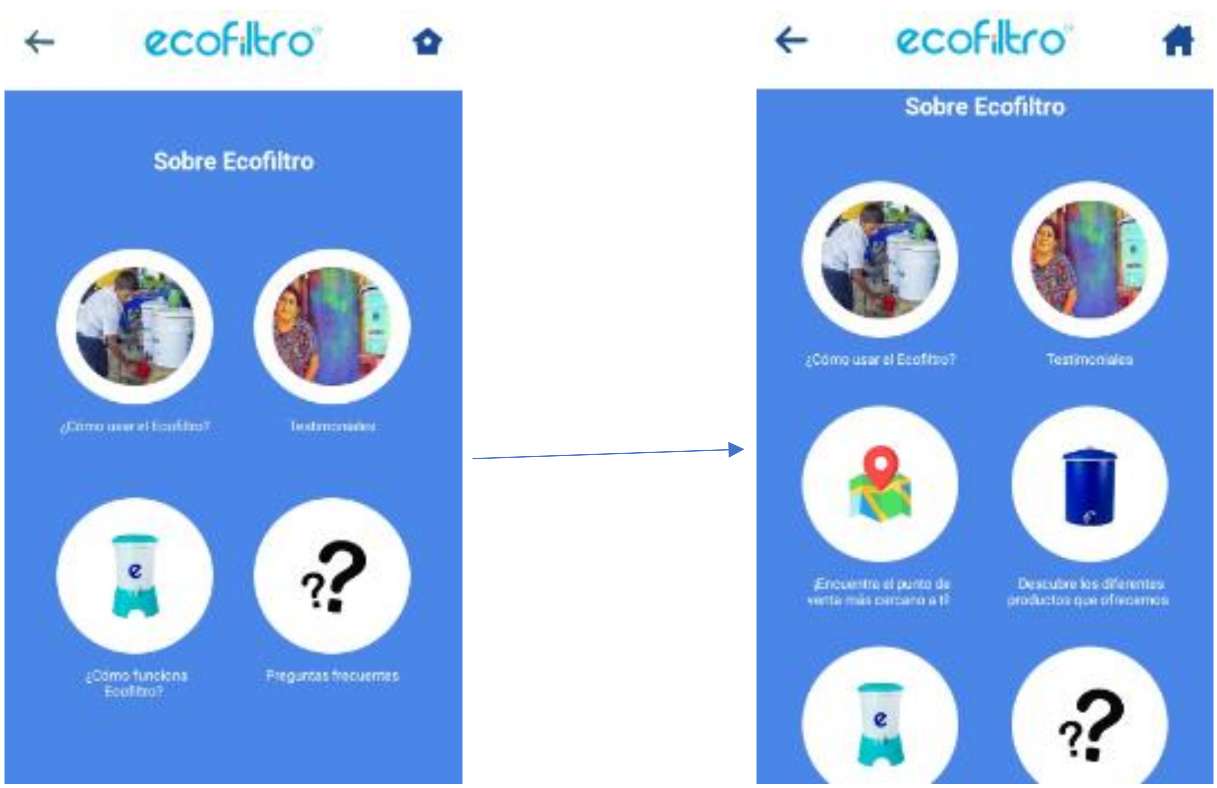

Figure 5. *Addition of a link to the digital EcoFiltro product catalog to the "About EcoFiltro" page (top), and the addition of an option to provide a voice note for the "Contact Us" messages (bottom).*

All of the feedback above was addressed with corresponding edits to the application. However, several suggestions are still being considered and discussed with EcoFiltro management staff. Examples of these include the ideas to add "a weight and height-for-age calculator" (such as the one created by the WHO), information on specific "gastrointestinal and parasitic diseases", and data on "how much is spent, for example, if a person gets sick" due to contaminated water–all to the "Water and your health" infographic (A2; A3; A2). One of these interviewees also suggested that the application include the laboratory test results that EcoFiltro undergoes every so often:

"Maybe… just to add a bit more: we send samples to be laboratory-tested every month. I'm not sure if you think that it is very important to not only have the WHO and PAHO parameters but like also to have something within the application that could take me to see the laboratory tests and update them as they are done? … They send samples to the laboratory, where they contaminate the water. This water passes through the EcoFiltro and after it does so then they take water from the container and analyze it, right? One before and one after. The water contaminated in the laboratory, and the water that comes out of the EcoFiltro" (A3).

One final recommendation for adding content that is still being discussed is within the "Other contaminants" infographic. Given that the infographic mentions plastic as a chemical pollutant, an interviewee proposed that another calculator be added in this subsection where the annual costs of buying water jugs and bottled water are made clear "so that they [clients] are conscious that at the end of 12 months… there is already an impact in their pockets" (A5). They elaborated that "families truly, at least in my area, live day by day, so we are not accustomed to making budgets for a year… By buying the EcoFiltro they can save that money" (A5).

4.1.3 Modifications to Existing Content and Tools

All alpha-tester interviewees had suggestions to modify the existing content of the application. Given that at the bottom of each "Contaminated water and your health" infographic, there is a link to the online WHO guidelines for drinking-water, one participant suggested that it should be made clear through written instructions what the underlined text is, "so that they know it's an external link" (A2). Similarly, this same interviewee along with another proposed the addition of a written explanation of what the link to the filter distribution point map actually was, such as "'Search for us in the map [below/above]'" or "'Where you can find us,' as a reference" (A2; A4). Furthermore, one of these participants also brought my attention to the fact that "sometimes they [community members] have a smartphone but they do not use an email," and suggested that I "make it an [optional} alternative" to the phone number in the "Contact Us" page (A4). This was addressed by removing the asterisk which indicated a requirement from the email field in the "Contact Us" page and would only be requested if no phone number was provided by the sender. Other minor improvements following the alpha-tester interviews included re-recording the audio narrative of the "Other contaminants" infographic so that it no longer had "an echo," changing the icon used in the Home Page bubble for "Contaminated water and your health" given that "a bottle is interpreted as purified water to drink," and making the megaphone icon that activates audio narratives larger because the participant "had not noticed it" (A2; A4: A5).

As with the suggestions for additional content, there are several that are still being explored and considered before taking a spot in the application. Three of the interviewees thought the video used in the "How to use the EcoFiltro" subsection of "About EcoFiltro," which showed a ladina EcoFiltro staff member, should be replaced with a more updated, animated one–using Caucasian characters (A3; A5; A6). Another participant also wanted to modify an image of *E. coli* in the "Bacteria in the water" infographic (See Figure 7), explaining that "it makes more sense, instead of one big bacteria, to have like a bunch--it freaks more people out when they see like a bunch of little bacteria than just one" (A1). The interviewee elaborated that "we want to let them know that there's, you know, thousands of colonies of bacteria in your water, you know if you're not purifying it" (A1). Finally, one other participant suggested that an image showing crossed-out eyes (See Figure 6)–indicating that one cannot observe the object with the naked eye–should be removed from the "Bacteria in the water" infographic because "the eyes are unnecessary–didactically speaking" (A2).

Figure 6. *Top portion of the "Bacteria in the water" infographic (now renamed the "Microbes in the water" infographic). The crossed-out eyes and E. coli image zoomed in from the magnifying glass are the ones that were being discussed by interviewees above.*

4.1.4 Structural Changes

More general modifications of the application framework were also brought up by four of the alpha-tester participants. Two interviewees thought that the order of the Home Page buttons should be altered as to have the issue presented first to them, followed by the solution (A5):

"So maybe what I would do on this Home Page would be to change/put the EcoFiltro icon in the corner where the contaminated water icon is--but this is just my idea--and the other one above. Why? To have the information of the solution at the bottom and the problem that people normally face at the top, right? So I would change it to: 'Water evaluation,' 'Contaminated water,' and then 'About EcoFiltro' and 'How to contact us'" (A2).

This same participant along with another also suggested that the filter distribution point map, originally present in the "Contact Us" page only, should also be included under the FAQ that specifically explains how to purchase the EcoFiltro, and in the "About EcoFiltro" page, respectively (A1; A2). The latter interviewee also thought that the testimonial videos should have their own place in the Home Page buttons. They elucidated that they "think a lot of people would go to it" (A1). "'How the EcoFiltro works,' I would move that to be first, to give you an example… and then later they would look at the installation," said one participant when observing the "About EcoFiltro" subsections (A5). One structural recommendation that is still being considered and discussed is the creation of completely separate applications for the urban and rural areas, respectively, and the use of differently designed materials for each demographic (A4).

4.2 Long-Term Potential Functions of the App

4.2.1 Future Additions

Several other recommendations were certainly valid but would ultimately depend on the finalization of the application or a longer process to introduce these materials to the software. Two alpha-tester interviewees described how the social enterprise was in the process of preparing short, "informative capsule videos," on a variety of topics, that could be incorporated "in different sections of the app" (A3; A1). The latter participant also suggested that once the application was finalized, a quick response (QR) code be introduced so that it could be easily downloaded:

> "We would have to figure out how to put it on the [delivery] box, you know because we distribute thousands and thousands of these. Would there be a way, like with a QR code, to download the app right off the box, you know because the most important thing is that it be used right?" (A1).

This interviewee also commented that the completed application could also be promoted by capitalizing on the company's "alliance with Guatemala.com," which has "1.3 million [followers] and a lot of them in rural areas" (A1). This same participant went on to describe EcoFiltro being "certified by the Ministry of Education," and how this would "be an easy way to share it to, you know, all the thousands of school directors in the country. And because we're accredited, then they can show our material to the students" (A1). This "accreditation with the Ministry of Education" and the ways in which the application could become a part of that was echoed in another interview (A2). A participant also considered that the audio narratives embedded throughout the application should be recorded by a professional, "a didactically pleasant voice so that people feel like they are much more awake and eager to listen" (A3). Finally, three interviewees expressed interest in creating translated versions of the application, particularly in "the Mayan languages: Kaqchikel, K'iche', Mam, Poqomam, and even Tz'utujil" (A6). Aside from suggestions to improve the application and maximize its impact, there were several additional themes that emerged from the data, which will now be discussed below.

4.2.2 Increased Sales and Community Reach

The application overall received a positive response from all participants in the alpha-tester interviews, who were eager to discuss how it would improve the sales of the filter, fit into existing company structures and processes, and push forward the EcoFiltro mission of reaching more Guatemalan families.

Sales Objective and EcoFiltro Mission: One interviewee responded to the question of how the application would further the mission of EcoFiltro by saying that it would help them in "reaching the goal of one million families" and could be used "as a sales tool as well" (A4). This objective of delivering as many filters as possible was reiterated when one asked “if through the ‘Contact Us’ page they [clients] could also order their EcoFiltro” (A5). In a similar manner, an interviewee explained that “when we go into ‘About EcoFiltro' I would probably kind of focus on where you can locate a distributor, you know, make it more commercial in that sense” (A1). They elaborated that this would be helpful “if people see that they have contaminated water and they’re like ‘Where can I fix it?’ And I’m like ‘Ok, here,’ we have 270 points now all over rural Guatemala where you can buy one” (A1). Other comments within this topic were more direct, describing how users “would use it [the application] to resolve queries and to sell,” and the application would allow them to “familiarize families with our brand” (A6; A5).

Compatibility with the Company: One particular quote from an alpha-tester interview perfectly encapsulates how most of these participants felt about the integration of the application into the EcoFiltro company:

> “In reality, people would install it [the application] in order to have like a manual, so to speak, once they are clients of EcoFiltro. Like a manual to answer their frequently asked questions, to have information directly saved on their phone because they will go into the application and will find everything they need… They will maybe no longer have that shyness of asking someone what EcoFiltro is, and instead they will get to know that on their own through the application” (A4).

Others focused on specific aspects of the application and how those would fall in line with processes in the company. For example, one participant described how “there’s a lot of back and forth, so we have a staff that all they do is respond to any contact request, so this [Contact Us page] would flow into their area” (A1). This same participant also admitted that “there might be some color changes” made to the application given that “there’s a brand book and we just have to respect the brand book" in order to fully assimilate the app with "the Facebook, the Instagram, the website" (A1). Another explained that the "User Settings" and "having people register themselves [with the EcoFiltro app] will help a lot… The phone number would also help us in the event that we need to contact the client" (A5). Finally, two interviewees also considered how the application would impact the EcoFiltro distributors throughout the country. One said "it could be useful for distributors. They could have an application specific to EcoFiltro, go into the catalog area, and show the images to a person they are selling to, or suggest to them that they download the application to know more about it" (A4). The other similarly explained that the application "has everything that we [at EcoFiltro] were hoping for, and the same goes with our distributors who have always asked us for materials. This is a good material for them" (A6).

4.2.3 The Water Testing Capability

Some participants also inquired more specifically about the Foldscope water evaluation component that was still in the early stages of development at the time but would theoretically allow EcoFiltro staff to test water at the point-of-use and also show microscopic images of water contamination to potential or current clients. One was particularly eager to see it come to fruition:

> "Excellent! And that's the problem right there. 'Water looks clear, why do I need a filter? Why should I filter it?' And that's where, you know, we've always talked about it right? … Having just an easy way to say 'Hey, I know the water looks clear but look what's in it'" (A1).

Another began to ask about the specifics of the technology, such as "with what method are you going to work this capability or how is that water evaluation going to work? … Will this only work on the microbiological and not with physicochemical analyses?" (A3). Finally, one participant gave a more detailed account of why they thought the water testing capability would assist them in their fieldwork:

> "That would help us a lot because when we are with a family, seeing the water that they consume, so they are a bit incredulous of the contamination part. Let's remember that these people's bodies, after being exposed to contaminated water, also create resistance, and when they do get sick it is at a smaller degree. For them, it is something normal. So if we have something more concrete, like something they can see, they're going to feel… or we're going to be able to take them to the reality that the water does indeed contain bacteria or contaminants… That would help us a lot… I find it interesting, for its application in the field" (A5).

Given these interests and the subsequent evolution of the Foldscope project, the following round of beta-tester interviews focused on the procedures around the microscopy-based water quality test, while the educational and supportive components were given less of a spotlight.

4.3 Culturally Appropriate Design for End-User Engagement

In addition, all alpha-tester interviewees praised either the educational content, the simplistic design of the app, or its cultural appropriateness, if not all three. They also engaged or hinted at future engagement with the agile development of the technology.

4.3.1 Simplicity

"I like that it's very simple, not too many buttons. You don't wanna lose people," said one of the participants (A1). "Less is better," they explained when discussing the infographics, "it doesn't seem cluttered and that's an icon [the megaphone] that everyone knows in Guatemala" (A1). In the same way, the word "simple" was used by three other alpha-tester participants to characterize either the entire application or a specific component (A2; A3; A4).

More elaborate reactions to the simplistic design included one participant saying the following about the Home Page:

> "It looks approachable because it has icons. Many times people will guide themselves more with icons, and not just with a text box or a button… They are sometimes more attracted to the icon than reading the text that is below it. It's easier" (A4).

This same interviewee also thought the application overall "guides us easily to what we are searching for or want to find" (A4). Another participant described how the purpose of the "User Settings" was "clear. They are the fields or items we need: name, phone, and email, filter code–which is the most logical, the fastest" (A3). "My impression [of the application]," said one, "is that it is very practical because it brings information about water and about our product" (A5). Finally, one other interviewee praised the limited use of words and sentences, "the phrases are short and that is what we want" (A6).

4.3.2 Cultural Accessibility

The majority of the participants were comfortable with the idea that an application–which needs to be accessed with a smartphone–would be introduced into largely resource-constrained areas in Guatemala. "We have handled other talks with another application," one explained, "and people in rural areas will rapidly download the app. I think the majority now have modern phones" (A6). This exact sentiment was echoed by another, saying that they "see a lot of potential [in the application] because it's what is in style and popular, it is what people have right now - phones with applications" (A2). However, it was contested by one interviewee, referring to how "in the rural areas, the principal problem is that not everyone has a smartphone, or in some where the majority do, the signal is a bit weak" (A4). The interviewee who recommended that a growth monitoring calculator and statistics on the cost of illness in Guatemala be added to the app justified their reasoning in the following way:

"Note that statistics work a lot. They really do… People who have children right now are people who already know how to read and write. Maybe it is not that they all like received higher education, but at least it is not as totally strange, right, the subject of reading" (A2).

Another expressed considerable support for the approach taken with the "Bacteria in the water" infographic:

"Yes, in the rural areas, as I was saying, where there are more stereotypes, right, and they are a bit more closed-off, the trainings and talks that are given are similar [to that infographic's content] so that families can understand better. So it does look very practical to me. The families no longer become alarmed when… one says 'poop.' It's not alarming but instead they are conscious that it produces contamination… It is not a text that is foreign to the culture… Culturally, it is acceptable" (A5).

Overall, the infographics on water contamination were found to be culturally sensitive, as explained here:

"So it is very clear, it is very specific. I love the graphic design because this is very understandable, not only for a child, but for people that do not know how to read or write, and that is very important, right? … I think that you did not make the application just for the sake of making it, but based yourselves in the cultural contexts, in the textual contexts, in the different ethnicities or the different geographies that exist in the country" (A3).

4.4 Approval of Educational Content

The two quotes above also indicated a degree of approval towards the infographics on water contamination, and the broader educational goals of the application. An additional interviewee stated that they were "even thinking about how we are going to use it, or how we are going to join it to the [Ministry of Education] school program to promote it there and have people download it" (A2). "The application, didactically, is very well-designed," said another, "what I love is the simplicity of the components and the way it is ordered didactically" (A3). One participant confirmed that the infographic on "Water and your health" was "something that we apply a lot in the field, the consequences of drinking contaminated water" (A4). Another expressed support for a variety of aspects in the infographics:

"Well, what I am seeing here is a reality, and with these drawings, yes it seems fine to me. And with this [megaphone], if you want to listen with sound, that as well, it is important… Everything is summarized. They are key words which the people can understand… This is great. These images indicate well what happens" (A6).

One of the previously cited interviewees also agreed with the focus given to the issue of water contamination:

"The educational part is very important… In fact, when I made sales presentations, little by little we understood that we did not even have to talk about the EcoFiltro so much, but rather about the problem of contamination, and how it affected people's lives. So obviously it subsequently takes you to present the EcoFiltro" (A2).

4.5 Agile Design Engagement

Finally, a few interviewees expressed interest in engaging with the application and updating the information that is included in it. One was confident that the entire application could be adopted and maintained by the company:

> "So [EcoFiltro] own[s] a tech company, and, you know, they… You know because we're [a] social enterprise, they give me like really good pricing, so I have an app person that could, you know, kind of take it over, maintain it, and update it" (A1).

This same participant expressed a similar trust in the use of the distribution point map, detailing how "the beautiful thing of a map is you can always be kind of, you know, modifying it, improving it, etc.–it's not like it's written in stone" (A1). Two others discussed and inquired about these updates to the map, and how they would reflect on the application. "How often will this be updated? In the event of a distributor dropping out," one asked (A3). The other explained what they thought would need to happen in that scenario:

> "And what we would do is that since Google takes about 15 days, I believe, to verify, to approve a [filter distribution] point... So, for example, if a distributor is unsubscribed, we remove it from the map, and those who are recruited... we also add them… To keep it as up-to-date as possible" (A2).

V. BETA-TESTER INTERVIEW RESULTS

The beta-tester interviews were carried out with a new sample of EcoFiltro staff, who were identified through snowball sampling based on the relevance of their role for field-testing. The beta-tester interviews also focused on the water testing capability and the preliminary field protocols that had been created using the Foldscope. If participants had any additional time to provide feedback, they were also able to briefly explore the educational and supportive content that was covered more comprehensively in the alpha-tester interviews. The qualitative data from this second round of interviews was coded in a similar way to the previous round, using the grounded-theory approach. Application edits and suggestions including language norming, additions, and modifications all returned as recurrent themes. The need for an appropriately handled design was again mentioned frequently, with a new theme around the clarity of the application's various functions emerging. Long-term possibilities for the app were also a pronounced subject (with a greater focus on community engagement), but broader considerations for the water-testing capability became a unique category that should be analyzed on its own.

5.1 Broader Considerations for the Water Testing Capability

Unlike the alpha-tester sample, the beta-tester interviews saw the water testing capability become the focus of most of the questions. Interviewees were presented with a video showing a colleague performing one of these water quality tests, and then dived into each protocol step more thoroughly. This allowed participants to give more detailed opinions about each of the water sampling protocol steps, as well as this testing capability overall.

5.1.1 Straightforwardness of the Procedures

Most interviewees thought the water sample preparation protocols were "clear" and "very straightforward" (B4; B2), and often had ideas for ways to support specific steps of the procedure in their own way:

> "Yes, it is not complicated at all. Find a table and one can start doing the tests. And to apply water [to wash the slide] at an angle, like cascading, one can utilize some type of water bottle, I think, in case we do not find any [clean] water nearby. Already carrying clean and disinfected water to be able to do that" (B1).

Participants thought that the images provided together with the written instructions were "very relevant" and "support what is written above them" (B2; B3). "Once we have all of the necessary resources to carry it [the test] out," they explained, "it can be done without any inconvenience" (B2). However, during the presentation of the third step, this same interviewee asked if the angled washing of the fixated sample would be done "with contaminated water," which means that it should be clarified in the written instructions that it should be completed with clean water (B2). Another participant described the procedure as being "easy and practical," and that "it does not seem to have many [potential] complications" (B3).

Given that the infographics used to show the three potential outcomes of the water quality test assume that there is a clear-cut division between the 'Positive, Negative, and Inconclusive Results', this same interviewee also inquired about whether there would be a certain "percentage for the water to be negative… the 'Negative Result'" (B1). They feared that some communities may interpret the "Negative Result" too straightforwardly "and perhaps there is something else that does not show in the sample, right?" (B1). On the other hand, another interviewee appreciated how the "Negative Result" graphic used the color green and was "synonymous to the green light… [meaning] it is good to drink" (B3).

5.1.2 Accounting for Resource-Constrained Environments and Communities

Some participants did have concerns with regards to specific steps, and how feasible it would actually be to carry them out in rural areas. For example, one interviewee identified several potential obstacles to the completion of a water quality test, including the possibility that "the person would not let the salesperson enter their house" (B4). The same participant also asked pertinent questions, all of which are being considered as the protocols are updated. This included questions such as what would happen “if the water has heavy materials [metals],” or whether the “syringe [included in the protocols], could… be reused?” (B4). Building on this factor, other interviewees acknowledged that having “sterilized” or brand-new, “packaged” equipment for the tests would increase the legitimacy of the process in the eyes of the communities (B2; B3). However, the most significant considerations by interviewees with regards to the water quality testing protocols also incorporated potential solutions:

> “I just have one question… for example, when one places the water on the glass slide and lets it dry, there for example, if there was dust, do you think that dust would ruin the sample? … Yes it’s because I see that inconvenience [occurring]... maybe using a box or kit [to cover the sample] or something like that where… or if the people or person would allow it to be performed, for example, inside a car I don’t know. Right? So that there is no contamination” (B4).

The idea of using “a container” to cover the sample was also echoed in another interview (B1). The comment also led the earlier participant to consider how such contamination could end up working against EcoFiltro and create distrust in the company, which is something that has wholeheartedly been taken into consideration:

> “The only thing I see as an inconvenience would be the dust. For example, if there was a lot of dust or that it could ruin the sample and cause the result to come out positive [despite it being filtered water from EcoFiltro], and people could generate distrust. That would be a point against [this procedure]... So not being able to close that sale because the test result was positive would be a bit… what a pity right? … There it would be a matter of having the salesperson explain ‘Look it came out negative [sic] because there is a lot of dust,’ I don’t know right? Because that is the only problem I see with this” (B4).

Given that the protocols require the EcoFiltro field staff to create darkfield images, meaning that they would need to find a certain balance between light and shade for the microscopy, several participants identified related drawbacks or confusions (B1; B3; B11). One of these explained that they would often be working "in places where we are very much outdoors, where we do have a lot of light," and "would need to move from one point to the shade, right, to be able to see that [microscopic] image well" (B1). In addition, they posed the idea that "a blanket" could be used to create the necessary shade, and that the glass slides should have a "mark" drawn into "their backsides" as to help field staff identify where to place the drop of water sample and dye, while "avoiding the contamination of the sample" (B1). This interviewee also considered how the "one [step] on the application of the drop of crystal violet [ink]" could be negatively affected by "one act of carelessness" where "one applies two drops, for example" (B1). They subsequently elaborated that "the rest [of the protocol] is indeed easy" for them and "well-explained (B1).

Conversely to many of the other participants, one interviewee saw more of a challenge in the water quality test's efficacy in urban centers, but thought it could serve to further reach these areas:

> "In [rural] communities it is a bit more noble… When one tells them that they have contaminated water and that it is necessary to buy the EcoFiltro to have secure water, they like accept it more. Where it is more complicated is in urban areas because there are many professionals, many teachers, many doctors, many nurses, so they ask questions. So I think that carrying out this practice in an urban area would be a good tool to convince them that they truly need to drink secure water, which is the EcoFiltro, right?" (B3).

5.1.3 Field Staff Training

As will be discussed in the future directions of the study, the project will move forward with preparing training sessions for EcoFiltro field staff to familiarize themselves more closely with the technology and testing procedure. Even so, many interviewees identified the need for such preparations without having mentioned them explicitly during the interviews. “I think these [protocol] steps are fine,” said one, “it would be a matter of training the person that will prepare the sample so that he/she also visualizes it and is present to see how it is done” (B4). Another participant also clarified that “more suggestions could emerge” once the application is “shown to us directly on our smartphone” (B1), which was brought up by others (B3; B8; B11).

Others acknowledged that the process would not be complicated “once we have practiced,” but it may be difficult “at the beginning” (B2; B3; B5; B10). “It looked very simple,” one elaborated, “but we would need to see it in the application [ourselves] and in real life… We would just need to wait to be able to begin applying it in the field” (B2). When asked about potential flaws in the app, this participant also mentioned that, “commonly, when we see that something is not going to work [in the field] and needs to change, we analyze it with the field team” (B2). An interviewee also explained that they would need to understand the procedure thoroughly, such as “what the materials are made of” or “what the dye does,” in order to “explain it to the client,” given that in “rural communities… when people do not know of something, they ask, they ask many questions” (B3).

5.2 Application Edits and Suggestions

All subcategories for the corresponding edits and suggestions section in the alpha-tester results were underlined here as well, albeit at a much smaller degree and with the exception of larger structural changes. Unlike the alpha-tester results, however, most of these suggestions are currently still being applied to the application. Therefore, even though all of these suggestions from the second round of interviews are being addressed or considered, there are few images to show how they are reflected on the application itself.

5.2.1 Language Norming

An interviewee suggested that the volume specifications in the first part of the initial step in the water sampling and testing protocols should be removed (See Figure 8). They felt that directing users to use "one drop" for the glass slide was enough and that the volume specification would over-complicate matters, explaining that "people get all 'No, there it says 100 milliliters.' And how do you know what 100 milliliters are?" (B4). This can potentially come into conflict with how WHO drinking-water guidelines on microbiological quality are standardized for a 100 mL sample. This same interviewee also believed that the graphic used to show a contaminated result for the water quality test could be misinterpreted by community members (see Figure 7):

> "Here [in the 'Positive Result' graphic] it is a bit confusing because it says the 'positive result' and that means that, what, it is not suitable to drink? That is a bit confusing to me because let's put it this way, remember that people in rural areas are barely accustomed to reading. So, for example, reading 'positive result,' [they could say] 'Ah! I can drink it' and that's it… [The image] could maybe be a glass of contaminated water" (B4).

While they did not provide any specific edits to make the title's intent clearer beyond changing the image, the title is currently being edited to "Contaminated Result" in order to be more direct.

Figure 7. *The first, unedited step of the water sample preparation protocols included in the "Evaluate your water" section of the application (left), and the unedited "Positive Result" graphic that would be shown to community members if their sampled water is contaminated (right).*

5.2.2 Additional Content and Tools

While this will be covered more comprehensively in the section on the sales objective of EcoFiltro staff below, an interviewee was eager to see a way to carry out transactions for the sale of EcoFiltro directly on the application. "Being able to charge [the user] at once or even sending the receipt and everything would be great," they explained, "I see this with a bit more of a sales perspective, because if people want something… a tool where the sale can be quicker" (B4). This participant also highlighted the importance of including a reminder for clients to replace the filtering unit every two years on the application itself:

> "Emphasizing that the filtering unit must be replaced every two years. That is something that I did not see… the emphasis on replacing the filtering unit. Maybe we could place it where it says "About EcoFiltro," because many people currently do not change, do not replace their filtrating unit because they think that the filter continues to work. And maybe it really does, right? EcoFiltro has ultimately shown that it does not only work for two years but

> there are units that are still doing well after four years. However, it also needs to be emphasized because not all waters are the same… Something like 'Renew every two years,' or 'Remember that your filtrating unit lasts two years.' I don't know something very simple but that emphasizes to the client that one must renew it every two years, because that is ultimately our motor, right?" (B4).

Furthermore, another interviewee gave suggestions for adding visual content within the water sampling protocols in order to make the written instructions clearer. For example, in the first step of the procedure, they recommended that "besides the [image of] the wells, maybe you could add the outline of a faucet with a container below it as well," since there are "the places where they use faucet water because they use a motor to take out well water" (B1).

5.2.3 Modifications to Existing Content and Tools

A few interviewees wanted further changes to be made to the icon showing a contaminated water jug used for the "Contaminated water and your health" Home Page button. One suggested that an icon of "a small river" should be used instead, or "something along those lines that is not as explicit as a contaminated water jug" (B4). One seemed to find the water jug image to be acceptable but suggested that it should be accompanied by "something else… given that it talks about health" (B1). Another simply was "not sure about what it [that section] is about" and thought that the image merely looked like a normal "water bottle" (B2). Furthermore, these same interviewees also found that the color scheme used on the "blue [background] box" on the Home Page did not fit that of the EcoFiltro brand book, with one suggesting that it "be made more or less with the color of the EcoFiltro letters, of the brand" (B4; B1). These two interviews also reiterated a point made by a few alpha-tester participants, where the video used for "How to use the EcoFiltro" should be replaced with "a new video about the use and maintenance," a "more updated one… with animations," which is currently still being considered

(B1; B4). This interview also led to the snowballing of the beta-tester sample with the recommendation that the person in charge of marketing and branding for EcoFiltro be interviewed as well.

With regards to the visual content in the water sampling steps, one the interviewees suggested that in the second step, the image used to allude to the crystal violet dye be replaced with one “of how the [actual] crystal violet looks like… the jar” (B1). They felt that this image should be accompanied by another showing “the dropper,” along with showing “one drop falling” (B1). This interviewee also considered that some animated images should be replaced with clearer, real-world images showing that part of the procedure. That includes the third step where staff would be required to wash the fixated water sample at an angle with clean water, the fifth step where the user must adjust the Foldscope’s levers and also zoom into the image accordingly, and sixth step where the staff would need to rotate the device with the Foldscope as to point away from the chosen light source (B1).

5.3 Long-Term Goals and Potential Functions of the App

While there were few suggestions for modifying or adding content that would require more long-term efforts and collaboration (which were largely brought up during the alpha-tester interviews), there was a considerably greater amount of brainstorming around how the application would fit into the company’s sales, community engagement, and overall corporate structure.

5.3.1 Sales Objective

As alluded to in one of the recommended additions above, an interviewee thought that building a function into the app with which to carry out a sales transaction “without the need for a printed catalog” was necessary (B4). This participant was particularly adamant with the idea:

"Look, I'm really focused on the sales area and I think that maybe having an application for sales would be great. I think that's what we are missing… the payment and billing. To have the client in front of me and be able to bill at that moment. Because remember that sometimes the sales are heated right? The people have the money, the availability, but the vendor does not have the means to charge them or bill them so the sale is lost, or [the client] goes to another point which is what, at the end as a vendor, one does not want, right? … Being able to promote the sale in that instant" (B4).

When asked how they would use the application, another interviewee described how it would support filter "distributors at the sales points" as well (B1), which was also mentioned by others (B2; B5; B11). A participant also spoke of plans at EcoFiltro that interestingly enough coincide with the sales objective described above as well as with the product catalog link already present in the app:

"Right now we are going to enter a system where we will be able to bill from the phone and automatically search for the [EcoFiltro] model that they [the client] ask for. So that we have access to the model because there are currently like 18 models of the EcoFiltro" (B3).

This participant also acknowledged that the water testing capability and "being able to instantly show the client that their water is contaminated would be a good hook to carry out a sale" (B3). They added that "the [rural] field staff would be able use it [the app] more so than the team in urban areas or those working on the business-end of things because over there, they sell mostly over the phone. So we sell more in person… we need a more focused explanation of how our product works" (B3).

5.3.2 Corporate Compatibility and Workload Relief

Interviewees in the second sample also reiterated many of the points made in the alpha-tester round about the application's compatibility with the company overall. In general, one interviewee mentioned that "everything you just showed me now [from the app] is exactly within the frame of what we manage [at EcoFiltro], this is the path we are taking and what we have been doing" (B3). They continued by saying that the application "will serve as great support, it will enrich and make what we do everyday more practical" (B3). This participant also considered that the "Evaluate your water" feature would fall nicely into the process that they normally go through with a potential client:

> "I feel like that "Evaluate your water" [button] is good because we [normally] start a sale through that [idea]. We start by asking the client what their water sources are, if its a faucet, river, lakes, or ravines where they obtain water to drink… Sometimes they tell us 'We boil our water,' so we talk to them about the cutting of trees, deforestation… how much they spend on wood everyday. And it depends on how they respond, but through that we are doing our [own] analysis, the evaluation in order to be able to give the solution to the client, eventually offering the EcoFiltro" (B3).

One participant also confirmed that the chosen repository for the "Contact Us" messages, the info@ecofiltro.com email, would work well. "For the time being, it is fine," they elaborated, "because as I was saying, at the end of the day, [an EcoFiltro staff member] receives the info messages, who is in charge of marketing, and they redirect them as well, right?" (B4). This same interviewee also made a case for why the app itself would relieve some of the workloads that EcoFiltro staff have:

> "I think it [the app] would help a lot because we get many calls just asking us to explain how the maintenance or how often the replacement happens to the client. So it would help greatly because people would no longer call [for that]... It would be a bit easier in that people would no longer pick up a phone or dial a number, and just see it or read it or listen to it. Because in the end, it is the same thing, except that there you are spending your [phone] balance, wasting your time, right?" (B4).

Another interviewee also touched on the enterprise's relationships with other NGOs in Guatemala, and ways in which the application could be "implemented so that the experts at the NGOs are also downloading it" (B1). They further explained that the experts would be able to "explain [the filter] well at the time that a [partner] NGO donates an EcoFiltro to a family" (B1).

5.3.3 Community Engagement

This section focuses more on how the application would contribute to the actual interactions that EcoFiltro has with Guatemalan communities. For example, one participant highlighted how they could use the application's educational content, explaining that "in the meetings and trainings that we do [in communities], we are always talking about water and what the World Health Organization mentions. So if this application has all of this information, we could be utilizing it as well to present it" (B1). This was also mentioned by other interviewees (B2; B6; B8; B10) and elaborated on by another interviewee with a focus on the previously mentioned accreditation by the Guatemalan Ministry of Education:

> "With regards to that [the integration to the Ministry of Education program], I think that it [the app] would be a very important tool because we would be reaching the parents, right? Not just the teachers, but the parents. I think that this would be generalized, no matter what area you are in as a collaborator, right? … In fact, now even elementary school children have a phone because of all that's happening with virtual classes. I think that the tool would reach

even the children… It could be a very interesting tool to use, and not just as collaborators, but also so that people can use it" (B4).

Another participant also referred to a "Week of Water" that happens at schools before EcoFiltro arrives to donate filers, and how "this information [in the app] could help teachers greatly" (B1). They then went on to describe how they could capitalize on the water testing capability in communities as well, particularly in schools:

"In the meetings at schools that we have with families, one step is focused on sales. So they are asked about the state of the water in their community. And after we get a response from these people and proceed to wrap up the [topic on] contaminated water, we could use the application, this water testing [to say] 'Oh look at the state of the water here in the school,' right? Which is what the children are drinking if it is not being treated. And since it is not much time, we are talking about five extra minutes from the activity, we can be conversing as the [water] sampling is being done… Afterward showing it to see how it ended up, I'd say" (B1).

This was echoed by the earlier interview, where they thought the water testing capability "would take advantage of bringing evidence that the filter does indeed filter. Maybe after the [community] talks, being able to show it, a way to verify that the water comes out purified" (B4). Other participants also highlighted this benefit, particularly one that mentioned that community members "see their water as being very clear or very clean with the naked eye, but they do not really know the state of the water, if it is contaminated or not" (B2). "The only way to show them [the contamination] quickly," they elaborated, "would be using the application, the water sampling [feature] … and that can also give them much more confidence to buy or acquire the EcoFiltro" (B2). They also mentioned that "there are community leaders, COCODES [referring to community development councils], or even in schools where the director asks us, 'Can we test a sample here?' … So that the families or the community members understand the water is contaminated" (B2). The fact that community members ask for "instantaneous" water quality tests was repeated in another interview (B3). Similarly, this participant expanded on that point by saying that "there are curious people. I think people who are curious and want to know if the water is truly contaminated will want us to share the application with them" (B2).

One participant also described "an [EcoFiltro] manual where there are research activities that children can do or ask questions about water to engage their parents with," and was eager "to see if there was a way to include the [app] information in the manual" (B1). Conversely, they also considered including the manual content in the app, explaining that they "give a copy [of the manual] to a [school] director who then makes copies for the teachers, but if it is already in the app then like [we could say], 'Just download this'" (B1). The participant emphasized the manual activity where students perform an "interview" with their "father, mother, or another person" on their water, and how "it [the app] can be included in these activities… showing it to their families and having a bit more awareness around needing to use a method of water purification" (B1). Raising awareness of water contamination among children was a frequent comment in the beta-tester interviews (B2; B3; B5; B10). One of these participants was "excited" to use the water testing capability to "show people" the contamination of their water, "this time with deeds and not words" (B3).

5.4 Appropriate End-User Design

Important comments on the simplicity and cultural appropriateness of the application, as well as how it fits with the company's branding, were also frequent in this sample. This time, however, they were extended more broadly to the application as a whole rather than just the educational content. Furthermore, an additional code for the clarity of the app's various functions was created.

5.4.1 Simplicity and Clarity of Functionalities

Similar to the alpha-tester sample, most beta-tester interviewees commented on how the application was designed in a very straightforward and "practical" manner (B3). "It looks like it will be easy to use," said a participant, "one can select the images and continue on to the next page" (B1). Another interviewee thought an infographic was "clear because the language is not complicated, meaning the language is good," and how "the application in itself is good, even the sales points and everything, it is easier for the user" (B4). A different participant appreciated how the audio narratives of the infographic are "in tune with the images" (B3). They elaborated that the educational content is "practical. I mean what we need is something practical, because I feel that this explanation is not boring… besides gaining knowledge, it is fun because it has images" (B3). The structure of the application overall was complimented as being easy to follow in several interviews (B1; B2; B3; B5; B6; B10; B11). One of these interviewees also mentioned that the app "is what we need in the company, right, something that is instantaneous, something that you enter and already have the answer for the client," (B3), which was echoed by others (B4; B8; B10).

As will be discussed in the sections below, the fact that interviewees confirmed how the gear icon used for the "User Settings" button would indeed be identified by users is an indication of the clarity of that particular function and was repeated in other interviews (B2; B3; B6; B11). An interview also reassured the clarity of the application's messaging feature, explaining that "it is clear to me… I understand what [the app] can help me with, and… the client can also send their comments" (B1). An interviewee also confirmed that the megaphone icon's purpose in the infographics–activating the audio narratives–was clear given that it “means sound” (B3). In general, clients described the application as being “clear, easy,” and “understandable” (B2; B3; B5; B6; B8; B10; B11).

5.4.2 Cultural Appropriateness

Many of the language norming recommendations above are clear indications of places where the application could improve in order to make it more appropriate for both the community end-users and the EcoFiltro staff who will be using it during their work. The interviewee who suggested that the “Positive Result” graphic (which is used at the end of the water quality test) be modified did, however, acknowledge that the educational infographics were appropriate on numerous occasions. “For me,” they explained, “the description [in the ‘Bacteria in the water’ infographic] is very good because, at the end of the day, what we want is to reach those places where the people do not know what water contamination is” (B4). Overall, they thought that the infographic “images are very good, they are well-described,” and also appreciated the “Other contaminants’ content and how “it would bring awareness so that people do not pollute with trash” (B4). A different participant also confirmed that community members would indeed be able to identify the configurations icon used for the “User Settings”:

> “The majority of families or people now use WhatsApp, so there they more or less already identify, ‘Ah this is the configuration’ [by looking at a gear icon]. And each phone also, when one is searching for the configuration, the settings, that [icon] also appears on the screen” (B1).

This reiterated in another interview (B4). Furthermore, with regards to introducing the application to the EcoFiltro school program, one of these participants also confirmed that “all teachers have their smartphone” and “the [school] directors can be presented [with the app content] on their computer" (B1). They elaborated that having school teachers download the application "would not be hard for them at all, right, maybe it would only cost them in terms of their phone data, for example" (B1). A different interview appreciated how the application would allow vendors to respect the busy lives of community members while fulfilling one of their major needs:

> "For me, this is a material for instant support… Look, when one talks with a client, there are many clients that are rushed, who do not have time to listen to you. So in a brief amount of minutes, we need to tell them what they need, and immediately show them what the solution is and what they need to follow in order to solve the problem [of water contamination]. Obviously no one wants to drink contaminated water, no one wants to waste their money on bottled water or water jugs, so they need a solution. So I think that this [app] material will serve as great support for us" (B3).

5.4.3 EcoFiltro Branding

While the application received a positive response, many interviewees stressed that the application would need to incorporate more accurate branding to fall in line with the graphic design used in EcoFiltro regularly. This eventually led to the inclusion of the company's head of marketing, as well as a representative from a design team that was hired by EcoFiltro to handle branding, in the beta-tester sample. The aforementioned suggestion to modify the Home Page's background design is an example of what led to the snowballing of the sample. "For me, it [the app] is complete," said one participant, "there are just a few things about the design that would need to change… following the [company's] line of graphic design" (B4). An interviewee, however, thought that the color scheme used in the Home Page looked "fine" (B2), and another also thought that the graphic design "coincides" with the EcoFiltro branding (B3).

Furthermore, one of the interviews was conducted after another participant recommended that a representative of a design company hired by EcoFiltro to manage the company's branding be interviewed as well. The interview was fruitful and resulted in the sharing of APK materials with the design company so that it could they could be "edited in accordance with the EcoFiltro brand book" (See Figure 8) (B9). Below is an example of how the protocol steps and water quality test result from Figure 8 were transformed into the new application design.

Figure 8. *The edited first step of the water sampling protocols (left), and the edited "Positive Result" graphic (right).*

VI. DISCUSSION

6.1 Individual End-Users

6.1.1 EcoFiltro Staff Members

The interview subjects identified several benefits that they could foresee with using the application in the future, particularly the water testing capability. By the end of both rounds of interviews, it was rather well-established that the content in the app fit precisely into the work that these staff members (especially the field team) already do routinely. This supports the success of the agile development of the application, and the importance of a user-centered design as determined in previous publications (Wilson et al., 2018; McCurdie et al., 2012). Unlike many applications in the study by Localytics in 2011–which found that around a quarter of apps downloaded in 2010 were used only once (Localytics, 2011)–the app development team in this project can be relatively sure that the technology will be adopted and used recurringly by EcoFiltro staff members. EcoFiltro leadership have committed to implementing the app in the company workflow for field visits. Successful future adoption was also indicated in several interviews that acknowledged how the app and the water testing capability filled major gaps in the field team's efforts in rural communities: the lack of comprehensive community engagement by EcoFiltro and community awareness around the contamination of their water sources. Even in the alpha-tester interviews, where the water quality testing button was merely hinted at, participants were already drawn to the project and eager to see it implemented in the field. Furthermore, it is important to remember that all EcoFiltro staff members have a smartphone or tablet provided by the company with which to access the application.

The topic of workload relief and providing "instant" support to the work that these employees do in Guatemala was especially motivating and indicative that the technology development carried their interests in mind (B3; B4). A small example of this was how the "Contact Us" page would allow many of the messages and queries that the management and field staff receive to be channeled into one medium which, at the same time, registers the client's relevant information along with their message. Participants liked to set up hypothetical situations where they repeatedly used the phrase, "Download this," to show several instances in which the application would facilitate explanations that they would normally have to do by word of mouth. Staff who work in the field clearly anticipate that convincing communities to use the EcoFiltro is a challenge due to the lack of concrete information and evidence that they can provide, in the moment, around water contamination. It was surprising to see many interviewees understand the water sampling protocols relatively well despite the virtual format of the meetings, albeit with a frequently mentioned condition that they be properly trained in the use of the Foldscope and the application overall. Their openness to learn more from the technology's development team is even further proof of the company's engagement with the agile design of the application and their commitment to implementing it in their work. In brief, it is clear the desired end-user experience specific to EcoFiltro staff was accurately captured through the preliminary prototypes of the app presented in these interviews.

6.1.2 Community Members

From the information that the knowledgeable EcoFiltro workers provided during the interviews, there are a few points that can be made with regards to the end-users in communities–particularly rural areas. The various language norming suggestions that were made by interviewees not only speak to their engagement with the agile development of the technology but also to the importance of colloquial language in communicating important concepts to largely illiterate populations. The fact the simplicity of the language and the overall design was frequently praised by the participants is also indicative of this. The significance of using colloquial terminology and simplistic language in health interventions employing edutainment has been supported across various contexts (Castle et al., 2002; Annapoorni & Devi, 2002). Furthermore, the cultural sensitivity with which the educational infographics were approached was also reflective of the considerations posed in previous work on mobile health technologies in developing contexts (Malkin, 2007). As described above, the comments from EcoFiltro staff alluded to the fact that the water testing capability and the educational content in the application would create instantaneous awareness for community members on the state of their water. This, in turn, has the potential to increase Guatemalan rural communities' confidence in EcoFiltro and lead individuals to not only purchase it, but also use it consistently. There is also an increased use of mobile phones (including smartphones or similar handheld devices) in rural areas. A 2018 study found that there was no significant difference between the proportions of urban and rural Guatemalan mothers who owned mobile phones (Domek et al., 2018). This further supports the fact that the community application will likely be accessible even in rural areas and has the potential to be successful in this demographic as well.

6.2 Ramifications for the EcoFiltro Social Enterprise

6.2.1 High Compatibility and Acceptance

Beyond having compatibility with the work that individual field workers do all over the country, it seems that the application will fit nicely into the corporate structure of the EcoFiltro company overall. This is indicated by the alpha- and beta-tester comments around the use of the "Contact Us" page, but also in the desire to have a QR code for the app advertised on EcoFiltro products, the integration of EcoFiltro educational materials already in use, and in development by staff, and the potential to extend the application to EcoFiltro's external NGO partners as well. There was not a single interview in both rounds of evaluation in which a participant was not enthusiastic about the incorporation of the application into the EcoFiltro model. As discussed in Section 6.1.1, many interviewees identified the topics of the educational content as being things that they were already sharing with communities during their talks and school programs in rural areas. This ensures that a transition from presenting concepts around water contamination either by word of mouth or through printed materials to using the application in their place will be somewhat seamless. Furthermore, the application interface has the potential to introduce much-needed reminders on the replacement of the filtering unit and can function as a medium to improve the customer service provided by EcoFiltro.

6.2.2 Building on the EcoFiltro Model

Many interviewees mentioned how the various EcoFiltro distributors spread across the country would benefit greatly from the application, and how it could ultimately help them close sales and spread more awareness about the issue of water contamination and the solution presented by the company. This established distribution chain is truly something unique to EcoFiltro and could be what allows the Foldscope project to become a success. The application's inclusion of Google Maps showing the geographical location of all these distributors can further facilitate this, as mentioned in the data. Sharing the application with distributors could create a much higher degree of community engagement, which is what several clients expressed as something that was lacking in the EcoFiltro model ("Lean Data Field Surveys," 2018). The efficacy of the company's accreditation by the Ministry of Education and the resulting school programs could be significantly improved. Through the use of the Foldscope, this is possible given that a few interviews mentioned how school directors and community leaders would often ask the field workers about the possibility of carrying out water quality tests right then and there. In summary, the qualitative data shows that the EcoFiltro model has a lot to gain from the use of this mobile health technology.

6.3 Contribution to Global WaSH

6.3.1 Novel Approach to Water Quality Testing

The several studies cited in Section 2.2.4 explored the use of microscopy along with image recognition as a viable tool to carry out water quality testing (Ephraim et al., 2015; Holmström et al., 2017; Breslauer et al., 2009). However, some of these studies used a microscopy device that was far too elaborate or expensive for rural fieldwork and all of them required that image analyses be run on hardware that is separate from the microscopy–meaning that these did not actually constitute strictly as point-of-use testing. Furthermore, explorations of WaSH interventions that do indeed rely only on the use of handheld devices (Free et al., 2013; George et al., 2019) did not explore potential applications to water quality testing through the use of low-cost microscopy. Although this quality improvement did not necessarily produce a working prototype of its water testing capability, it introduced this novel intersection between handheld devices, low-cost microscopy, and IR code that is directly integrated into the device's software. There have been no previous studies that explore the possibility of carrying out affordable water quality testing exclusively at the point-of-use through these methods. The potential applications of such a technology are seemingly endless within the fields of microbiology and WaSH. Even though this project focuses on the detection of *E. coli*, the use of the DIBaS database (Zieliński et al., 2017) opens up an entire world of possibilities and enteric pathogens that could be identified through the use of the Foldscope. For the technology to reach such an aspirational level, however, the working prototype must be completed, and rigorous evaluation is needed to determine if it is an efficacious and feasible, point-of-use water quality testing method.

6.3.2 Potential for Scaling Up Water Purification

As mentioned in Section 6.2.2, the uniqueness of EcoFiltro's local manufacturing of filters and well-established supply distribution chain really lends itself to further expansion. Unlike attempts by the Guatemalan government to scale up chlorination, or attempts by researchers to scale up the use of flocculant-disinfectant (Chiller et al., 2006; Luby et al., 2008), the taste of water purified through the EcoFiltro is unchanged and the wide-reaching distribution chain permits for effective scaling, potentially even to the national level. This indicates that these factors are pertinent to the scaling up of water purification in Guatemala, but such findings could be extrapolated to similar contexts in Latin America and around the world, especially through leveraging EcoFiltro's wide global reach. Given that the 2015 NAPA-OT Field School discovered that EcoFiltro clients did indeed notice a decrease in the incidence of diarrhea (Handojo et al., 2015), the scaling up of the EcoFiltro can truly have monumental effects on the burden of diarrheal disease in Guatemala specifically, but potentially elsewhere too. The Foldscope component of the application can also provide the much-needed visual evidence of water contamination to further justify the use of a water purification technology. Therefore, this novel approach to water quality testing may in fact have a direct effect on the use of water purification strategies worldwide. Nevertheless, as discussed above, this ultimately depends on a stricter evaluation of the water testing capability in the coming months.

VII. LIMITATIONS

The COVID-19 pandemic introduced obvious challenges to the agile co-design process, and changed the format of the interviews. The alpha-tester interviews (and sections of the beta-tester interviews that were subsequently conserved) were not affected too greatly because of the Zoom feature that allows one to share a device's screen during the meeting. This led to an accurate depiction of the end-user's experience when browsing through the educational and configurational content as well as the messaging feature. On the other hand, the section of the beta-tester interview focusing on the water testing capability depended heavily on the participants' observation of the sampling process, and how the microscopy tool fit into the protocols and was used concurrently with the Android devices they are familiar with. For example, it would have been productive to show the Foldscope to EcoFiltro staff in person, demonstrating how it connected to their device and resulted in microscopic images taken on the phone or tablet's camera. Furthermore, the water testing protocols themselves could have been performed in front of the interviewee so that they had a clearer idea of how a contaminated water sample could be observed and analyzed more thoroughly using only one's device. This was somewhat accounted for by the preparation of a video showing the UVG microbiology student performing the water quality test, and by briefly showing the Foldscope's coupling to an Android smartphone during the virtual meeting. However, the overall quality of the interaction with EcoFiltro staff during the beta-tester interviews through Zoom meetings was subpar. In-person interviews could have resulted in a greater understanding of the technology's components and purpose and, therefore, may have yielded more specifications and recommendations around the protocols.

Social distancing guidelines also forced microbiology labs at UVG and the bioinformatics labs at the Emory School of Medicine to close, largely during the Fall 2020 semester. This moderately delayed the production of precise water sample preparation protocols, seeing as the microbiology component's progress largely hinged on the delivery of bacterial cultures and other required materials to the respective student's home. The pace at which the microscopic images were being taken and analyzed by the image recognition team was, therefore, affected and reflected in the preliminary protocols presented during the beta-tester interviews. For example, specifications around the type of consumable equipment that would be provided to the EcoFiltro field staff were rather vague, which, as discussed above, several beta-tester participants touched on. Even though these circumstances were out of our control, they did limit the extent to which beta-tester participants understood the preliminary protocols and the workings of the image recognition strategy–beyond already having to meet virtually rather than in person.

There are also limitations to the water quality testing strategy overall. As mentioned in the background and methods, it will certainly be difficult to create a gradient of detection through image recognition given that pathogenic and non-pathogenic strains of particular bacterial species often look identical. The specificity, sensitivity, accuracy, and limit of detection with regards to the image recognition strategy will need to be thoroughly evaluated in the coming months. If not, the risk of false negative results may give EcoFiltro clients a false sense of security and can endanger the entire enterprise. However, even if this technology cannot be relied on as a measure of water safety, it can still be used to show EcoFiltro clients what bacteria in aqueous environments look like through microscopy. If in the near future, the project fails to develop a working detection method for pathogenic *E. coli*, the Foldscope can still be paired with other established point-of-use water quality testing methods, such as the H:S water quality test, Compartment Bag test, or the Colilert presence/absence test, which involve a color change which would be a visual confirmation of water contamination (Islam et al., 2017; Aquagenx, 2021; IDEXX, n.d.).

Nonetheless, the sample size was also relatively small. If more EcoFiltro staff members and community stakeholders could have been included, more considerations for the application could have been identified. Furthermore, the results from this quality improvement study should genuinely be interpreted with attention towards who the interviewees were. While EcoFiltro leadership and field staff have years of experience working in rural Guatemalan areas, they are not necessarily representative of the community end-users for which the educational objective of the project is intended. Therefore, to truly evaluate the cultural appropriateness and acceptability of the application in indigenous Maya populations, the project will need to finalize a working prototype of the application and pilot the technology in these communities, with EcoFiltro field staff as the delivery method. This will require that EcoFiltro field staff be familiarized more thoroughly with the technology and trained accordingly, which was also mentioned in some beta-tester interviews and is essentially where the project is headed next.

VIII. FUTURE DIRECTIONS

Over the next two months, the compiling of microscopic images on a variety of water sources–including water contaminated with *E. coli* cultures, and using both the Foldscope and a traditional optical microscope–will continue. These will be analyzed by the image recognition experts and used to continue creating the AI algorithm which will enable the detection of *E. coli* in water samples. The team will hopefully produce a working prototype of the application with the water testing capability by the end of May 2021. Over an eight-week period throughout June and July, this prototype will undergo a second agile co-design process through which it will be field-tested with EcoFiltro community workers in Guatemala. The first two weeks will focus on the training of EcoFiltro staff with regards to the application itself, water sampling protocols, and how to capture an appropriate microscopic image. During the following month, I will shadow EcoFiltro field staff during their work and observe their approach to the water testing procedure. Images that are taken by the field staff will be shared with the Atlanta-based image recognition experts, who will run laboratory comparisons of community water samples between the Foldscope and traditional microscopy using the established ML and CV models.

This will hopefully culminate in the development and finalization of the *E. coli* detection algorithm by the end of July. As the algorithm is being prepared, user-feedback interviews with EcoFiltro staff will resume throughout the eight weeks. This will allow for agile updates to be made to the application, water sampling protocols, and training materials as they are recommended. Furthermore, another subset of the team will work alongside EcoFiltro leadership to determine the scale of the future pilot implementation during the first two weeks of June. During the rest of the summer, they will then proceed to develop more detailed plans for the pilot implementation as well as the metrics for how it will be evaluated. The implementation will likely take place during the Fall of 2021, through which community end-user data will also be collected as part of the technology's evaluation. The findings of the pilot implementation will ultimately determine how the project evolves from there, though the results of the work done over the summer may adjust this timeline.

IX. CONCLUSION

The results from the two rounds of semi-structured interviews suggest that the EcoFiltro application has a high degree of compatibility and acceptability within the company's employees and leadership. The educational content seems to coincide with what EcoFiltro field workers are already applying in the field, and the various recommendations and suggested edits indicate a high level of engagement with the agile co-design process of the technology. Leadership and employees both recognize that the use of the application's content and in-development water testing capability will address two major issues that the company has faced in recent years: lack of community awareness on water contamination and poor customer service and community engagement. As identified by several interviewees, the application interface can function to include reminders about filtering unit replacements and has the potential to result in increased confidence in EcoFiltro as well as increased filter uptake.

The wider use of the EcoFiltro can ultimately reduce the burden of diarrheal disease in the country, which is bolstered by how the application takes advantage of the social enterprise's nationwide distribution chain. With the aid of the application in promoting the use of the filter on a national scale, the social enterprise and the app together can potentially disrupt the cycle of child undernutrition and growth stunting in Guatemala given that drinking water sources are a significant pathway of exposure to fecal contamination. The novel method for water quality testing presented in this dissertation may serve as a foundation for new approaches to community-based water quality monitoring and facilitate safe water provision in low-resourced environments. The Foldscope and application's AI-based pathogen detection have the potential to be adopted rather easily across various settings (with some context-specific considerations) and can be fundamentally used to provide visual evidence of water contamination worldwide. This, in turn, can encourage the use of other water purification strategies around the world with similar potential for scaling as the EcoFiltro social enterprise.

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Appendix

Preliminary Water Sampling and Analysis Protocols

Universidad del Valle de Guatemala

Facultad de Ciencias y Humanidades

Departamento de Bioquímica y Microbiología

Tecnología de bajo costo para educación y pruebas en el punto-de-uso sobre la calidad del agua: Aspecto microbiológico.

Práctica Profesional

María Gabriela Croissiert Muguercia

Universidad del Valle de Guatemala Prácticas Profesionales	Procedimiento Operativo Estandarizado	POE: Versión: Primera Fecha: 3 de diciembre de 2020
		Páginas Totales:

	“Tecnología de bajo costo para educación y pruebas en el punto-de-uso sobre la calidad del agua”	**Autores:** María Gabriela Croissiert, Muguercia **Revisado por:** M.Sc. Yunuen Soto

1. **Propósito**
   1.1. Diseñar un método de microscopía de bajo costo para la detección de *Escherichia coli* como organismo indicador de contaminación en el agua consumo.
   1.2. Generar una base de datos con imágenes de muestras de agua para el entrenamiento de un algoritmo basado en machine learning que facilite la detección de *Escherichia coli*.

2. **Aplicación**
   2.1. A nivel mundial, se considera que la exposición a patógenos microbianos transmitidos por las haces es uno de los principales riesgos a la salud humana vinculados al consumo de agua contaminada. Por lo tanto, la detección de organismos microscópicos constituye un indicador útil en el control de la calidad del agua. Sin embargo, los precios de las pruebas microbiológicas de la calidad del agua pueden ser de hasta $31, lo que se traduce a un costo prohibitivo en ambientes de bajos recursos. Los instrumentos de microscopía han tenido un rol importante en la detección de patógenos, pero poseen un costo elevado y su empleo in situ es restringido. Como una alternativa, se han comercializado instrumentos de microscopía de bajo costo. Dentro de ellos cabe resaltar el desarrollo del foldoscopio, cuyo diseño se basa en las estructuras de origami, y los microscopios digitales.

3. **Referencias**

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4. **Terminología y abreviaciones**
   4.1 Foldoscopio: microscopio de papel de bajo costo que ofrece una magnificación de 140X y una resolución de 2 micrones.

5. **Documentos asociados**
   - NA

6. **Seguridad**
   - Lavar las manos apropiadamente posterior a la manipulación de la muestra de agua y el desarrollo del ensayo de detección de microorganismos.

7. **Equipos materiales y reactivos**
   8.1. Reactivos
   8.1.1. Cristal violeta

   8.2. Cristalería
   8.2.1. Portaobjetos

   8.3. Materiales y equipo
   8.3.1. Foldoscopio
   8.3.2. Dispositivo móvil

8.3.3. Fuente de luz artificial
8.3.4. Encendedor

9. Procedimiento

9.1. Toma y fijación de la muestra

9.1.1. Tomar una muestra de 100mL del agua que se desea analizar en una botella de agua limpia
9.1.2. Colocar una gota de la muestra en un cubreobjeto

Figura 1. Muestra colocada sobre el portaobjeto.

9.1.3. Dejar secar la gota al aire libre.
9.1.4. Aplicar calor con un encendedor en la parte inferior del portaobjeto durante 3 segundos.
9.1.5. Colocar una gota de cristal violeta en la muestra y dejar actuar durante 1 minuto.

Figura 2. Tinción de la muestra con una gota de cristal violeta

9.1.6. Lavar con agua corriente, dejando deslizar el agua por el portaobjeto. Evite dejar caer el agua directamente sobre la muestra.
9.1.7. Eliminar el exceso de agua sobre el portaobjeto con una toalla de papel. Evite pasar el papel sobre la muestra fijada.
9.1.8. Dejar secar completamente la muestra al aire libre.

Figura 3. Muestra teñida con cristal violeta

9.2. Observación en foldoscopio

9.2.1. Colocar el portaobjeto en el foldoscopio, asegurando que el sitio sobre el cual se fijó la muestra quede hacia el lado donde se encuentra en lente.
9.2.2. Colocar el foldoscopio en la extensión magnética previamente adherida a la cámara del dispositivo electrónico.
9.2.3. Colocar el foldoscopio a unos 10 cm de la fuente de luz.
9.2.4. Enfocar la muestra desplazando la rampa de enfoque hacia la izquierda o derecha, según sea necesario.

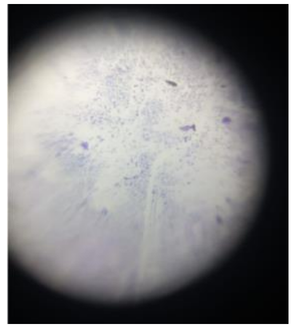

Figura 4. Observación de la muestra empleando el foldoscopio acoplado al dispositivo móvil (140X)

9.2.5. Aumentar la magnificación manualmente del dispositivo móvil.

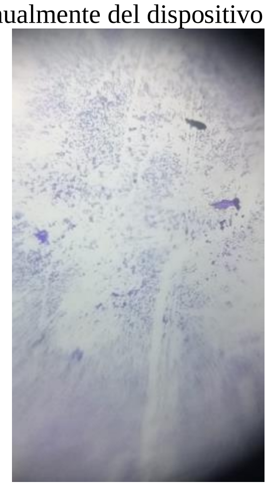

Figura 5. Observación de la muestra empleando el foldoscopio (280X)

9.2.6. Cuando observe claramente la sección teñida de violeta, gire el foldoscopio alrededor de la fuente de luz con el fin de oscurecer el fondo de la imagen.

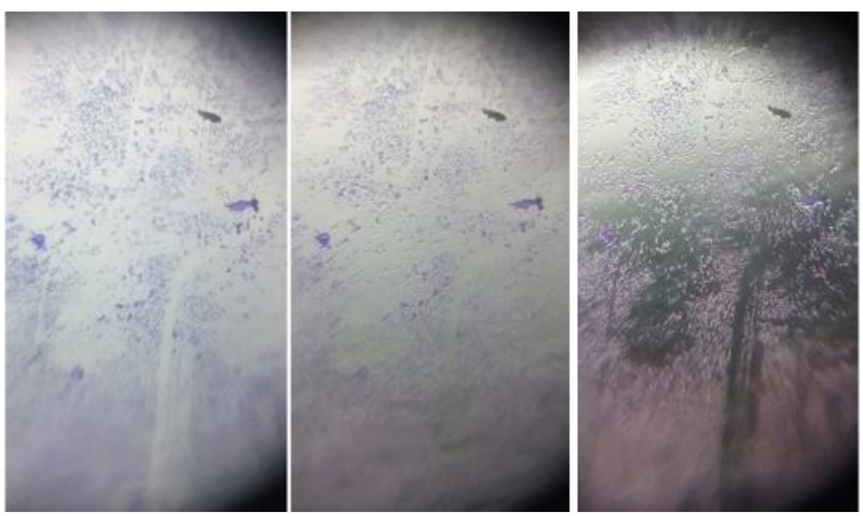

Figura 6. Proceso de oscurecimiento del campo del foldoscopio (280X)

9.2.7. Si es necesario mejorar la calidad de la imagen, cambiar sutilmente la posición del foldoscopio respecto al dispositivo móvil y/o moviendo la rampa de enfoque

Figura 7. Enfoque de la muestra mediante el ajuste de la posición del foldoscopio respecto al dispositivo móvil (280X)

9.2.8. Tomar la imagen

10. Cálculos: NA

11. Control de calidad

11.1. Análisis bioinformático de las imágenes

12. Reporte de datos y documentos utilizados

13. Reporte: NA