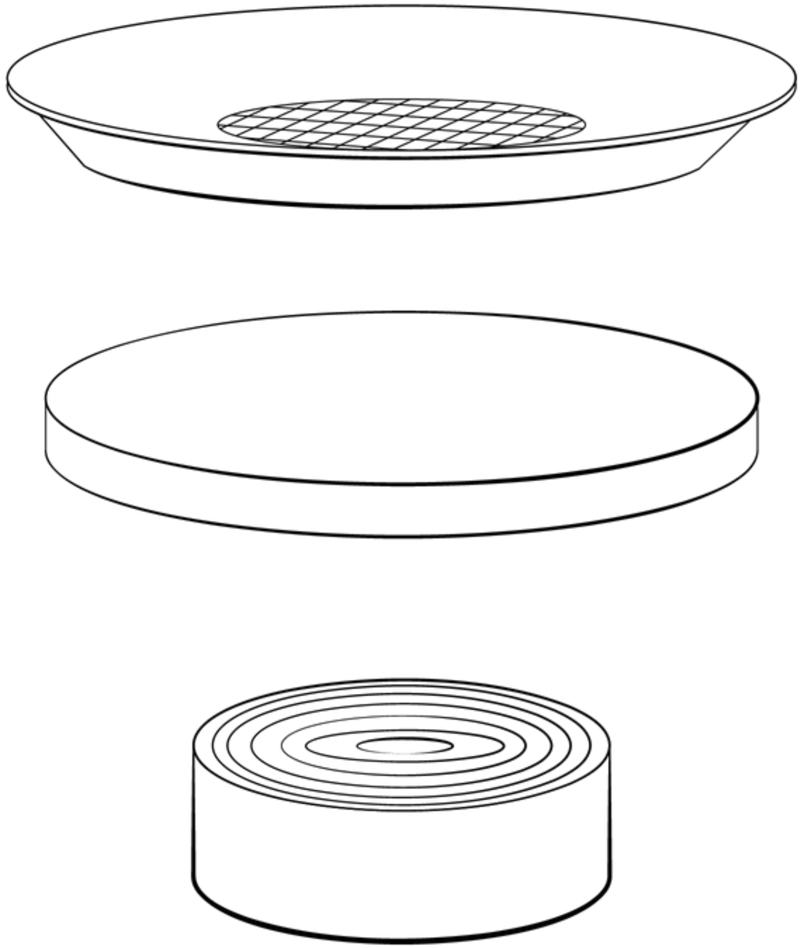
Xylem Water Filtration



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David Wenner Master's Thesis
Collaboration with Alexandre Vacher

Degree Project for Master of Fine Arts in Design,
Main Field of Study Industrial Design, from Lund
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Abstract

This project explored the usage and effectiveness of a natural water filtration system using xylem from Picea Abies, or Norway Spruce.

The project is concentrated on the region of southeast and south Asia where people suffer from water contamination, providing a concept of a water filter with comprehensive protection against waterborne diseases. The study implemented secondary research on product design, material selection, conceptual testing and followed by filtration system design.

The filter successfully filtered challenged test water, leaving a clear liquid free from dirt. Additional filters were introduced, such as ceramic and metal filters to filter larger particles to prolong the lifespan of the wood filter. A solution to tackle the natural variation of the wood filter, a flexible silicone socket was developed.

The final design housed all filters within a box, making it possible for easy cleaning and replacement. The product was designed to exhibit a clinical look to emphasize cleanliness, precision, and functionality. A color coding system guided users in assembly, with red indicating the dirty water entrance and blue indicating the exit of clean water. Materials considered for construction included recyclable, durable aluminum and transparent plastic, each with its advantages and drawbacks.

The product is powered by solar energy and uses a pay-as-you-go model, offering affordability and scalability. The system includes a microcontroller that alerts for filter replacements and manages the system's operation.

Potential areas of further research include real-world water testing for quality verification, addressing leakage issues, understanding the influence of cultural contexts on product acceptance, and exploring the potential benefits of pressure integration in the system. While the system performed well under controlled conditions, its effectiveness in real-world scenarios and under varying operational pressures remains to be tested.

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Efficiency For Access Design Challenge

Introduction

The project is part of the Efficiency for Access Design Challenge, a global competition, that encourages university students to accelerate clean energy access by creating affordable, high-performing off-grid appliances and technologies. Students worldwide collaborate on designing innovative solutions for off- and weak-grid settings. The brief aims to deepen understanding of clean energy access and solar appliances to guide project framing and solution design.

Approximately 789 million people lack access to electricity and essential electric appliances, while an estimated 441 million have gained access since 2010. However, by 2030, 670 million people will still be without electricity. Amid a climate crisis, biodiversity decline, and cost of living challenges, it's crucial to enhance renewable energy-based modern energy services and develop accessible appliances for solar home and mini-grid systems. Co-creating and designing products with the end-users in mind can address global energy access inequalities. All students are free to select an area to work with. The themes have previously been in agriculture, power management, cooking, healthcare, refrigeration, and water and sanitation. This project has focused on water and sanitation.

Reflection

The challenge of this project is designing a product for a culture and socioeconomic context different from our own. We were unable to meet the end users in person, and our understanding of their needs and circumstances relies largely on secondary sources.

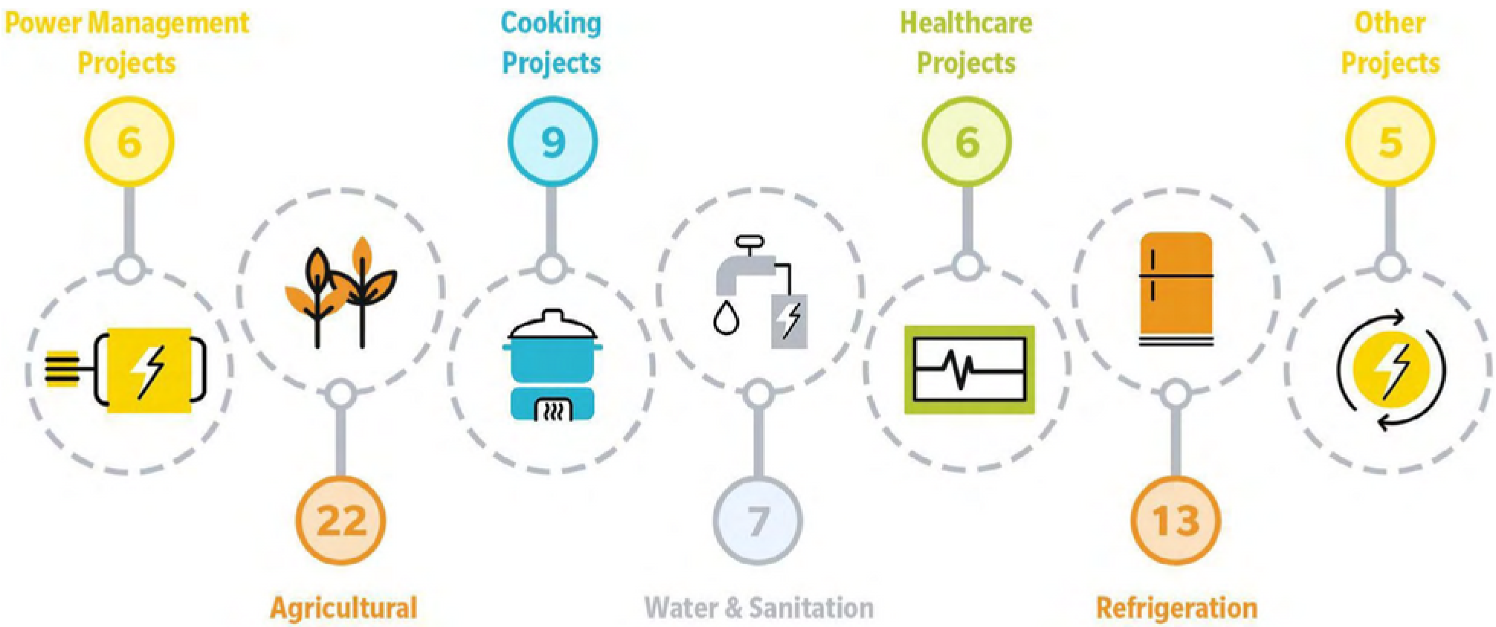
Reflecting on this, we understand the importance of cultural sensitivity. Different cultures have varying norms, customs, and beliefs that may affect how our product is received and used. To design a product that is not only well-received but also effectively used, it is important to understand the cultural context of the communities we aim to serve.

This project is not about economic exploitation, but rather about helping to build an infrastructure that empowers the local population to thrive. We wish for the community to be active participants in both the design and implementation process. We are mindful of the potential environmental impact of our product and aim to ensure that it is not only efficient and effective, but also environmentally responsible. We were not able to meet the end user within this project, which is something that would be valuable to understand more about the setting the product will be used in.

EFFICIENCY FOR ACCESS




EFA



(Efficiency for Access)

Problem Statement

According to GBD 2016, diarrheal Disease Collaborators, (2018) diarrhea caused over 1.6 million deaths, it was identified as the eighth leading cause of death worldwide. It ranked as the fifth leading cause of death among children under the age of 5 and was responsible for 446,000 deaths. Rotavirus was found to be the leading cause of diarrheal mortality in all age groups, where unsafe sanitation and water were the primary risk factors for diarrhea. Diarrhea disproportionately affects regions with limited access to healthcare, safe water, and sanitation, and low-income or marginalized populations. South Asia and sub-Saharan Africa accounted for approximately 90% of diarrheal deaths in 2016.

Water Game Plan country, area or territory	Population (thousands)	% urban	NATIONAL					Population without access (using surface or unimproved)	Proportion of population using improved water supplies						Priority because of poor access to water (over 24 % of Pop or over 8 million people with unimproved or surface water access)	Priority country because of water quality issues	Priority country because of fragile context/ protracted emergency	Water scarcity/high climate risks Remarks (no added countries)
			At least basic	Limited (more than 30 mins)	Unimproved	Surface water	Surface + unimproved		Safely managed	Accessible on premises	Available when needed	Free from contamination	Piped	Non-piped				
Bangladesh	164,670	36	97	2	<1	<1	-1	2,371	55	78	-	55	15	84		x		x
China	1,409,517	58	93	<1	6	<1	-7	89,091	-	92	90	-	76	18	x			x
India	1,339,180	34	93	<1	6	<1	-7	87,862	-	63	82	-	44	50	x	x		x
Myanmar	53,371	30	82	<1	9	9	18	9,727	-	55	-	-	25	57	x			x

UNICEF's Water Game Plan report, 2020, focused on 4 countries

Stunting

According to Exemplars of Global Health (2022.), stunting occurs when a child does not develop and grow to their full potential due to insufficient nutrition. The effects of stunting are long-lasting and non-reversible, leading to poor health, reduced cognitive abilities, and lower educational outcomes. (Exemplars of Global Health, 2022.).

Our World in Data (2022), highlights that stunting occurs when a child can not absorb nutrition, which is common during diarrheal diseases caused by poor drinking water, health, and sanitation. To avoid illnesses like these, people must have access to clean water to drink and for sanitation purposes.

Bangladesh - 97% have access to at least basic clean water
China - 93% have access to at least basic clean water
India - 93% have access to at least basic clean water
Myanmar - 82% have access to at least basic clean water

User Group

According to UNICEF's Water Game Plan report, published in 2020, which strives to attain universal access to safe and sustainable water services for all by the year 2030, the region for our target group was identified. The focus area is in the South Asia region, including Bangladesh, China, India, and Myanmar, where these regions face challenges such as inadequate infrastructure, limited access to clean water sources, water pollution, and a high prevalence of waterborne diseases. According to UNICEF, 81 to 92 percent of the population in this region has access to safe drinking water, leaving up to 19% without. The population consists of about 2 billion people, meaning about 126 million people are in need of clean drinking water where 102 million are based in rural areas. The region is experiencing increased weather events such as flooding, landslides, and damage to water and sanitation systems due to the impact of climate change, resulting in negative effects on health. It is projected that the regions of India and Bangladesh, particularly the dry and semi-dry areas, will also face the impact of droughts in the future.

Contamination

In the report by World Bank Group (2018), it is stated that nearly 4 million people, or less than 3% of Bangladesh's population, use unimproved water sources such as ponds, rivers, streams, or unprotected wells and springs, while the majority relies on groundwater infrastructure. About 90% use tube wells, which may not filter all contaminants. Piped water, often accessible to wealthier urban populations, provides convenience and centralized regulation but still faces over 80% E. coli contamination, similar to ponds and streams. Only 39% have access to uncontaminated, on-premise water sources, and less than 2% to contamination-free piped water. Poor hygiene practices are also prevalent, with just 28% having access to a handwashing station with water and soap, contributing to disease and contamination.

People collecting water from a communal well

Surface water such as from a river or spring

Buying water from informal water vendors

Using rainwater harvesting systems

Water Filtration Technologies

A comparison was made to understand what types of water filters there are available on the market today. We intended to get an overview and select a suitable water filtration system for the chosen scenario. The screening process had requirements such as; Protection against waterborne disease, a flow rate of about 10-50L /day to match our user, repairable, locally sourced, affordable to produce, environmentally safe, and easy to maintain. These criteria were selected with keeping our user group in mind, and the 17 SDG goals as well as 'leave no one behind'.

Solar stills

A low-cost and low-energy, using only direct sunlight for providing drinking water. The water is evaporated and collected, where studies have shown that it is capable of desalination of seawater. Solar stills have been proven effective in filtering bacteria and viruses (Hamwi et al. 2022; Tiago do Nascimento et al. 2018).

Reverse Osmosis (RO)

A water-cleaning technique capable of removing minerals, ions, and pathogens by passing it through a semipermeable membrane under pressure. It is capable of desalination. It has a high capacity and could support a larger population of drinking water, but at the same time is relatively high energy-intensive. RO systems are a practical and cost-effective option for addressing water scarcity in small-scale operations with limited access to electricity (Maftouh et al. 2022). Various forms of water treatment systems, such as microfiltration, ultrafiltration, and nanofiltration, are highly efficient in removing bacteria, protozoa, and viruses, with nanofiltration being the most effective and microfiltration being effective against bacteria and protozoa (Centers for Disease Control and Prevention, 2008).

UV Disinfection

By using LED to emit a specific wavelength, or through direct sunlight, water can be treated. UV disrupts waterborne pathogens' DNA and eliminates them from the water. The method is relatively safe, non-toxic, and cost-effective. UV sterilization can be used just by using PET bottles and exposing them to direct sunlight. Most solar disinfection methods are highly effective in killing waterborne pathogens according to WHO (2019) standards. (Szolga and Cilean 2021; Amatobi, D. A., & Agunwamba, J. C. 2022).

Ceramic

Ceramic filters (CWFs), are filtering water through the porous structures of the ceramics, and are commonly used worldwide. CWFs have limitations in removing viruses and chemical pollutants, but silver-modified filters are more effective against protozoans and bacteria. CWFs do not alter the taste of water and can function effectively for up to 5 years without external energy. Developing a filter with a high flow rate and efficient microbial removal remains a challenge. (Yang et al., 2020).

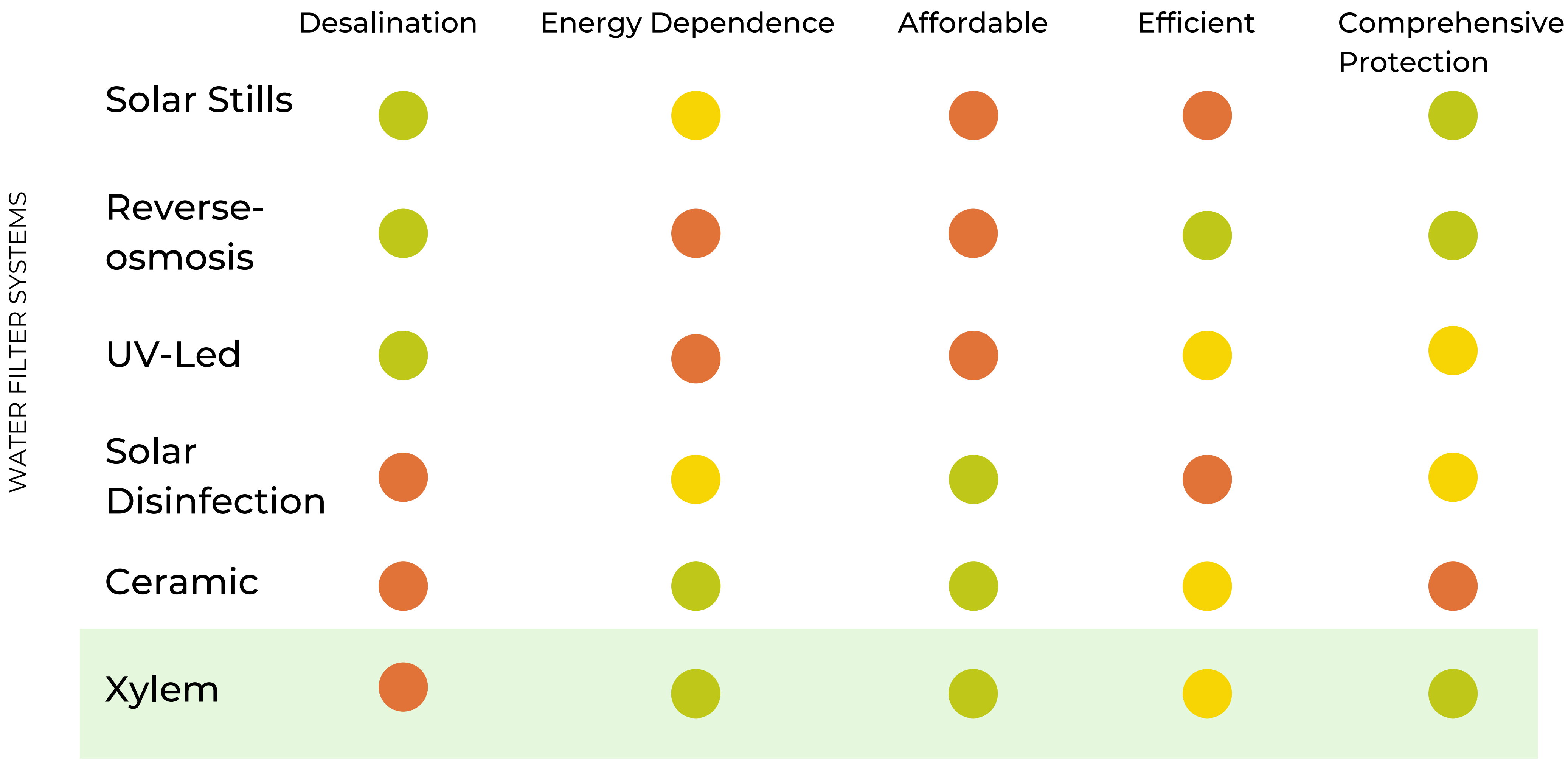
Xylem

A method of cleaning water with the help of wood has been developed, using the naturally occurring membranes in the xylem tissue. The filters have comprehensive protection against waterborne pathogens. The xylem filters could reduce barriers to access and affordability, making them suitable for low-income communities. Xylem filters are compact, lightweight, and have the potential for application in other filtration needs, including in disaster situations. (Ramchander et al., 2021).

Conclusion

An affordable filter, with locally sourced materials, and simple to maintain is preferable. Price and efficiency, and how much maintenance is needed varies among the methods. There is a possibility of combining filters for better results, such as extending the lifetime by using pre-filters. Most methods do not perform desalination, which is not required by our user group because they are located inland rather than on the coast. The Xylem Water Filtration system, which uses wood, shows promise due to comprehensive pathogen protection, affordability, and circular material use. Investigating ways to improve the flow rate, lifetime, and usability of wood-based filters is of interest to this project. Not all methods are being looked into, and there is still potential to look into other ways of water filtration, such methods could be: charcoal filtration, phytoremediation, Nanofiltration, forward osmosis, advanced oxidation processes, microfiltration, and magnetic water treatment.

Filter Technologies



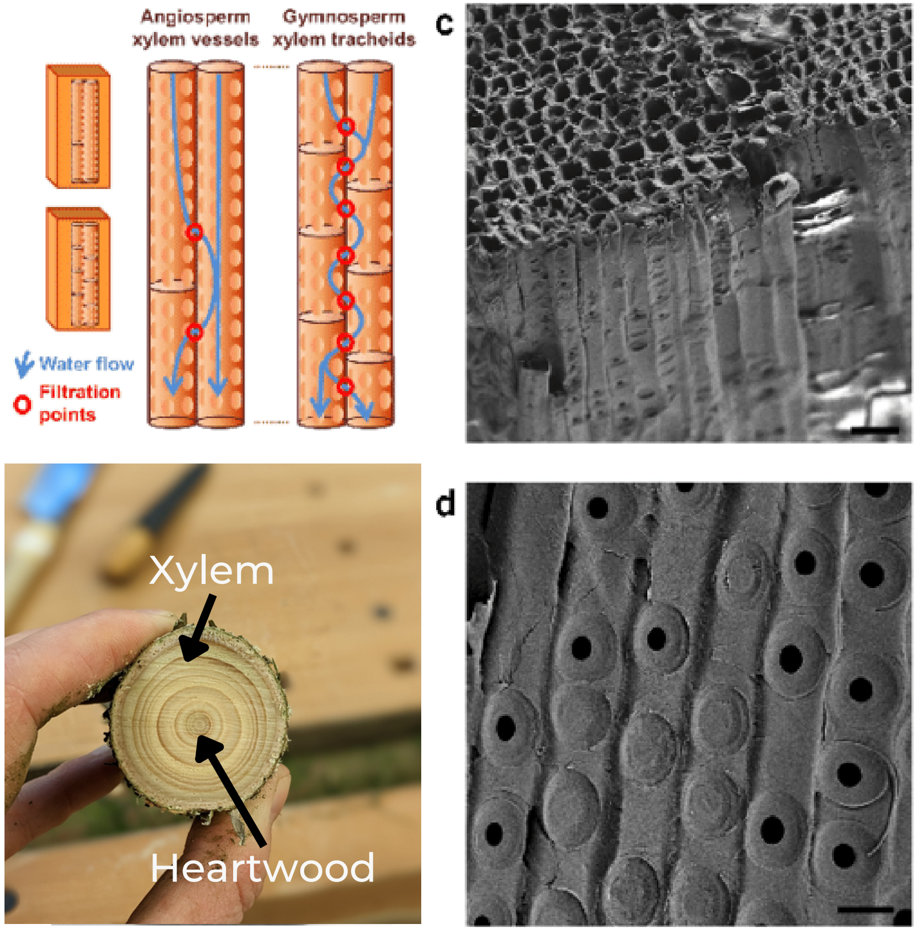
Other methods boiling, charcoal filtration, phytoremediation, Nanofiltration, forward osmosis, advanced oxidation processes, microfiltration, magnetic water treatment.

Xylem Filter

Acccording to Ramchander et al., 2021 field studies in India, a water filter should process at least 8 L of water per day, and have a flow rate of minimum 1 L/h, and effectively remove contaminants in order to be valuable for households in resource-limited settings. Xylem filters from Ginkgo biloba, show promise for practical use. These filters can process around 55 ± 21 L of general test water without prefiltration and 28 ± 3 L of challenged test water with granular activated carbon and cloth pre-filtration, meeting the daily drinking water requirement of a household. They also yield peak flow rates of 1.5–9 L/h depending on water quality.

In their study, Ramchander et al. (2021) found that the cost estimation for the xylem filter is approximately 0.06-0.1 USD, with a replacement frequency of 1-5 days, whereas conventional filters cost 5-10 USD and require replacement every 3-6 months. This suggests that the xylem filter is not only cost-effective but also more affordable than conventional filters currently available in the market, especially if the lifetime of the filter could be extended. In the setting of Indian urban slums, where people typically purchase 0.28-0.56 L or government-operated water for 0.06-0.1 USD per 20 L, the xylem filter could possibly be an affordable option for water filtration.

During the survey conducted by Ramchander et al. (2021), 40% of the respondents noted that the simplicity and the natural nature of the xylem filters were the primary attributes they liked about them. This suggests that the xylem filters may have cultural appeal among the target population in India.



Images of Xylem structure, (Ramchander et al., 2021)

Chopped and processed tree trunk pieces of Pinus Abies

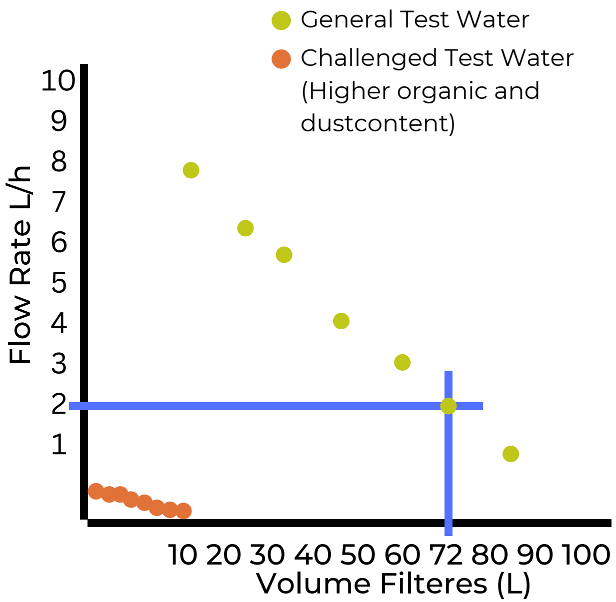
Main Takeaways from User Research

Contamination of groundwater, surface water, and tap water is a significant issue in many regions. The Xylem water filter is meeting the requirements of the end user where the natural nature of the filter is something people prefer. The filter is capable of providing between 1.5 to 9 liters per hour, where the target user group requires 1 liter per hour and 8 liters per day per person.

The water filter could potentially be suitable for piped water as well, where 80% of the water suffers from E-coli contamination in the targeted region. The implementation of the natural water filter is meeting the end users need in efficiency and ability to provide comprehensive protection against water-bourne disease.

Simplicity and the natural nature of the xylem filters were appealing attributes

Piped water suffers for 80% of e-coli contamination



70 litres can be processed at > 2L/h

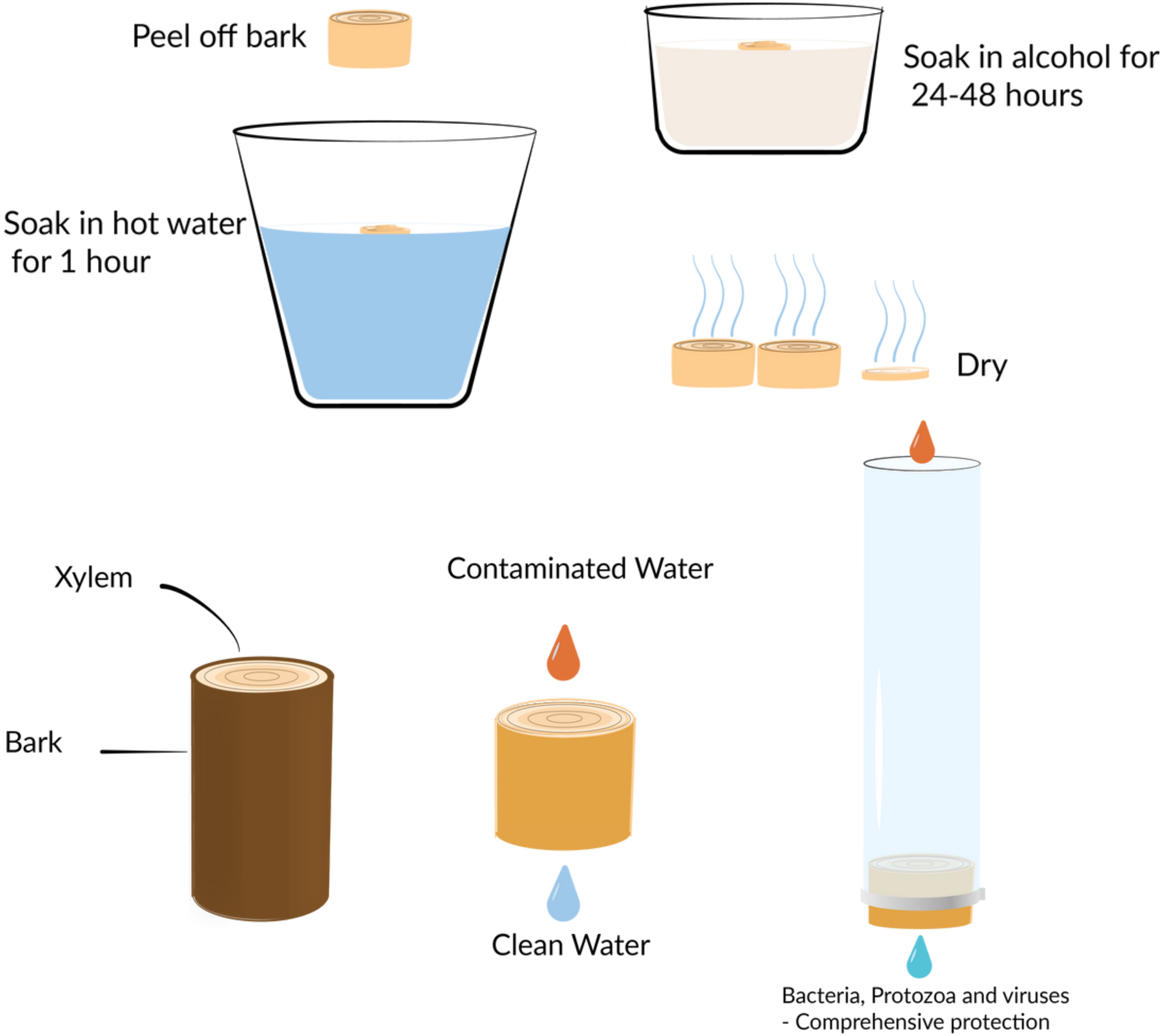
Replicating Previous Study

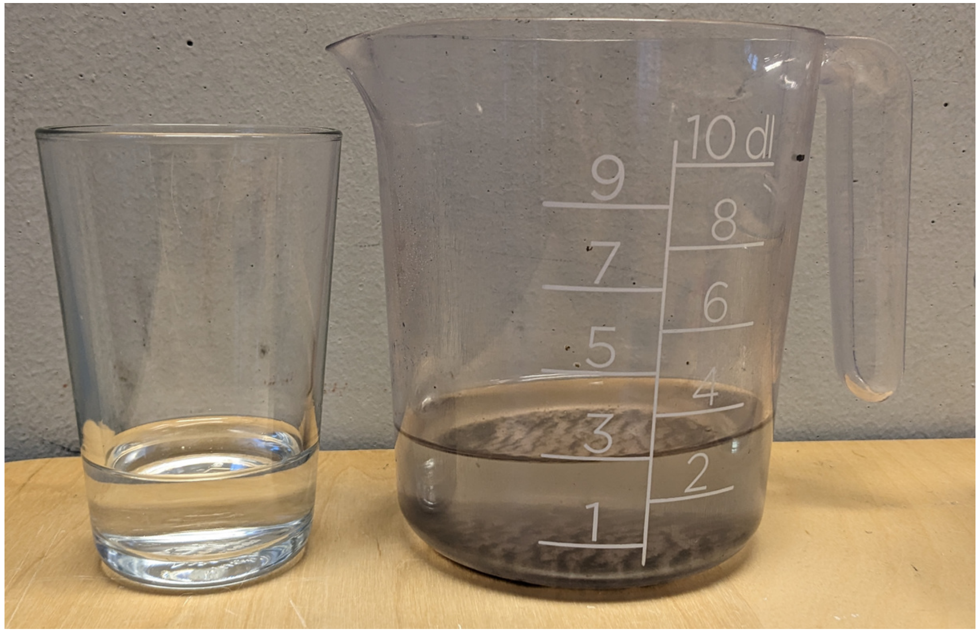
According to Ramchander et al. (2021), the species Norway Spruce, also known as Picea Abies where young branches have been tested before and proven to work as water filters. This will be the tree we are doing our experiments on because it is very easy to procure in Scandinavia as it is commonly used as a Christmas tree. Worth mentioning is that suitable trees for our target group, living in India, Bangladesh, China, or Myanmar would be Cedrus Deodara, Pinus Kesiya, or Pinus Wallichiana. These trees could not be retrieved during our experiments in Sweden due to their Asian origin but should function similarly to the Norway Spruce according to Ramchander et al. (2021).


Skum

Testing The Concept

The xylem filtration system was prepared and tested according to previous studies, Ramchander et al., 2021. The intention was to understand if the lifetime of the product could be extended, as well as how the filtration works. Material was sourced from a local spruce producer, Norregarden in Dalby, who supplies Picea Abies which is a suitable species according to Ramchander et al., 2021. The spruce measured about 2.5m tall and a width from about 10 cm to 1cm. The wood was cut into 1-3 cm thick pieces in order to test the performance of various thicknesses. The bark was peeled off and the wood pieces were put into a bucket filled with water to keep the pieces moisturized. The wood was then put in hot water for one hour at 60 degrees and then into a mixture of 75% ethanol and 25% isopropanol for 24-48 hours. The wood pieces were then left to dry in a drying cabinet before use. After that treatment, the shelf life of the wood is 2 years.


Peel off bark
Soak in alcohol for
24-48 hours
Soak in hot water
for 1 hour
Dry
Xylem
Bark
Contaminated Water
Clean Water
Bacteria, Protozoa and viruses
- Comprehensive protection


10 dl
9
8
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3
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10

Process

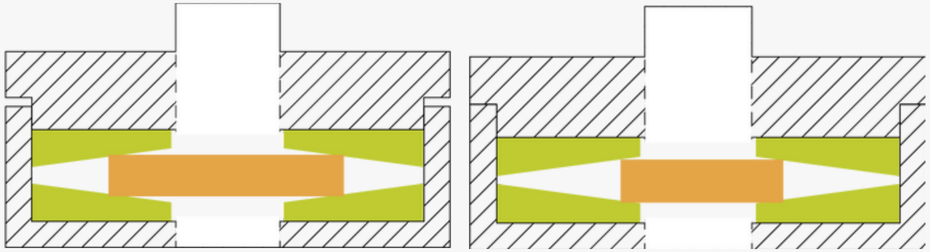
Dirty water was collected and the filtration was tested. After 24 hours the water was filtered through the xylem of the wood and a clear liquid was produced. The dirt was collected on the top of the wood.

Ceramic Pre-Filter

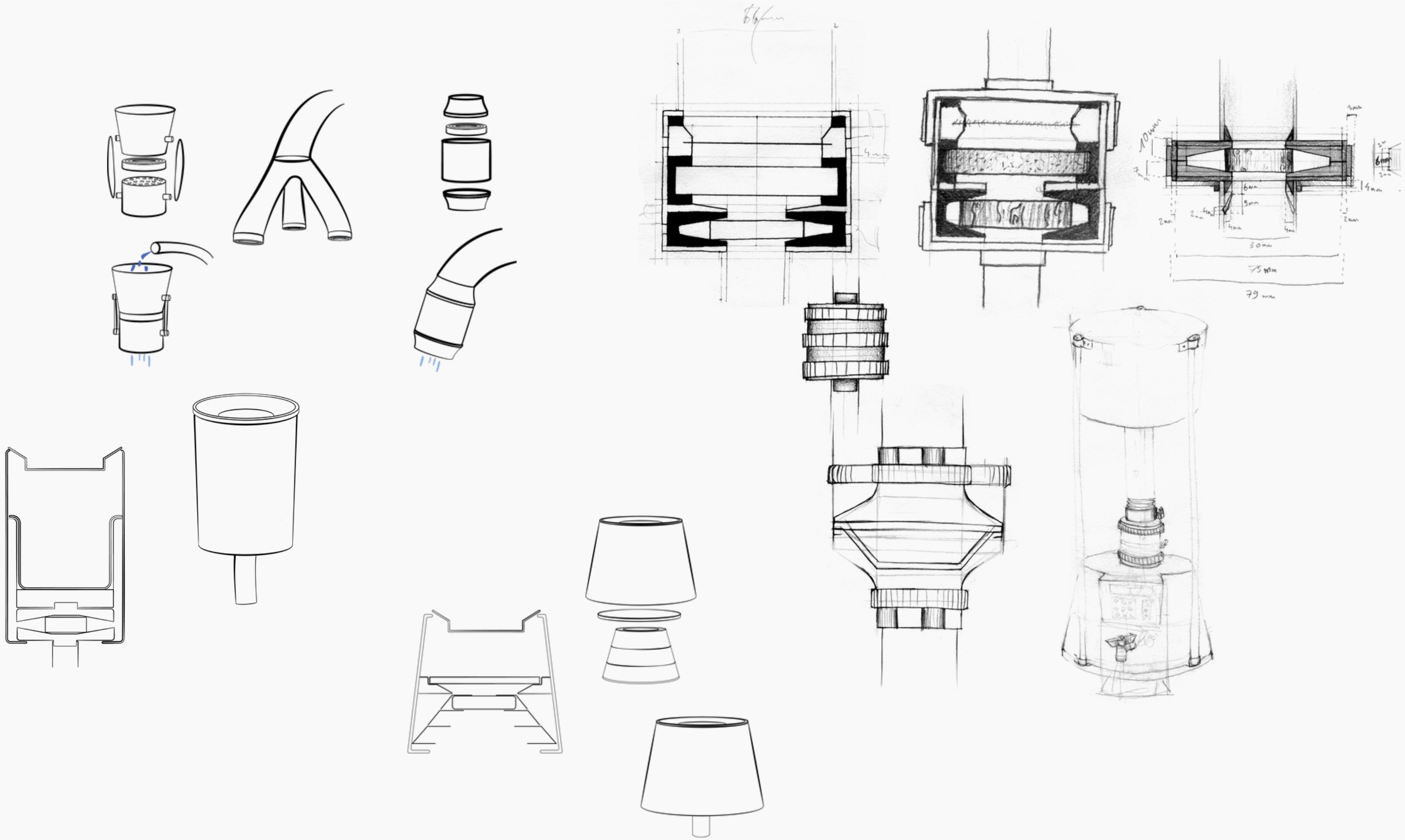
To filter larger particles and extend the lifetime of the wood filter, a ceramic filter was made according to Low-tech Lab. (2020). The material used was earthenware clay and sawdust as combustible material. The sawdust evaporates during the firing process of the ceramic and helps make larger pores in the finished ceramic which traps bacteria and larger particles, (Yang et al., 2020).

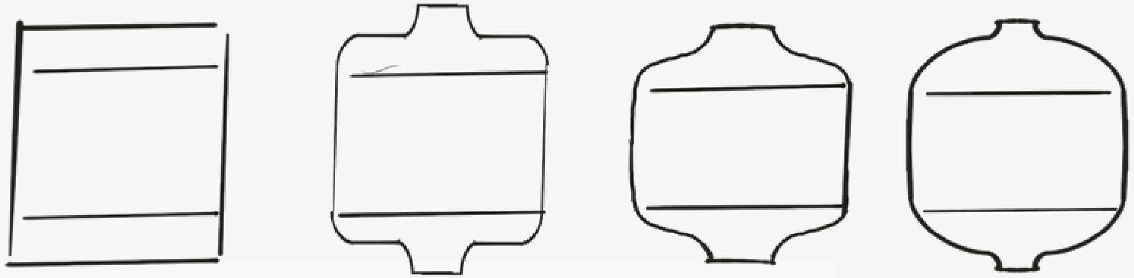
Silicon Socket

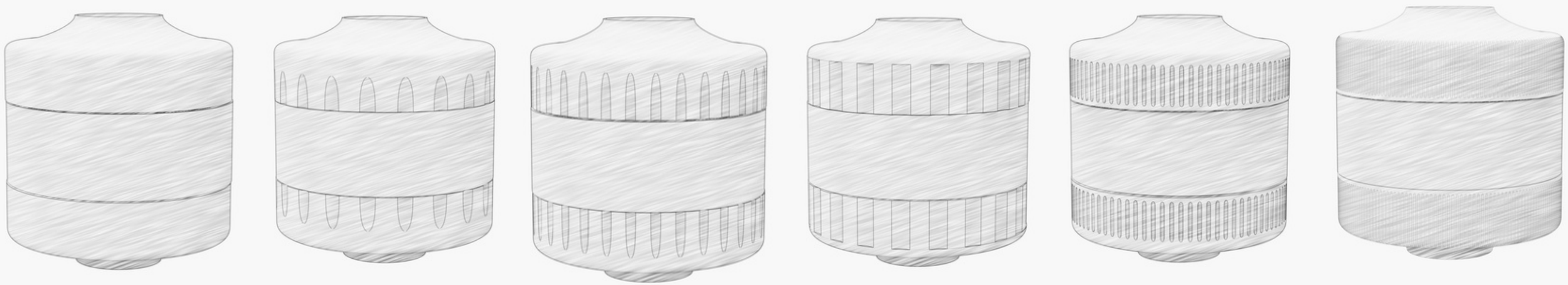
One of the key problems was that the wood naturally comes in various diameters. We needed to come up with a solution to fit different pieces into the same closed water system. The solution we came up with was to use a silicone socket shown in the picture below, with an angled construction to fit a diameter from 3mm to 10mm.

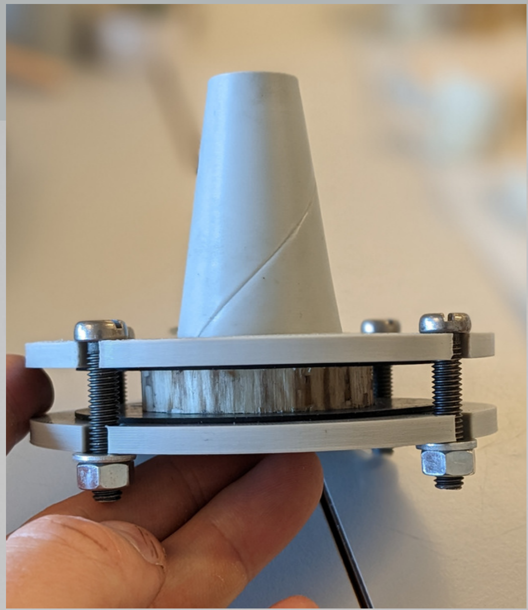


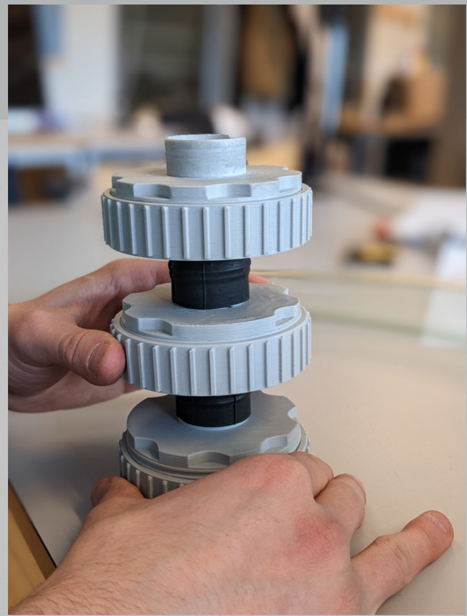
SKETCHES & MODELS



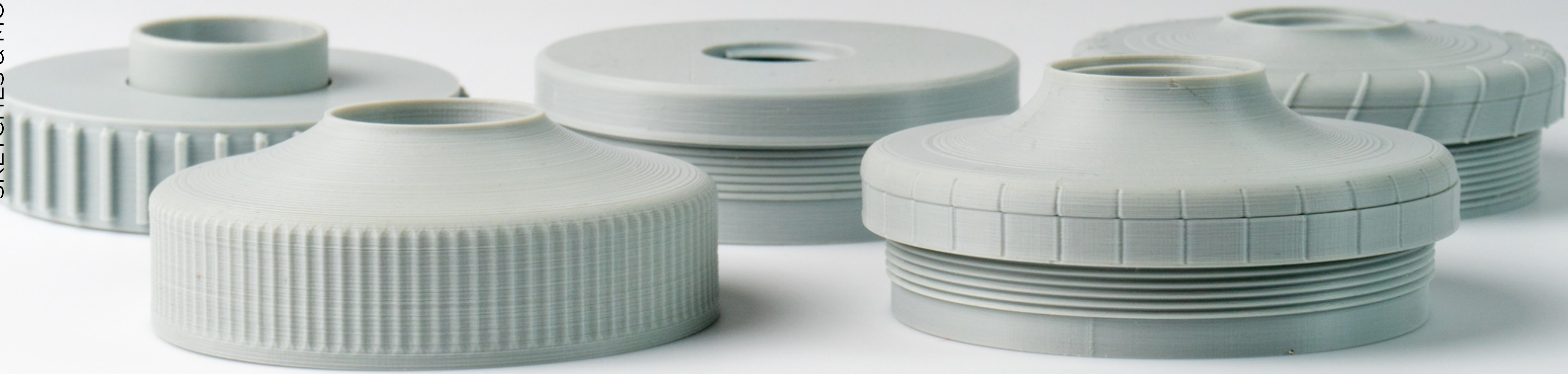









VITAMIN
WELL
DEFENCE



Evaluation & Conclusion

In our initial models, we incorporated a single filter, maintaining a simple construction for prototyping. Eventually, we transitioned to a three-part filter system and engaged in thorough discussions on implementing the trio of filters, which comprise a metal prefilter, a ceramic prefilter, and a xylem wood filter. Our final decision was to house all these filters within a single box, designed for easy removal, cleaning, or replacement.

The overall shape is intended to project an image of cleanliness, precision, and functionality, what we describe as the 'Clinical look'. This aesthetic is fitting for a water filter, as it communicate an uncluttered, hygienic, and sterile impression, and give the impression of reliability. We explored various forms and eventually decided that a cylindrical shape, with a protruding connector, was most suitable. To facilitate user access for filter change or cleaning, we added two openings on each side to access the metal mesh, ceramic, or the wood filter.

In terms of usability, we tested various grips to make the box functional without adding unnecessary complexity. The design needed to indicate the ability to grip and rotate the object, to open up the box. To provide users a clear connection point with a water bottle or hose, we decided to create a protrusion on the box to connect either a hose or water bottle.

Usability


Mesh Filter
Ceramic Filter
Wood Filter

CMF

Aluminum is chosen for its strength, recyclability, and corrosion-resistance. It is heavier than plastic but has a higher material and production cost. It is given a brushed and anodized finish for a durable and aesthetically appealing texture and color.
The plastic alternative could be valid from a usability standpoint because the user can see inside the box, and what you can see you can trust. It is lighter and could be manufactured with 3D printing or injection molding. Durability is not as good as aluminum, and the afterlife of plastic could potentially have an impact on the environment if not recycled properly.

PET, a safe and recyclable plastic, is used for its transparency and modified for a cloudy, matte finish. A textured surface ensures grip, and UV-coating protects against sun damage.

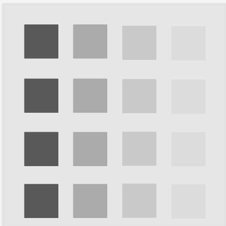
Usability

When taking apart the product, some parts only correspond to one side of the filter. For the user to understand where all the parts should fit, we use color coding. The red color where the dirty water comes in, is at the top. The blue color is the part of the filter where the water has been cleaned.

Colors

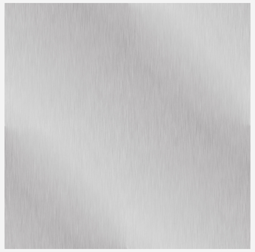
Silver

Transparent



Materials

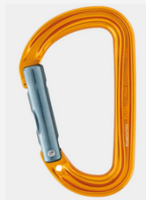
Aluminum



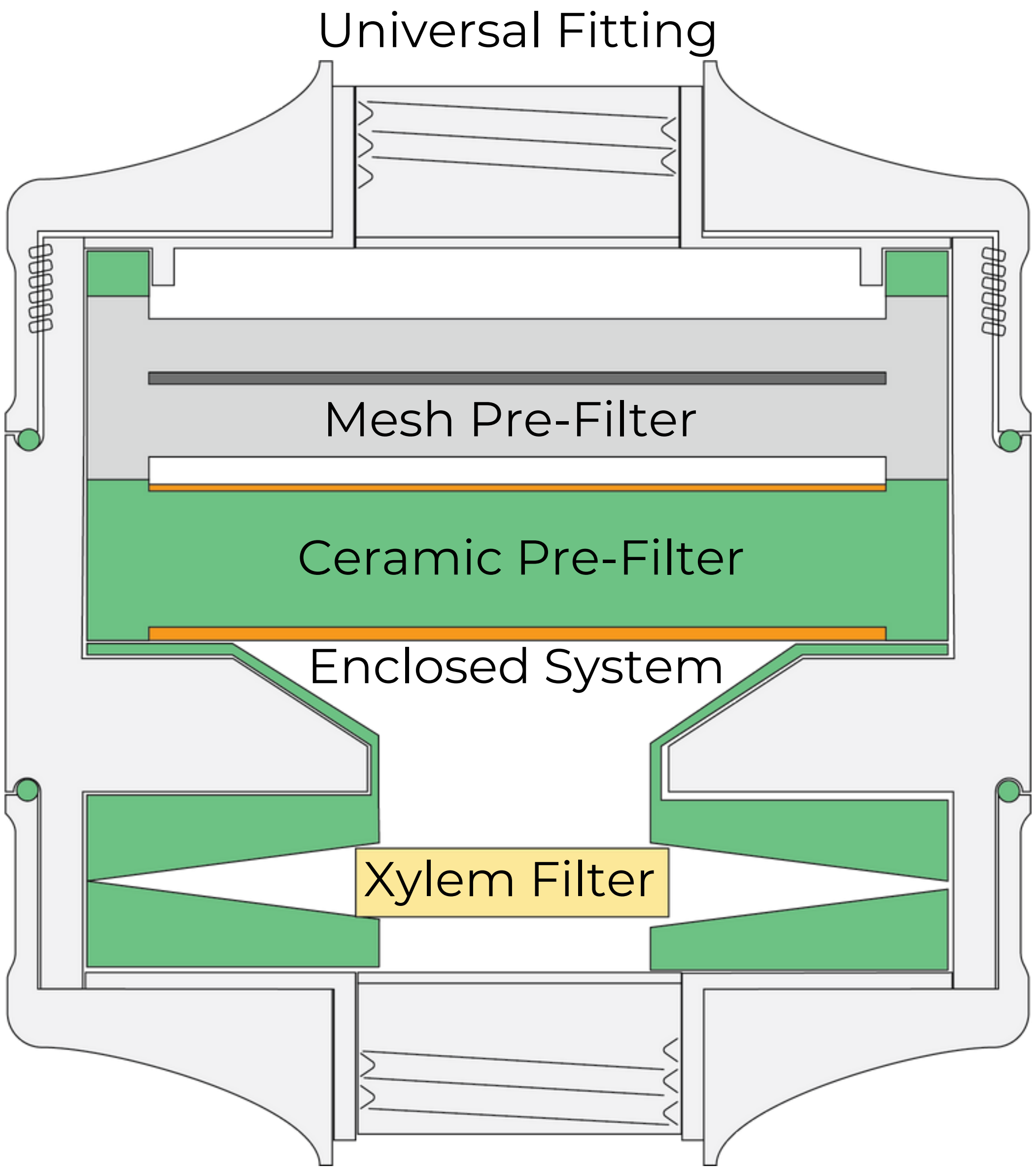
PET

Finishes

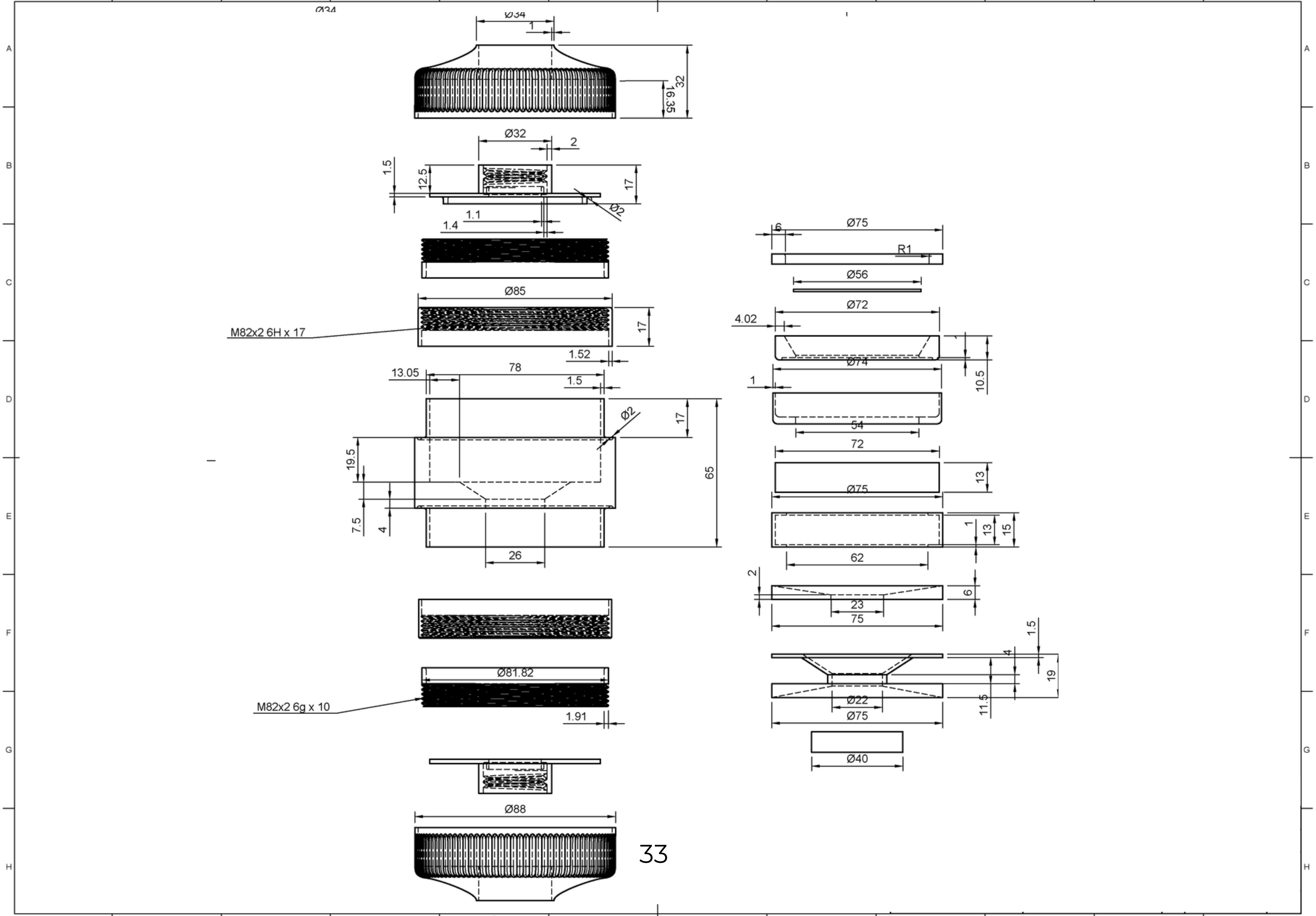
Anodized, Brushed

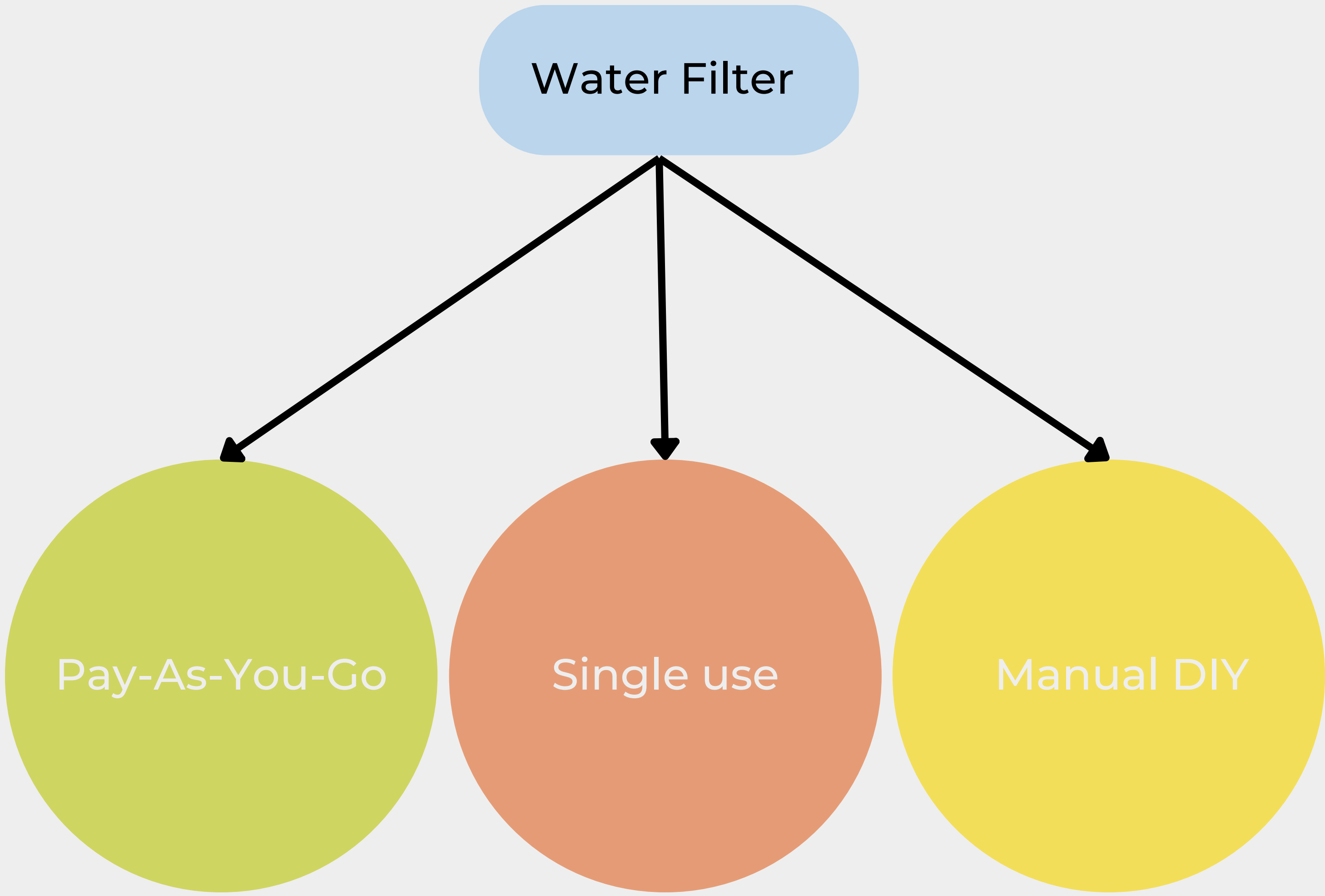


Matte, Cloudy Textures, UV-Coating


Universal Fitting
Mesh Pre-Filter
Ceramic Pre-Filter
Enclosed System
Xylem Filter

TECHNICAL DRAWING




Water Filter
Pay-As-You-Go
Single use
Manual DIY

To cater to different needs, we designed our water filter to accommodate a range of use cases.

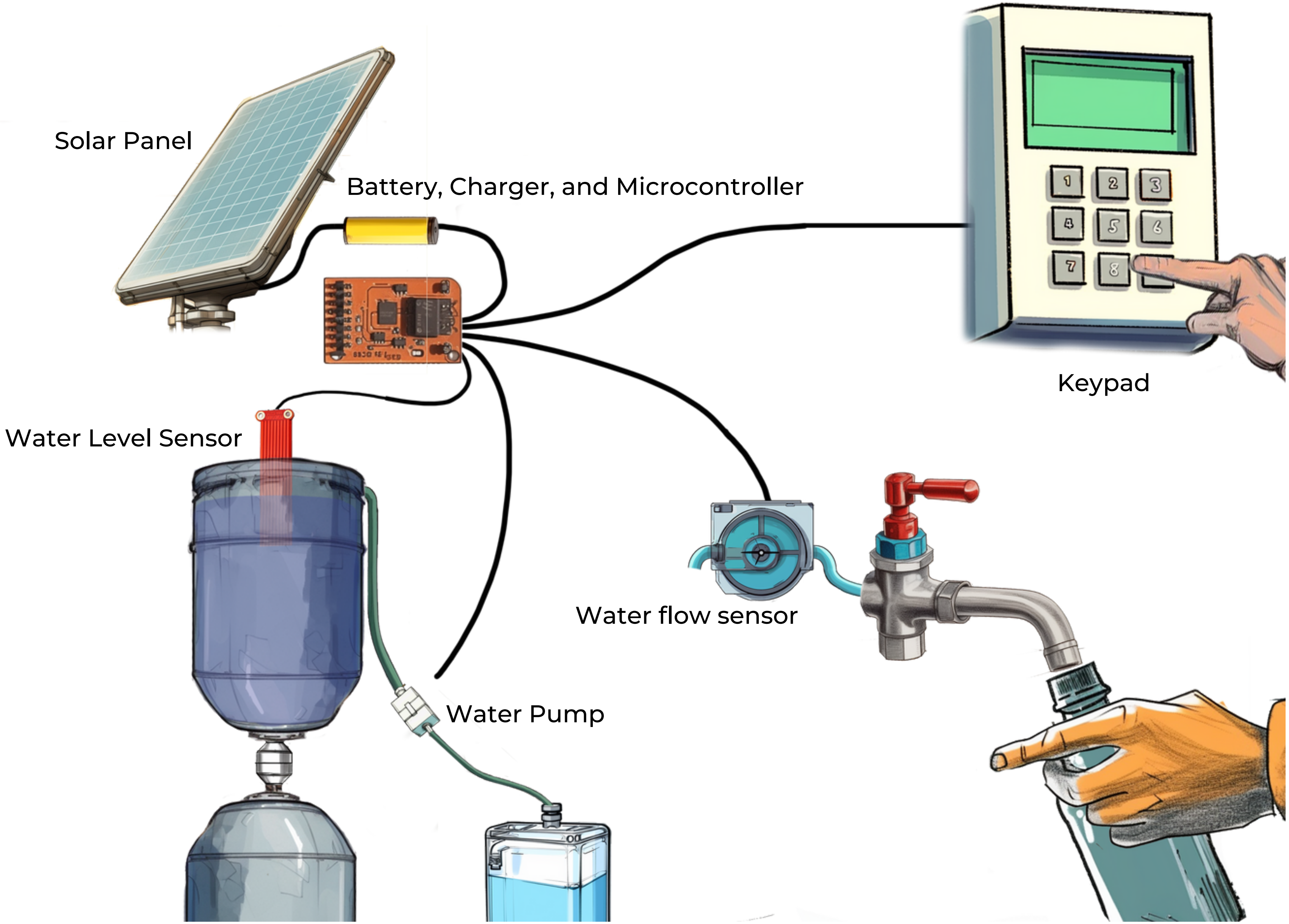
PAY-AS-YOU-GO

Scenario

The water filter is a sustainable pay-as-you-go solution that uses wood-based filtration to provide
clean water. A solar cell is powering the system, and with the help of a microcontroller and a water flow sensor, that triggers filter replacement alerts the filter is maintained. The water filter is implementing a pay-as-you-go technology, where the user makes payments through SMS or a token purchased at a local shop. With a water pump automatically refilling the tank, low maintenance requirements, and sustainable energy use, our system offers a convenient and eco-friendly way to access clean water. The water filtration system, incorporating a water flow sensor, ceramic pre-filter, and xylem filtration, powered by solar energy, provides a reliable, eco-friendly, and low-maintenance solution for clean water access. It ensures efficient filtration and alerts for timely filter replacements.

Pay-As-You-Go

The pay-as-you-go solution offers affordability, scalability, flexibility, and automatic convenience while being technologically dependent. Pay-as-you-go will allow the user to access clean water without the need for large investments, making it affordable for communities with fewer financial resources. The affordability leads to scalability where more people can be reached, and where the system could be installed in a wider range of communities. It promotes responsible water usage where people are billed on their actual water consumption. The drawback with such a system is that it requires additional infrastructure, such as SMS-based payment which could be seen as complex. The system has a technology dependence, where technical features are needed to run the system. It is sensitive to technical failure, and constant access to GPS connections where unserved areas do not have access.

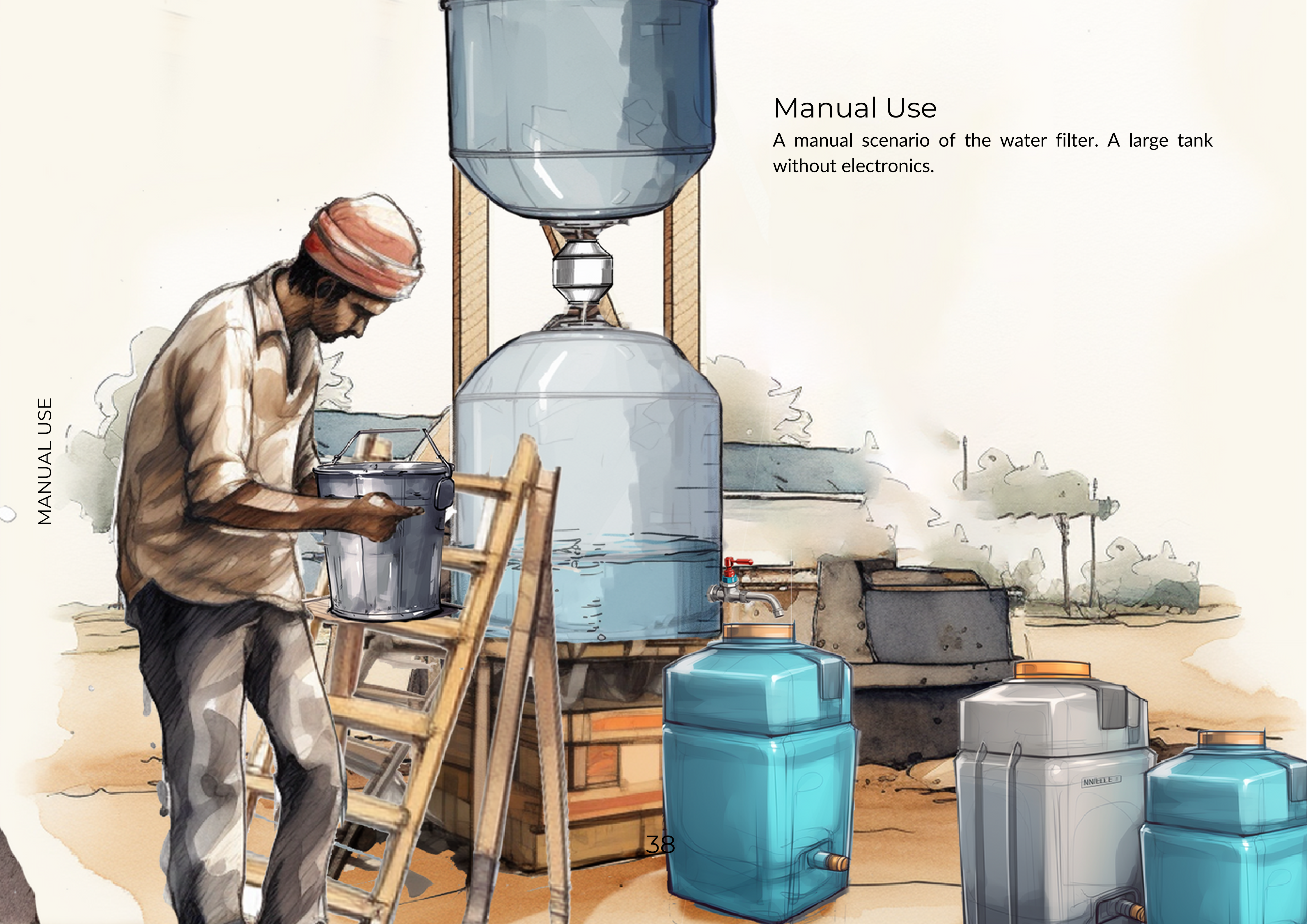

Solar Panel
Battery, Charger, and Microcontroller
Keypad
Water Level Sensor
Water flow sensor
Water Pump

Interaction

A solar panel is giving power to the system, making it possible to install in off-grid settings. A battery is charged which is running the water station 24 hours a day. The microcontroller is controlling all the sensors. There is a water level sensor that signals the microcontroller when it is time to activate the water pump to refill the upper tank. The water flow sensor is giving information when it is time for filter replacement, and alerts the person who is maintaining the system. The keypad is where the user can enter a code attained from SMS or bought as a token from a local shop. When the code is entered, the user can collect clean water from the lower tank.

Single Use

The water filter is modular and could be used as single use



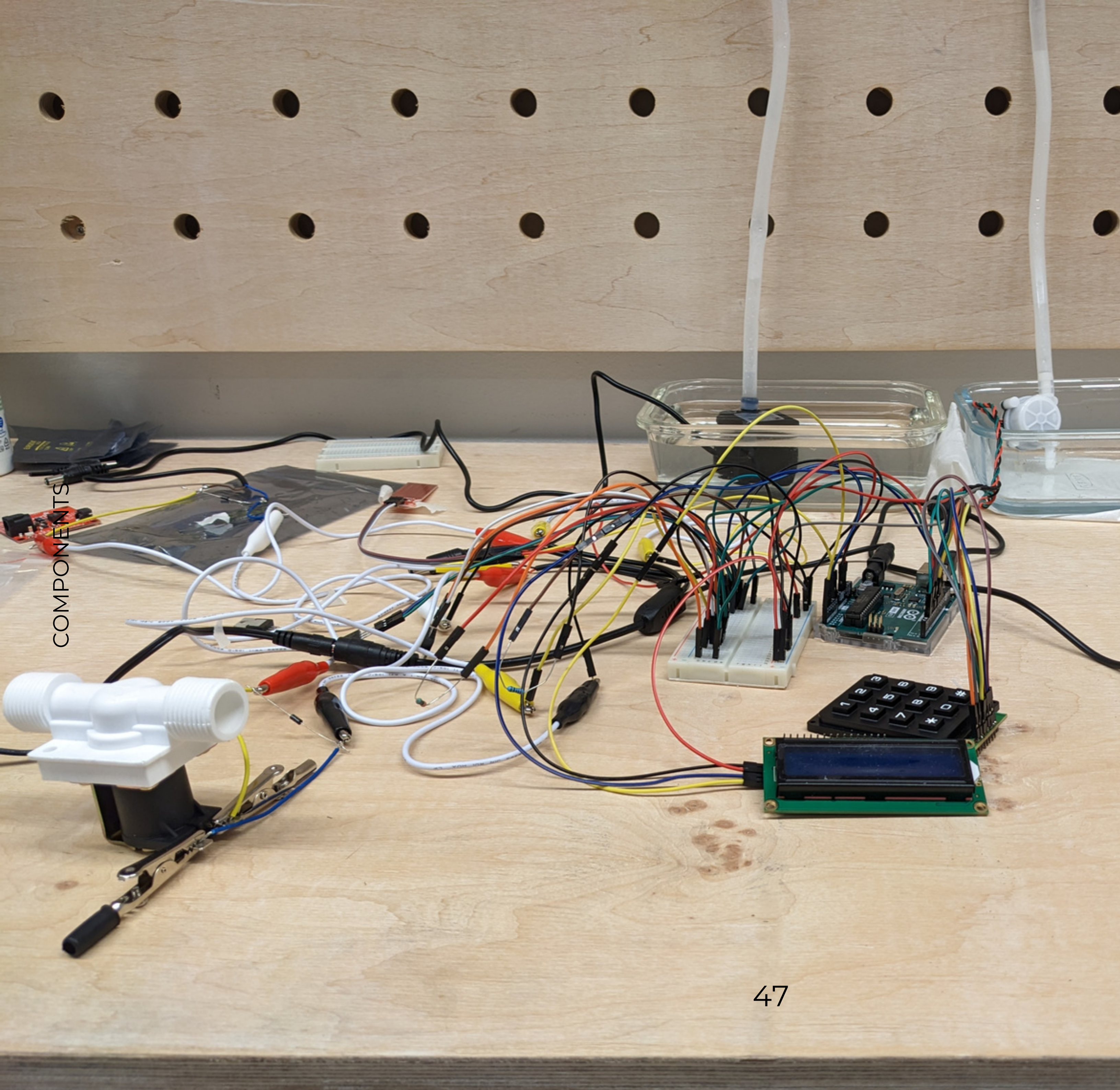
Manual Use

A manual scenario of the water filter. A large tank without electronics.

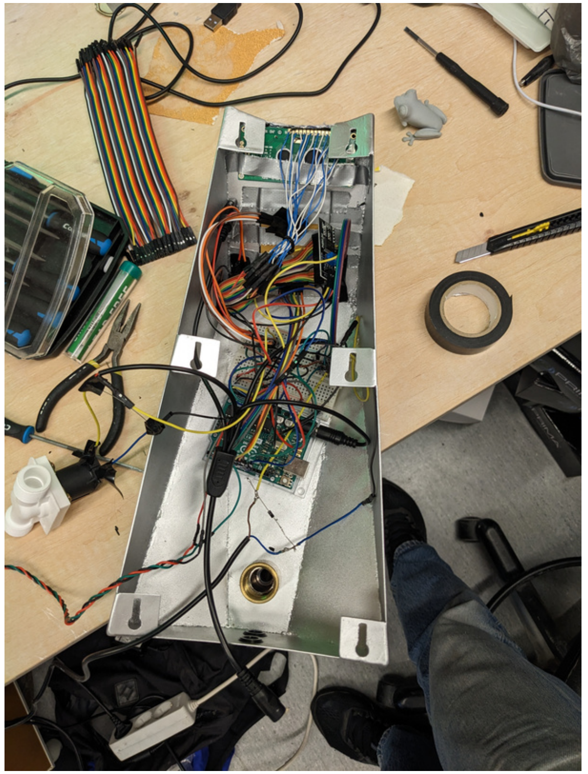
MOCKUPS

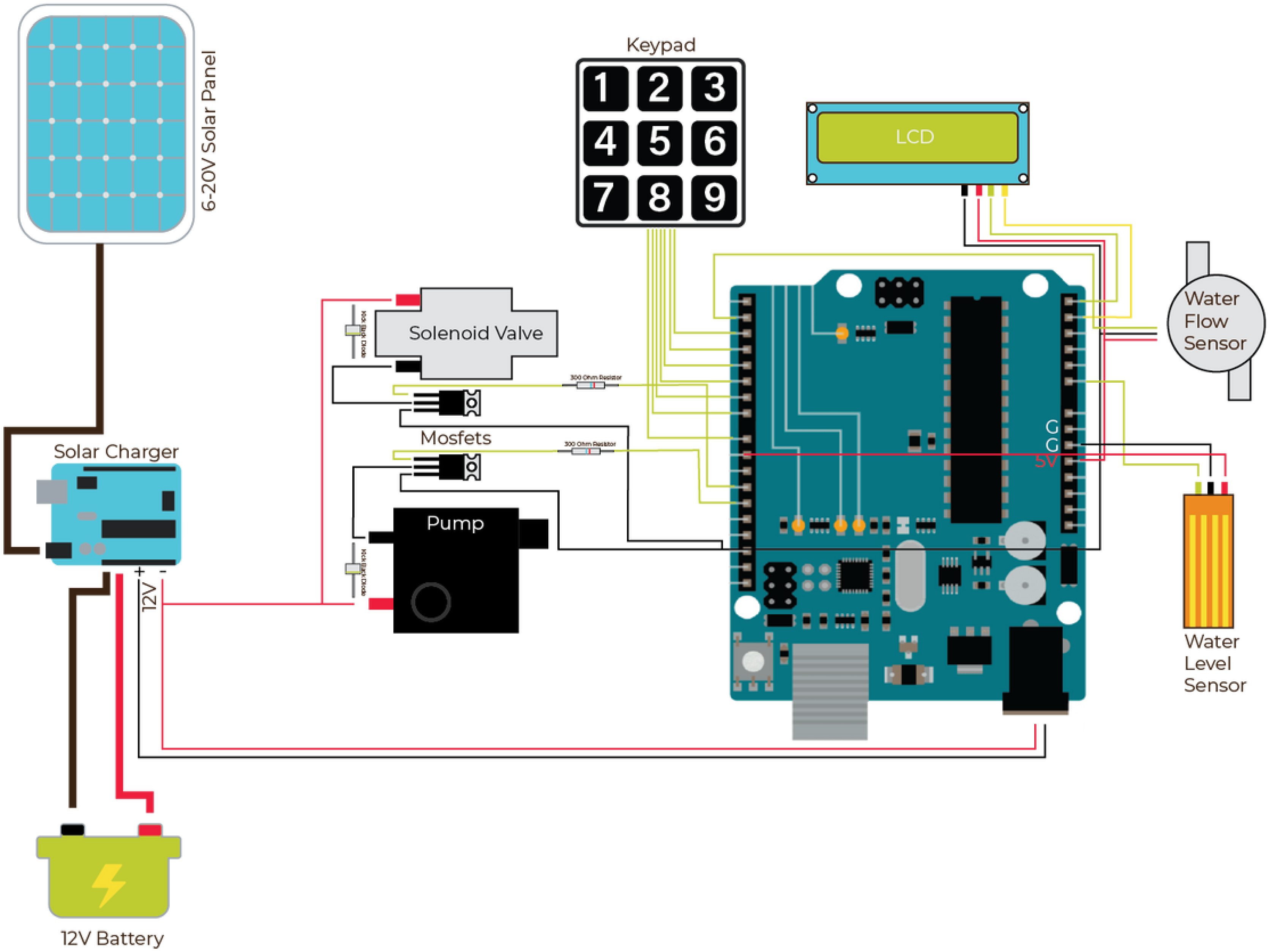
Our initial mockup for the efficiency for access design challenge. We managed to do a full-scale prototype in order to try out interaction and scale of the product.


Speedglas
3M




Main Menu




6-20V Solar Panel
Keypad
1
2
3
4
5
6
7
8
9
LCD
Solenoid Valve
300 Ohm Resistor
Mosfets
300 Ohm Resistor
Water
Flow
Sensor
G
G
5V
Solar Charger
+
-
12V
Pump
Water
Level
Sensor
12V Battery

COMPONENTS

Name	Item	Current	Voltage	Cost
Arduino Uno	Microcontroller	Max 200mA	Operating: 5 V Input: 7-12V	$28
DFRobot FIT0563	Waterpump	65mA-500mA	Operating: 6V-12V	$9.5
DFRobot SEN0216	Water Flow Sensor	15 mA	5~12V Operating at 5V	$9.3
HD44780	LCD Screen	20-40 mA	5V	$7.2
Keypad 3845	Keypad Panel	1-5 mA	5V	$6.2
997 Solenoid Valve	Solenoid Valve	1) 160 mA 2) 320 mA	1) 6V 2) 12V	$7
Water Detection Sensor with	Water Level Sensor		3 to 5V	$1.98
ENERpower Battery 10.8V-11.1V (12V)	Li-Po Battery	5000 maH	12V	$45.66
Sparkfun PRT-12885	Solar Charger	Charging up to 2A	Input: 6-20V	$27.5
Kickback diode, Mosfet	Other			$1.53+$2.3
Volt Solar Panel - ETFE	Panel		Input 6-18V	$49
DollaTek V2.0	GSM Reciver	50-200 mA	5V	$13.8
Total consumption / Totalt Cost		1280 mA	12V in 5V out	$209

Future Improvements & Reflection

Secondary Research

We relied on secondary research during this project. We would still need to conduct water tests to verify the water quality. We did not verify what the water tastes like, or how well it filters contaminants.

Leakage

We still have some issues with leakage of the prototype, where it sometimes works well and other times not so well. This could be a problem like the 3D-printed prototype where the material reacts with the water and cracks.

Reflection

The challenge of this project is designing a product for a culture and socioeconomic context different from our own. We were unable to meet the end users in person, and our understanding of their needs and circumstances relies largely on secondary sources. Reflecting on this, we understand the importance of cultural sensitivity. Different cultures have varying norms, customs, and beliefs that may affect how our product is received and used. To design a product that is not only well-received but also effectively used, it is important to understand the cultural context of the communities we aim to serve. This project is not about economic exploitation, but rather about helping to build an infrastructure that empowers the local population to thrive.

We wish for the community to be active participants in both the design and implementation process. We are mindful of the potential environmental impact of our product and aim to ensure that it is not only efficient and effective, but also environmentally responsible.

Pressure Test

We did not implement pressure in the design because of its operational complexity, however, we did tests to see how the filter would be affected by pressure. The flow rate increased significantly. This method could be integrated into our existing design to improve the flow rate of the water filter. A air-tight chamber was constructed with help of part of a water pump, and air was pumped into the chamber, raising the pressure to about 1 Bar of air pressure. The water inside was directly pouring out through the wood, increasing the flow rate signifiable. A verification if impurities are being trapped or if the filter looses performance still needs to be tested. However, excessive pressure could possibly damage the xylem vessels and reduce the filter's efficacy.

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- Scenario illustrations generated by Midjourney and edited in photoshop
- ChatGPT4 has been used to support with text and code.