Design and Implementation of a Water Filtration System

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Abstract

This research paper addresses the global issue of water scarcity by designing and testing a portable water filtration system for regions with limited access to clean water. The system incorporates a physical filter, a pump, a battery, and a solar panel to purify water while maintaining portability and affordability. Methods included testing the flow rate, mineral content, pH balance, and battery performance with and without solar support. Results showed the system successfully reduced harmful minerals and ran for 2 to 10 hours depending on solar use, though the 0.4 GPM output rate and 17-pound weight indicated areas for improvement. Future work will focus on reducing the system's weight, enhancing filtration efficiency, and extending battery life to make it more effective and user-friendly.

Introduction

Water scarcity is a pressing issue that impacts over 2 billion people globally, leaving many without access to clean drinking water essential for life and health. In Sub-Saharan Africa, for instance, women and children often walk up to six hours daily to collect water, usually from contaminated sources (UNICEF). This struggle for clean water contributes to serious health issues, including waterborne diseases like cholera that claim thousands of lives yearly (WHO). The financial toll is also significant, with an estimated annual loss of $260 billion globally due to the time spent collecting water, which could otherwise be used for education or work, perpetuating cycles of poverty and social instability (World Bank). To tackle this crisis, it is crucial to develop innovative water filtration systems that can purify large volumes of water, making it safe for consumption. This paper focuses on designing and constructing a water filtration system for regions grappling with severe water scarcity. This project aims to play a part in the global fight against water scarcity and its harmful consequences by providing a detailed blueprint for creating an effective filtration system.

Filtration methods

Different filtration methods have varying designs and effectiveness, like physical filtration, absorption filtration, adsorption filtration, distillation, and reverse osmosis. Physical filtration works by physically trapping particles, like dirt and debris, as water passes through a filter. The filter has tiny pores that let water through but block larger particles, effectively cleaning the water (ExplainThatStuff, 2023). Absorption filtration works by soaking contaminants into a material, usually carbon, like a sponge absorbing water. The pollutants get trapped inside the material, removing them from the water (SpringerLink, 2020). Absorption filtration works by attracting and holding contaminants on the surface of a material, like how a magnet pulls metal toward it. As water flows through, the pollutants stick to the surface, cleaning the water (MyPureWater, 2023). Distillation filtration works by boiling water into steam, leaving impurities behind. The steam then cools and condenses back into clean water, free of contaminants (Freedrinkingwater.com, 2023). Reverse osmosis filtration pushes water through a special membrane that blocks contaminants, letting only clean water through. It effectively removes impurities like salts and chemicals, making drinking water safe (Applied Water Science, 2020). However, the process takes a large amount of water with a low output, and most of the water put into the system comes out as wastewater (MyPureWater, 2023). Ultimately, I chose physical filtration as it is the most portable of all the options while still providing excellent results. Maintenance was not a big issue with the system I designed, and bacterial filtration was addressed with the physical filter I designed.

Filtration Method	Pros	Cons
Physical Filtration	• Improved water quality • Inexpensive • Very good at removing solids	• Maintenance is time-consuming • Struggles with bacterial filtration
Absorption	• Low maintenance • Very cost efficient	• Struggles with bacterial removal • Not available on more minor scales
Adsorption	• Very effective • Simple to use	• Short lifespan • Doesn't filter everything • Expensive maintenance
Distillation	• Removes all live contaminants from the water	• Takes a lot of energy • Struggles removing mineral contaminants
Reverse Osmosis	• Very filtered water • Sustainable	• Wasteful of water • Takes a lot of energy

Table 1: Filtration method advantages and disadvantages

Design Criteria

When designing the water filtration system, I carefully selected criteria based on practicality, functionality, and specific needs. I chose a filtration rate of at least 0.5 gallons per minute to ensure the system could efficiently meet the daily water demands. Daily water demands in most underprivileged countries is 50-100 liters (13.2-26.4 gallons) per person, so 0.5 gallons per minute provides more than enough water for a household. Slower filtration rates could leave users waiting long for sufficient drinking water, especially in emergencies or high-demand situations.

I set the system's price limit at $120 to ensure affordability, mainly because the 12-volt, 3-amp pump—capable of moving water at a rate of 1 gallon per minute—needs to remain cost-effective. Keeping the overall cost low makes the system more accessible to communities in rural and remote areas, where financial resources are often limited. This price point allows for the widespread distribution of the filtration units, helping more people access clean water without the burden of high costs. Most portable water filters with automated pumping and similar flow rates cost roughly $200, so my pump, being under $120, is a 40% reduction in price, which is a fairly sizeable amount.

Portability was another critical consideration. I set the weight limit at 15 pounds as most adults can comfortably carry up to 20% of their body weight, and in underprivileged communities, the average adult weight is around 55-60 kg (121-132 pounds), allowing for a manageable load (Thomas et al., 2020). The shape of the system also matters because compact, easy-to-carry designs ensure the system can be used in various settings. Heavy or bulky systems could discourage portability, making them less useful for those on the move or in tight spaces.

Additionally, the focus on removing common contaminants such as chlorine, sediment, and bacteria was a deliberate choice. These contaminants are among the most prevalent in drinking water and can cause serious health issues if improperly filtered. By focusing on these common impurities, the system provides essential protection without driving up costs or adding unnecessary complexity.

Specific criteria, like advanced filtration of heavy metals or water softening capabilities, were not prioritized. The reason for not including these is that they would have added significant cost and size to the system, making it less portable and more expensive. While removing heavy metals and addressing water hardness are necessary in some contexts, they were not deemed critical for the intended use of this particular filtration system, which prioritizes portability and affordability over advanced features.

Finally, durability and ease of maintenance were considered but not covered explicitly as criteria. While durability is important, most portable water filters are inherently designed for rugged environments, so it was not singled out. The 3D-printed polyurethane shell of the system is very water resistant, making durability not a concern. Maintenance simplicity was another implicit consideration; complex maintenance requirements could deter users from regular upkeep, potentially reducing the system's effectiveness over time. I addressed this by keeping the system streamlined and straightforward, reducing the need for constant maintenance.

Design

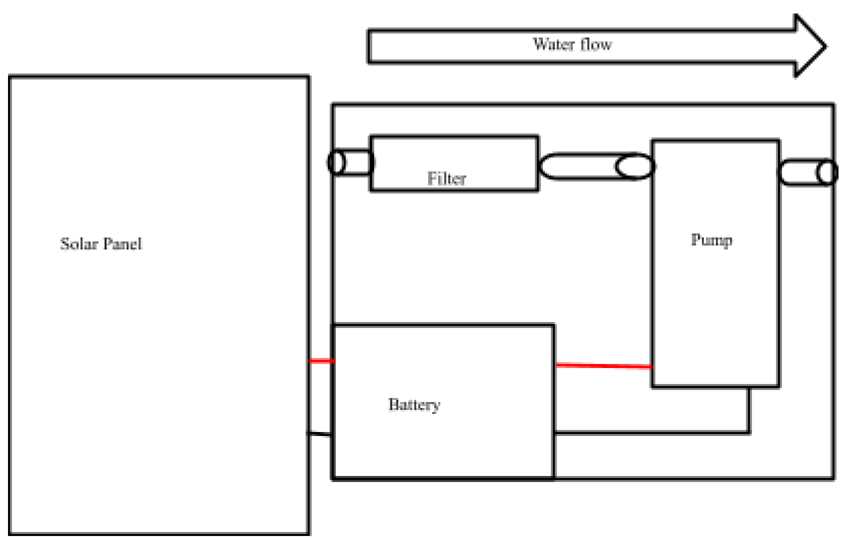

Figure 1: Schematic of design: power flows from the solar panel into the battery, which provides power to the pump. Water flows through a tube, which feeds the water through the filter and pump, outputting drinking water.

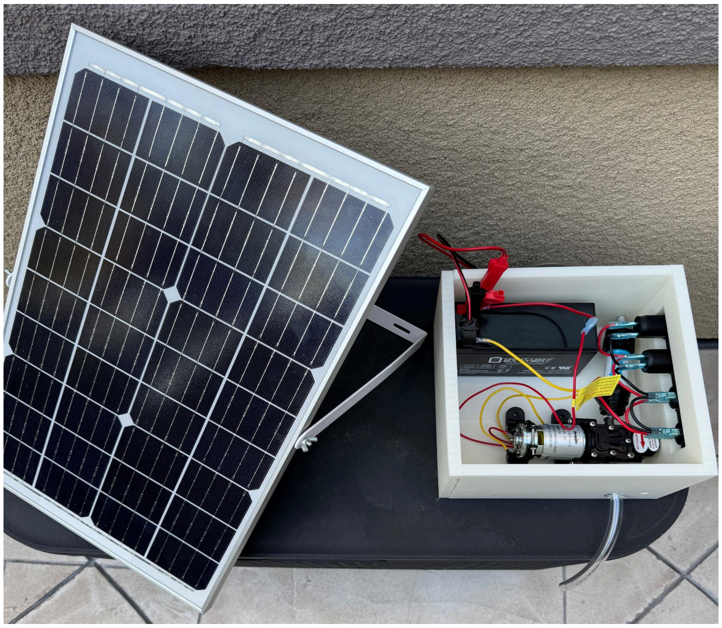

Figure 2: The actual design of the system. The solar panel powers the battery via clips, and the battery provides power to the pump through wiring. The switch panel on the right controls the pump. Water flows through the filter, connected to the pump, and comes out of the tube at the end.

I strategically placed each component for optimal functionality and efficiency in designing the filtration system. The physical filter is positioned at the beginning of the system to ensure that the water passes through it first, removing large contaminants immediately. This is crucial because it prevents clogging in other parts of the system and prepares the water for subsequent treatment stages, like pH neutralization.

The 12-volt, 7.2 Ah battery is centrally located and reliably powers the water pump. I chose this specific battery because its capacity is sufficient to run the pump for several hours without frequent recharging, which is critical for remote or off-grid areas where electricity is scarce. The battery's weight (6 pounds) was a consideration, but I balanced its power capacity against the need for portability.

The pump, a 12-volt, 3-amp, 80-pressure per square inch (PSI) model with a max flow rate of 1 GPM, is positioned directly after the filter. This ensures that filtered water moves efficiently through the system, maintaining a steady flow rate. I chose this pump because it provides enough pressure to push water effectively while keeping power consumption low to extend battery life. The pump's compact size and lightweight design (3 pounds) make it an ideal fit for a portable system.

The solar panel, which weighs 6 pounds, is connected to charge the battery when needed but is not permanently attached to the filtration system. This decision ensures the system remains lightweight and portable when the panel isn't required. In off-grid scenarios, the solar panel can be deployed to extend the battery life significantly, making the system more sustainable in the long term.

Lastly, I housed the entire system in a 3D-printed polyurethane box chosen for its water-resistant properties and durability. Polyurethane can withstand significant water exposure and is rated to last up to 20 years in harsh conditions, making it an excellent choice for a system that needs to function in challenging environments. Additionally, the 4-pound box keeps the system compact and lightweight, contributing to its overall portability.

Each component was carefully placed to balance effectiveness, portability, and cost, ensuring the system would be practical and accessible.

Calculations

I needed to run calculations to project various system variables. Specifically, I calculated the expected battery life with and without the solar panel and determined how long it would take to charge the battery using the solar panel. Given that the battery specifications are 12 volts and 7.2 amp hours, and the pump specs are 12 volts and 3 amps, it is possible to find how many hours the battery will last. First, multiply the battery voltage by the amp hours to get the battery capacity in watt-hours. $12V * 7.2\,Ah = 86.4\,Wh$. We must discover the pump's power consumption by multiplying the voltage by the amps. $12V * 3A = 36W$. The battery life can be found by taking the battery capacity in Wh and dividing it by the pump's power consumption in W. $86.4Wh/36W \approx 2.4$ hours as the expected battery life without solar panel support.

Finding the battery life with the solar panel support is straightforward. Using the numbers from the previous calculations, all we need is the net power draw. The solar panel provides 30 W at its peak, so to find the net power draw, subtract the solar panel input from the pump's power consumption output. $36W - 30W = 6W$. Now, divide the battery life in Wh by the net power draw to get the battery life. $86.4\,Wh/6W \approx 14.4$ hours is the expected battery life with the solar panel backing.

Methods

To evaluate the pump's performance, I conducted several tests, focusing on flow rate, filtered water's mineral content, the filter's weight change, pH levels, and battery life with and without the solar panel. I set up two buckets for the flow rate test: one filled with water and one empty. The filled bucket was elevated to ensure consistent water flow into the filter system. I ran the pump for 10 minutes and measured the weight change of the empty bucket, converting this value into gallons per minute. This calculation helps determine how efficiently the system processes water in a given time.

Next, I measured the mineral content using a mineral tester on a 1-liter filtered water sample. Before the test, I wet the filter to ensure accuracy, as dry filters may produce unreliable results. Using a dry filter as the control weight and comparing that to the post-filtration filter weight adds the water weight to the calculations, incorrectly measuring the amount of filtered minerals. The goal was to verify if the filtered water contained safe levels of critical minerals. Specifically, I looked for calcium levels under 75 mg, potassium at or below 31.1 mg, magnesium under 30 mg, and a ppm below 300 ppm. These four measurements of water quality are critical as they determine the hardness of the water. Higher water hardness could lead to cardiovascular disease. These thresholds are essential for determining whether the water is safe for consumption and free from excessive mineral content.

Figure 3: Mineral content test being conducted. On the right, unfiltered water in the blue bottle is passed through the system and coming out as filtered water in the glass cup.

To determine the filter's weight change, I recorded the filter's weight before and after running the system for 90 minutes. The weight difference indicated how much material the filter had removed from the water during the operation, giving insight into its effectiveness over time.

To assess the pH difference, I first took a small water sample before filtration and used a pH strip to measure the initial pH. After filtering this sample, I tested the pH again and compared the result to a standard tap water pH of 7.5. This comparison helped determine how much the filter altered the acidity or alkalinity of the water sample.

Finally, I tested the system's battery life by running the filter until it thoroughly drained the battery. I then attached the solar panel to recharge the battery and reran the system with the solar panel connected. This allowed me to compare the battery's performance with and without the solar panel's assistance, providing insights into the system's sustainability under different conditions.

Results

The results from testing the water filtration system closely followed the design criteria. The water was made with eight tablespoons of drinking water mixed with 32 fluid ounces of water, which was chosen because it is easy to observe the filtration system's effects visually. The system achieved a flow rate of 0.4 gallons per minute, which fell slightly below the target of 0.5 gallons per minute. In terms of mineral content, the filtration process significantly reduced the levels of harmful minerals, ensuring the filtered water met California's drinking water safety standards. See Table 1 below for specific values:

Mineral	Before Filtration	After Filtration	California Standard
Calcium	90 mg/L	50 mg/L	<75 mg/L
Potassium	40 mg/L	30 mg/L	<31.1 mg/L
Magnesium	35 mg/L	20 mg/L	<30 mg/L
PPM (parts per million)	1687 ppm	500 ppm	<300 ppm
pH	9.5 pH	8 pH	7.5 pH

Table 1: Mineral Content Changes in Filtered Water

After running the filter for 90 minutes, the system's physical filtration component weighed 0.1 grams more, indicating the removal of particulate material from the water. The pH of the water also improved; the initial sample had a pH of 9.5, which was more acidic than standard tap water, but after filtration, the pH decreased to 8, approaching the standard tap water pH of 7.5. Battery life testing showed that the system could run for 2 hours on battery power alone and for 10 hours when supported by the solar panel. During these tests, the system successfully filtered approximately 48 gallons of water.

Discussion

In reflecting on the performance of the water filtration system, it's clear that the results aligned with the system's primary purpose, which was to provide a portable and affordable means of filtering water for communities in areas facing water scarcity. The system successfully reduced harmful mineral content, brought the water's pH closer to safe drinking levels, and demonstrated reasonable battery life, particularly with the solar panel. However, the flow rate of 0.4 gallons per minute fell short of the intended 0.5 gallons per minute, which could impact the system's efficiency in providing sufficient water to larger households. The 17-pound weight of the system also exceeded the portability target, making it less ideal for easy transport in remote areas.

Several factors can be improved. First, optimizing the pump and filter configuration might have allowed for a higher flow rate. The pump's pressure can be adjusted, and a larger filter with less resistance can be tested to increase water flow without compromising filtration quality. Additionally, using lighter materials for the filter housing and battery will reduce the overall weight, improving portability while maintaining functionality.

Despite these areas for improvement, the system demonstrated several strengths. Its ability to reduce mineral content and balance pH levels showed that the core filtration technology effectively addressed key contaminants, making the water safer for consumption. Additionally, the solar-powered battery successfully extended the system's operational time, highlighting the system's potential for off-grid environments. The system's overall design was well-executed, maintaining portability without sacrificing filtration quality or power efficiency. I also integrated the components to maximize the system's functionality while ensuring it remained user-friendly and practical for real-world applications.

I will conduct additional tests to test the filter's effectiveness further. One crucial test would be a long-term durability study, running the system continuously to assess how long the filter maintains its effectiveness before needing replacement. Another helpful test would involve measuring the system's ability to remove bacterial contaminants, as the current focus was on mineral content and pH balance. Testing the filter's performance with different water sources, such as heavily polluted or brackish water, could provide more insight into how the system performs under varied conditions. Finally, conducting efficiency tests under different environmental conditions, such as fluctuating temperatures and sunlight availability, would offer a better understanding of how the system operates in diverse settings. In summary, while the filtration system achieved many of its intended goals, improvements in flow rate, weight reduction, and additional testing could make it more effective and versatile.

Conclusion

In conclusion, the water filtration system I designed and tested shows significant promise in addressing the global issue of water scarcity, particularly in regions like Sub-Saharan Africa, where access to clean drinking water is often limited. The system achieved a flow rate of 0.4 gallons per minute and effectively reduced harmful mineral content, ensuring the water met safe drinking standards. This filtration system could offer a practical solution for communities where women and children walk up to six hours daily to collect water, often from contaminated sources. Providing a portable and affordable method to purify water could help reduce the time spent collecting water and alleviate some health risks associated with waterborne diseases like cholera.

The battery life of 2 hours without solar support, extending to 10 hours with the solar panel, demonstrates the practicality of the solar-powered design, especially in remote or off-grid environments. However, the system's 17-pound weight limits its portability, and the slightly lower-than-expected flow rate indicates areas for improvement. Future work will focus on reducing the system's weight, enhancing filtration efficiency, and extending battery life, making the system more effective and accessible to communities struggling with severe water shortages. By refining these aspects, the system could contribute meaningfully to the global fight against water scarcity and help improve the quality of life for many needy people.

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