# MicroXtract: A Sustainable IoT System for Microplastic Filtration and Water Monitoring

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ABSTRACT

Microplastic contamination in freshwater ecosystems is a growing environmental concern. This paper introduces MicroXtract, a solar-powered microplastic filtration system, designed to overcome limitations in current methods. The background underscores the urgency of addressing microplastic pollution, emphasizing the need for an efficient, adaptable, and economical solution. MicroXtract employs a sophisticated multi-layered filtration system incorporated with Internet of Things (IoT) without requiring pre-treatment, offering advantages over existing methodologies. Challenges identified in previous approaches, such as electrode wear and biofilter maintenance, are addressed through the simplicity of MicroXtract's design. Experimental trials showcase its adaptability and superior efficiency in filtering microplastics. Results demonstrate a significant removal rate of around 70%, positioning MicroXtract as a practical, scalable, and eco-friendly solution. The study concludes by asserting MicroXtract's potential as a transformative tool for combating the escalating global issue of microplastic contamination in freshwater environments.

## Introduction

Microplastics, defined as plastic particles measuring less than 5 millimeters, manifest as a consequence of both intentionally manufactured small plastic components and the gradual breakdown of larger plastic objects. Despite the undeniable societal benefits derived from plastic use, it is imperative to acknowledge the myriad challenges associated with it.

Extensive research underscores the widespread presence of microplastics in the marine ecosystem, reaching polar regions and the deep ocean [1]. Globally, our oceans harbor an estimated 5.25 trillion plastic particles, collectively weighing nearly 269,000 tons [2]. The ingestion of microplastics has been observed across a diverse array of marine species, although comprehensive studies on their biological impacts remain limited. Notably, a significant proportion of marine microplastics is thought to originate from terrestrial sources, including surface waters.

Mitigating the entry of microplastics into the marine ecosystem might be achieved by addressing their presence in freshwater ecosystems. This proactive approach could potentially curb the progression of microplastics from terrestrial to marine environments. Microplastics pose physical threats to both humans and living organisms, with entanglement and ingestion as prominent mechanisms. These minute plastic particles also function as carriers for various toxins, encompassing additives from industrial processes and enduring environmental contaminants absorbed from aquatic surroundings. The accumulation of these toxins in fish species, for instance, leads to issues such as intestinal damage and metabolic profile alterations [3].

While the issues associated with microplastics may not appear immediately urgent, global authorities are increasingly imposing limitations on plastic use. Despite the absence of an imminent apocalyptic environmental outcome, the continuous production and decomposition of plastics into microplastics raise concerns. The inadvertent ingestion of these particles becomes progressively inevitable for both humans and animals. Preventing the gradual buildup of microplastics and averting potential disastrous pollution necessitates their proactive removal from bodies of water. It is crucial to address this issue promptly to safeguard the long-term health of ecosystems and mitigate the cumulative impact of microplastics on both environmental and human well-being.

The first methodology by Sembiring et al. tests the rapid sand filter's effectiveness in removing microplastics. Their approach, while successful for larger microplastics (>200 $\mu$m), requires pre-treatment processes and exhibits lower efficacy for smaller particles. MicroXtract, in contrast, eliminates the need for pre-treatment and addresses this limitation by efficiently filtering microplastics smaller than 1 $\mu$m, showcasing improved versatility.

Elkhatib et al. explore electrocoagulation for microplastic removal. While effective (90%-99%), this method demands regular electrode maintenance and has a short lifespan due to wear and tear. MicroXtract addresses these shortcomings by utilizing a simple filtration system with terracotta components, reducing maintenance complexity and ensuring prolonged functionality.

Liu et al. employ a biofilter to reduce microplastics in wastewater by 79%-89%. Despite its effectiveness, biofilters require substantial surface area and periodic material replacement. MicroXtract, with its compact design, provides a practical alternative, balancing efficiency while minimizing space requirements and maintenance concerns.

Our innovative solution—MicroXtract—introduces a self-operative solar-powered microplastic filtration system, featuring a cellular device that seamlessly transmits real-time water quality data to our dedicated application through scientific sensors. The system is strategically positioned on a wooden platform supported by floating pontoons made from 2 customized PVC pipes. Another customized and sealed PVC pipe serves as the filtration component, with a connecting tube facilitating the extraction of contaminated water via a submersible pump powered by a 12V solar panel. Since the filter is sealed, it also acts like a reverse osmosis filter due to the inner pressure. Designed for deployment in rivers or lakes, this cutting-edge microplastic filter employs a multi-layered filtration approach, encompassing rock, coarse sand, fine sand, activated carbon, and fabric filters. The intricate design ensures the efficient entrapment of microplastic particles within its layers during the filtration process.

Beyond the filtration mechanism, our setup incorporates a Total Dissolved Solids (TDS) sensor, a temperature sensor, and a turbidity sensor. These sensors are seamlessly integrated with a compact cellular device called the Boron LTE Development Board (BRN404X), enabling the transmission of data to our dedicated app through cellular connectivity for the user to view. The cellular device is further equipped with a lithium battery to power electronic components, which is recharged by a 6V solar panel.

Compared to alternative solutions such as regulating plastic production, wastewater treatment, and bioengineering, our method stands out as a more practical and cost-effective approach. Government restrictions and individual awareness associated with regulating plastic production may prove impractical, while wastewater treatment involves significant financial investment. Similarly, bioengineering demands specialized scientific equipment and laboratories. In contrast, our method relies on simple logic and equipment for microplastic removal, presenting a scalable and cost-effective solution with the potential for widespread application across various water bodies.

To evaluate the effectiveness of MicroXtract, a series of controlled experiments was conducted under three different sunlight conditions: 100%, 90%, and 80% exposure. Each trial involved pumping lake water mixed with microplastics through the device while measuring key water quality indicators—Total Dissolved Solids (TDS), turbidity, temperature, and microplastic mass—before and after filtration. The results were analyzed to determine the relationship between solar energy input and filtration efficiency, revealing clear performance trends across varying environmental conditions. This experimental approach provided both quantitative data and qualitative insights into the system's real-world viability. These experiments collectively emphasize the need for fine-tuning MicroXtract's design and operational parameters to ensure consistent and optimal performance across diverse environmental scenarios.

## Related Works

Researchers Emenda Sembiring, Mutiara Fajar, and Marisa Handajani have tested how effective the rapid sand filter's filtration process is, where they tested it solely on microplastics [7]. Compared to our project, they utilized tyres and plastic bags for the source of artificial microplastics, where the tyres and plastic bags are ground into diminutive pieces of plastic, whereas in our project, we collected small plastic flakes and ground them to get even smaller plastics. To extract microplastics using rapid sand filters, a pre-treatment process is required to apply to the water, and it consists of "pre-sedimentation, coagulation, flocculation, and sedimentation". In their solution, they tested out that the rapid sand filter can remove 85% to 97% microplastics, and they are mostly greater than 200 µm. However, it is shown that the rapid sand filter is not as effective when it comes to microplastics that have sizes less than 200 µm. In addition, pre-treatment processes are indispensable. In contrast, MicroXtract not only doesn't require a pre-treatment process, technically speaking, it can filter out microplastics smaller than 1 $\mu$m, due to the porosity of our filter.

Researchers Dounia Elkhatib, Vinka Oyanedel-Craver, and Elvis Carissimi studied the efficiency of electrocoagulation for microplastics removal [8]. “Electrocoagulation consists of pairs of metal sheets called electrodes, that are arranged in pairs of two—anodes and cathodes. Using the principles of electrochemistry, the cathode is oxidized (loses electrons), while the water is reduced (gains electrons), thereby making the wastewater better treated” [9]. The efficiency of the electrocoagulation process in which the percentages of removal, according to the study, is about 90% to 99%. The electrocoagulation process provides a method for treating microplastics without adding any chemicals, juxtaposed to a rapid sand filter, which requires chemical pre-treatment. Electrocoagulation requires electrodes to feed the current into the solution. However, the process of coagulation is difficult and places a lot of strain on the electrodes themselves, resulting in wear and tear. Thus, regular cleaning and maintenance of the electrodes are involved in the process. This can be labor-intensive work, without mentioning the cost. Therefore, this leads to a short life span for the electrodes, which need to be exchanged often. Similarly, MicroXtract requires maintenance for the device to successfully operate, though not often, thus offering an advantage over existing solutions.

Researchers Fan Liu, Nadia B. Nord, Kai Bester, and Jes Vollerton investigated how a biofilter can remove microplastics [10]. Biofiltration is a pollution control technique using a bioreactor containing living material to capture and biologically degrade pollutants. The result of their study is that there are still microplastics left that are not filtered out. However, the biofilter was able to reduce the amount of microplastics in wastewater by 79% to 89%. The biofilter method does contain a few downsides, such as a large surface area needed and the filter material must be periodically replaced. Compared to MicroXtract, which has a much smaller size, expectedly, it is expected to have weaker power to extract microplastics, but with thousands of MicroXtract deployed, a promising microplastics removal rate could be achieved.

# Challenges

In order to construct the project, a few challenges have been identified as follows.

## Selection of Materials

A key hurdle in advancing this filtration system centers on the critical selection of materials. The project's overarching goal of alleviating microplastic pollution in freshwater ecosystems demands a strategic approach to minimize reliance on plastic-based materials. This emphasis is crucial to ensure alignment with the project's fundamental intentions. Excessive use of plastic components in our material choices poses a direct contradiction to the project's purpose. The risk lies in the potential gradual degradation of these plastics, leading to the generation of microplastic particles that could inadvertently infiltrate freshwater environments—precisely the opposite of our intended outcome.

The significance of material selection for this filtration system cannot be overstated, given its direct implications for the project's overall efficacy. Opting for pre-fabricated microplastic filters proves impractical, as they often come with prohibitive costs, running counter to the cost-effective objective intrinsic to this project. However, simply choosing non-plastic materials may hinder the effectiveness of the filter and thus subvert the purpose of the project as a whole—to remove microplastics. Consequently, our approach entails the development of a customized, economically efficient filtration system. Despite being made from plastics, PVC pipes emerge as a promising choice, as they are extremely cost-effective and render the filter more effective than other materials, offering a viable solution to address the challenge at hand. Indeed, the current solution is just a prototype, and the materials can be replaced by more environmentally friendly ones, but due to the limited resources and the cost-effective nature of the project itself, PVC pipes serve an incredible job for now.

## Maintaining the Confidentiality of User Information

Ensuring the exclusive association of each device with its respective user is crucial to safeguarding privacy and preventing data crossover between users. This challenge is pivotal in maintaining the confidentiality of user information. In the scenario of mass-producing the microplastic filter device, each unit is assigned a unique ID stored in the Firebase database. Initially ownerless, these IDs only acquire a user association during registration. Users input the device ID during registration, streamlining the process for both users and administrators. The application then records the user's ID under the corresponding device ID in the Firebase database, establishing clear ownership. This meticulous procedure guarantees the protection of each user's device and data, averting any inadvertent exposure to unauthorized individuals.

## Methodology

The structure of this project consists of three main components: the hardware, the microplastic filter, and the application. The hardware includes all electronic components mounted on a buoy-style platform supported by pontoons, allowing the device to float stably in natural freshwater environments such as rivers or lakes. A sealed PVC pipe now houses the filtration system, preventing overflow and acting similarly to a reverse osmosis filter. When the system is activated, a 12V solar panel powers the submersible water pump, which draws water through an eco-friendly silicone tube into the filter [14]. The contaminated water then passes through a multi-layer filtration system composed of rocks, coarse sand, fine sand, cloth, and carbon filters, effectively trapping microplastics. Clean water exits through another tube connected to the filter and returns to the surrounding water body. A second 6V solar panel powers a Boron LTE microcontroller, which collects and transmits sensor data. The system includes a TDS sensor, a turbidity sensor, and a temperature sensor, all powered by solar energy. The microcontroller translates the sensor data into readable values and transmits them to a Firebase database in real-time [15]. Users can log into the companion mobile application, register the device, and instantly view live and historical water quality data.

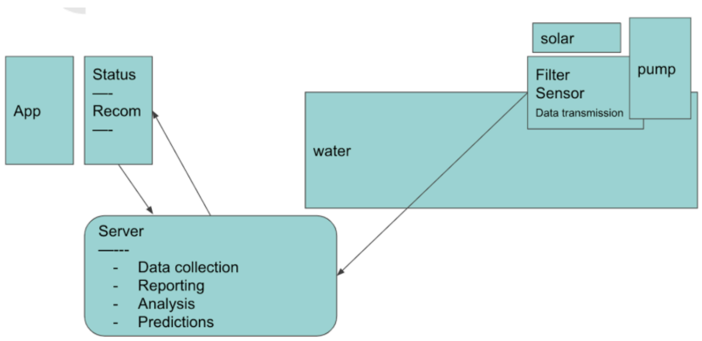


**Figure 1**. Overview of the Solution

The electronics component manages all system operations and data processing within the device. It includes a submersible water pump that draws water into the filtration system and three scientific sensors—a TDS sensor, a temperature sensor, and a newly added turbidity sensor—that collect and relay data to the microcontroller. The TDS (Total Dissolved Solids) sensor does not directly measure solid particles, but instead detects the electrical conductivity of dissolved substances in the water. Higher conductivity often indicates more dissolved solids, which can disrupt aquatic ecosystems by altering water chemistry. Elevated TDS levels may lead to issues like algal blooms, habitat degradation, and skin irritation, while low TDS supports healthier aquatic conditions and reduces maintenance risks [11]. The sensor works by emitting a small, harmless electrical current through the water and tracking how well the current flows—this is then converted into an indirect TDS reading. Since temperature can influence conductivity, a temperature sensor is required to provide real-time thermal compensation. In addition to improving TDS accuracy, the temperature sensor also offers insight into seasonal changes in water temperature, which may impact filtration performance over time. All sensor data are processed by a Boron LTE microcontroller, which supports both cellular (LTE Cat M1) and Bluetooth Low Energy (BLE) connectivity. Based on the Nordic nRF52840 chip, the Boron includes built-in battery charging circuitry for seamless integration with a solar-powered Li-Po battery setup. It serves as the central hub of the system, translating sensor input into readable values and transmitting them to a Firebase real-time database for remote access. All electronics are mounted on a floating platform with pontoons, which keeps the system stable and buoyant in rivers or lakes, allowing the electronics and filtration components to operate reliably in natural water environments.

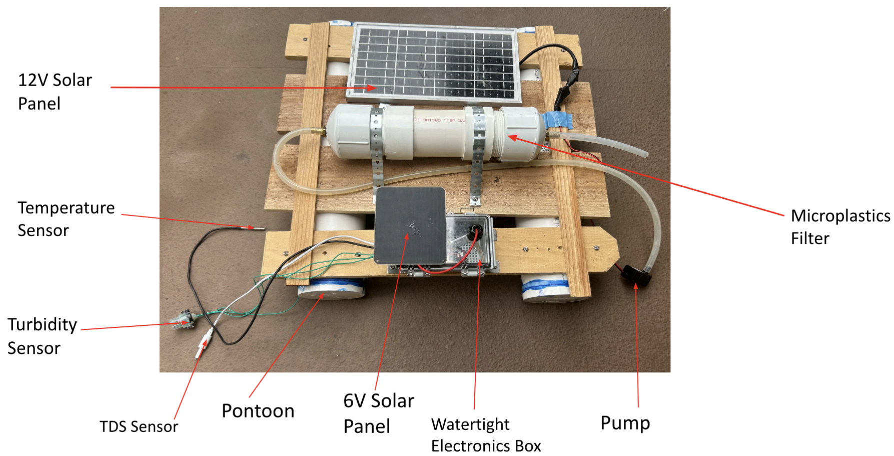


**Figure 2.** The Components

**Figure 3.** MicroXtract in a Real-world Setting

```
void loop() {
    if (millis() - timeStamp > sampleRate)
    {
        timeStamp = millis();
        analogBuffer[analogBufferIndex] = analogRead(TDSpin);
        analogBufferIndex++;
    }

    if (analogBufferIndex >= SCOUNT)
    {
        analogBufferIndex  = 0;
        averageVoltage = 0;


        turbidity = analogRead(Turbiditypin);

        temperature = sensor.getCRCTempC();
        sensor.requestTemperatures();

        calculateTDSvalue();
        publishData(TDSvalue);
        delay(5000);
    }
}

void calculateTDSvalue(){
    for(copyIndex=0;copyIndex<SCOUNT;copyIndex++){
      analogBufferTemp[copyIndex]= analogBuffer[copyIndex];
    }

    averageVoltage = getMedianNum(analogBufferTemp,SCOUNT) * (float)VREF/ 1024.0; // read the analog value more stable by the median filtering algorithm, and convert to voltage value
    float compensationCoefficient=1.0+0.02*(temperature-25.0); //temperature compensation formula: fFinalResult(25^C) = fFinalResult(current)/(1.0+0.02*(fTP-25.0));
    float compensationVolatge=averageVoltage/compensationCoefficient; //temperature compensation

    TDSvalue = (133.42 * compensationVolatge * compensationVolatge * compensationVolatge - 255.86 * compensationVolatge * compensationVolatge + 857.39 * compensationVolatge) * 0.5; //convert voltage value to tds value
}
```

**Figure 4.** Main part of the microcontroller’s code

In Figure 4, the first void function called loop is responsible for continuously sending data to the Firebase database every 5 seconds, which is why there is a delay (5000). It requests the temperature data from the temperature sensor and uses that as an input for calculating the TDS value. It will then call the calculated TDS value function, publishing the data afterward. Turbidity data is also requested from the sensor. The second function, titled calculateTDSvalue, contains a series of formulas that are built on top of each other to get the final TDS value. In this algorithm, we use the median of the average voltage data because it is the safest and most stable. A float variable named compensationCoefficient is being created to store the result of the formula that takes in temperature as an input; another variable, compensationVoltage, stores the value of the averageVoltage divided by compensationCoefficient. The variable for TDS stores the result of a formula that calculates the TDS value while incorporating the compensationVoltage variable.

The filter component is responsible for sieving out microplastics and potentially other detrimental substances from the contaminated water. Inside the filter, there are 6 layers of ordinary materials: activated carbon is the first layer, rocks are the second layer, coarse sand is the third layer, fine sand is the fourth layer, cloth is the fifth layer, and finally, activated carbon is the last layer. The multi-layer technology of filtration will make sure no microplastics can slip through. Eventually, the microplastics would get stuck inside the layers. Clean water will then travel via another silicone tube and back to the freshwater environment.

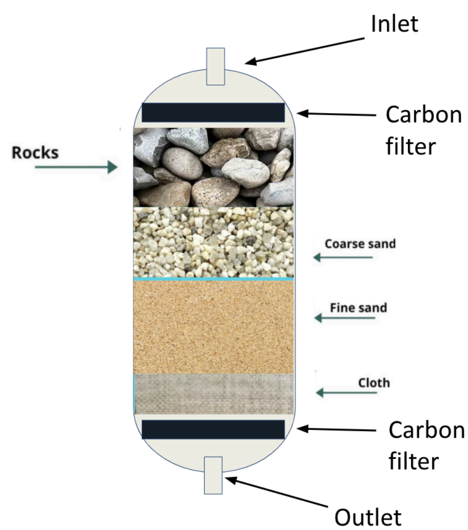


**Figure 5.** A Breakdown of the Filter

This filter is sieving out microplastics and other harmful substances as long as there is water flowing through the filter. The relatively big substances tend to get trapped in the first two layers, which are coarse sand and rocks. Since these two layers are made up of objects that have larger sizes compared to the last two layers, they have a relatively larger pore size, meaning small substances like microplastics can slip through. Microplastics' sizes range from 1 to 1000 $\mu$m [5]. The pore size of fine sand is 0.425 mm, which is equivalent to 425 $\mu$m. Due to the pore size of fine sand, it can already tackle about 42.5% of the sizes of microplastics [6]. But microplastics aren't always going to have the smallest sizes, according to the size range of microplastics. Still, we have to consider the edge cases that a small portion of microplastics could be comparatively diminutive, and that is why we added the layer of cotton cloth. The porosity distribution for cotton fabrics supported the idea that the pores tend to be around 50 nanometers, which is 0.05 micron [4]. This piece of information tells us that not only can the cloth layer of the filter successfully tackle every possible size of microplastic, but it might even be able to trap some nanoplastics. In addition, there are activated carbon filters, which are even less porous, fully preventing any microplastics from passing through.

The application is called MyRiiver, which consists of 3 main subparts—frontend screen, home screen, and settings screen. The frontend of this app was created using Flutter, which is an open-source UI software development kit created by Google. It is used to develop cross-platform applications from a single codebase for any web browser. When the user opens the application, the first screen would be seen containing our app logo, textboxes to enter email and password, and a login button to allow the user to enter the main gist of this application. If the user does not have an account, there is a sign-up button available to click in which takes the user to the sign-up screen. It requires the user to enter their email and password. The users' emails and passwords will be safely stored in the Firebase database. When the user gets to the home page, it would first show that no device is registered with a Register Device button at the bottom. By clicking on the button, the user needs to type in their device ID and name their device. When the device is registered and the sensors start detecting the water, data will be shown: TDS value in ppm and temperature, with date of the data taken. There is a refresh button at the bottom for the user to click to get the latest data from the sensors. On the home page, there is also a frequently asked questions (FAQ) button that contains frequently asked questions to help the user further navigate through the application. An account icon will be shown on the top right corner of the home page, and the user will get to the settings screen when they click on it. The user will see the email they used when they signed up, and they can either log out or delete the account.

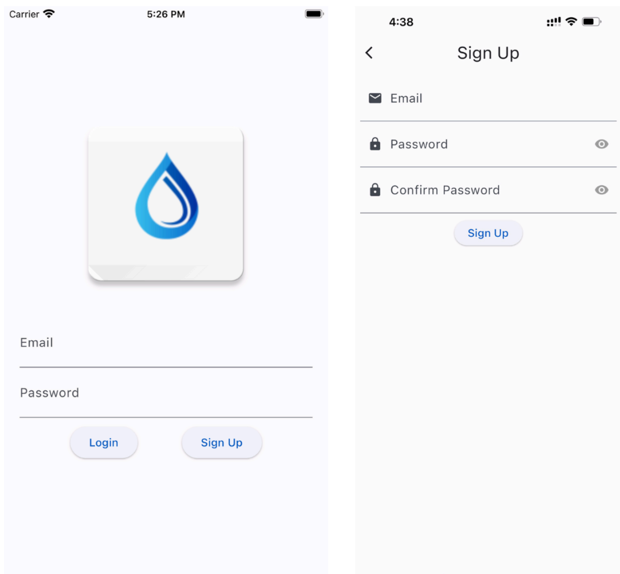


**Figure 6.** Main Page and Sign Up Page

```
void onPressedLoginButton() async {
  if(_formKey.currentState!.validate()){
    try {
      String email = emailController.text;
      String password = passwordController.text;
      await FirebaseAuth.instance.signInWithEmailAndPassword(
          email: email, password: password);
      navigateToHomePage();
    }
    on FirebaseAuthException catch(e){
      if(e.code == 'user-not-found'){
        showSnackBar('That Email is not registered');
      }
      else if(e.code == 'wrong-password'){
        showSnackBar("Wrong password.");
      }
      else{
        print(e.code);
        showSnackBar("Can't connect, please try again later.");
      }
    }
  }
```

**Figure 7.** Main and Sign Up Page Code

The code above checks if the user is entering the correct email and password when trying to log in. If the user enters the wrong password or email, this part of the code is triggered. There are two string variables created: email and password. The email variable stores the email the user entered, and the password variable stores the password the user typed in. Then it receives the error that firebase gives since all the email and passwords are stored in firebase database; if the error is "user not found", then it means the email is not registered so there would be an error message popped up on the application telling the user the email is not registered; on the other hand, if the password is wrong, the error message would then change to wrong password.

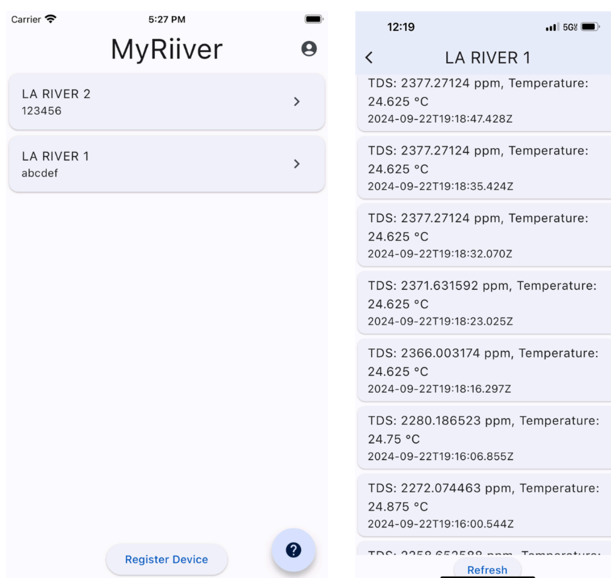


**Figure 8.** Home Page

```
  );
}

Widget deviceListView(Map<dynamic, dynamic> data){
  List<dynamic> keys = data["devices"].keys.toList();
  return Column(
    children: [

      Expanded(
        child: ListView.builder(
          itemCount: keys.length,
          itemBuilder: (context, index){

            String deviceName = data['devices']["${keys[index]}"];
            String deviceID = keys[index];

            return Card(
              child: ListTile(
                title: Text(deviceName),
                subtitle: Text(deviceID),
                trailing: Icon(Icons.chevron_right),
                onTap: (){
                  navigateToDeviceDetailsPage(deviceID, deviceName);
                },
              ),
            );
          }
        ),
```

```
FutureBuilder deviceDataFutureBuilder(){
  // String path = "deviceList/${widget.deviceID}/data";
  String path = "e00fce683127b7ea952c6b90";
  return FutureBuilder(
    future: FirebaseDatabase.instance.ref(path).limitToLast(25).get(),
    builder: (context, snapshot){
      if (snapshot.hasError) {
        return const Center(
          child: Text(
            'An Error has Occurred',
            style: TextStyle(fontSize: 18),
          ),
        );
      }
      else if (snapshot.hasData) {
        if(snapshot.data.value == null){
          return noDataView();
        }
        else{
          return Column(
            children: [
              Expanded(child: dataListView(snapshot.data.value)),
              ElevatedButton(
                  onPressed: (){ setState(() {}); },
                  child: const Text("Refresh")
              )
            ],
          );
        }
      }
```

**Figure 9.** Home Page and Device Details Page Code

This piece of code in Figure 9 displays all the devices registered under the current account. When the user enters the home page, the devices would be displayed in a list with the name of the device and the ID. The user can click any one of the devices to instantly view the real-time data. There are two variables made in this code: deviceName and deviceID, which are stored when registered.

The second piece of code is triggered when the user clicks the device card, and the application goes to the device details page. It checks if there is any error; if so, it displays the error message. Then it checks if the data is empty; if so, it displays no data. Otherwise, it will display the data in lists with each one in a card, which contains the TDS value at that moment in ppm and the temperature with a date on the moment the data is taken. Turbidity data is not showing yet on the app in Figure 8 because the App Store is still processing our request to update the app to include turbidity.

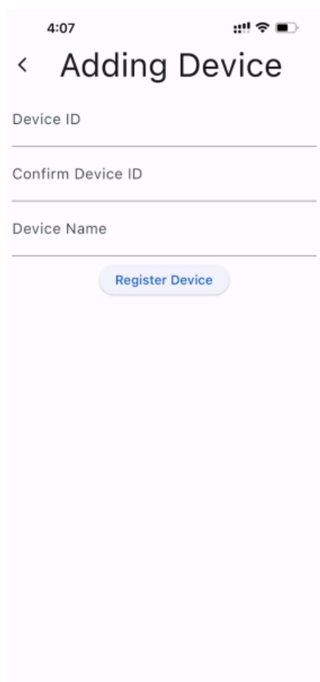

**Figure 10.** Device Registration Page

```
void onPressedRegisterDevice() async {
  if(_formKey.currentState!.validate()) {
    String deviceListPath = "deviceList/${deviceIDController.text}";
    DataSnapshot data = await FirebaseDatabase.instance.ref(deviceListPath).get();
    print(data.value);

    if(data.value == null){
      showSnackBar("The Device ID does not exist?");
    }

    Map<String, dynamic> dataMap = Map<String, dynamic>.from(data.value as Map);

    if(dataMap.containsKey("uid")){
      String uid = dataMap['uid'] as String;
      if(uid.length > 1){
        showSnackBar("This DeviceID is already registered.");
      }
      else{
        showSnackBar("Registering...");
        dataMap['uid'] = FirebaseAuth.instance.currentUser!.uid;
        await FirebaseDatabase.instance.ref(deviceListPath).update(dataMap);
        await updateUsersDevices(deviceIDController.text, nicknameController.text);
        showSnackBar("This DeviceID is Free .");
        navigateToHomeScreen();

      }
    }
```

**Figure 11**. Device Registration Page Code

Figure 11 shows the section of code that checks if the device ID the user enters is included in the Firebase database [13]. If the returned value from Firebase is empty, then the device ID the user entered doesn't exist. It also checks if the device ID is already registered. After passing all those checkpoints, the device should be successfully registered and stored in the Firebase. There are two variables being created: a string variable called deviceListPath and a data variable that holds the data transmitted back from Firebase.

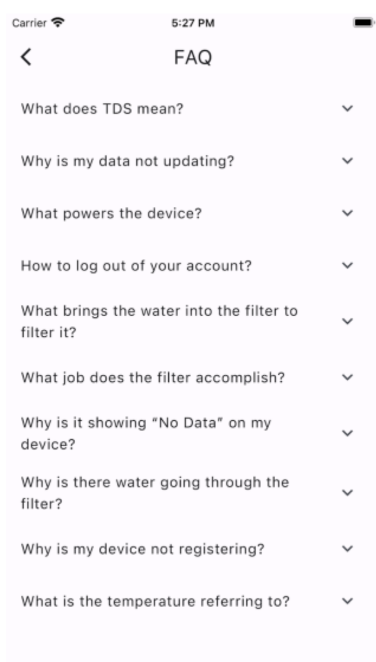


**Figure 12.** FAQ Page

```
Widget faqBody(){
  return const SingleChildScrollView(
    child: Column(
      children: [

        ExpansionTile(
          title: Text('What does TDS mean?'),
          children: [
            ListTile(title: Text("It stands for total dissolved solids. These can be organic and inorganic substances s
          ],
        ),

        ExpansionTile(
          title: Text('Why is my data not updating?'),
          children: [
            ListTile(title: Text("You have to manually click the refresh button at the bottom to see the latest data up
          ],
        ),

        ExpansionTile(
          title: Text('What powers the device?'),
          children: [
            ListTile(title: Text("The Sun, because there are two solar panels that power all the electronics."))
          ],
        ),
```

**Figure 13.** FAQ Page Code

This piece of code is part of the FAQ page, where it will run when the user clicks the FAQ button at the bottom right corner of the home page. Here are all the pre-made FAQs that are hard-coded into the program. We used expansion tiles here to make it easy to navigate to any question with a single click. The question answer will then drop down like a drop-down menu.

## Experimental Results

Exploring the efficacy of MicroXtract's microplastic filtration process is critical to addressing potential blind spots, particularly if the filtration's effectiveness proves to be suboptimal, indicating insufficient microplastic entrapment. Conducting an experiment becomes imperative to thoroughly assess the functional capabilities of the project. This experiment aims to provide insights into the system's performance, ensuring that it meets the necessary standards in microplastic removal. By meticulously evaluating the filtration process under various conditions, we can gain a comprehensive understanding of its functionality, enabling us to make informed enhancements and optimizations if required.

To evaluate the performance of the MicroXtract device under varying environmental conditions, three sets of experiments were conducted, each under a different level of solar exposure: 100%, 90%, and 80%. Each condition consisted of five trials using 10 liters of lake water contaminated with 10 grams of microplastics per trial. All trials were conducted from 10 AM to 4 PM under similar temperatures and sunlight. Multiple water quality parameters were measured before and after filtration, including Total Dissolved Solids (TDS in ppm), turbidity (NTU), and water temperature (°C). The mass of microplastics remaining after filtration was also recorded to assess the removal efficiency.

**Table 1**. Results with 100% Sunlight Exposure

| Trials | Water Amount (L) | Initial TDS (ppm) | Final TDS (ppm) | Initial Turbidity (NTU) | Final Turbidity (NTU) | Initial Temperature (°C) | Final Temperature (°C) | Initial Amount of Microplastics in Water (g) | Final Amount of Microplastics in Water (g) |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 10 | 18.673 | 20.243 | 442 | 202 | 24.39 | 24.25 | 10.00 | 3.034 |
| 2 | 10 | 17.323 | 19.289 | 439 | 349 | 24.31 | 24.50 | 10.00 | 3.123 |
| 3 | 10 | 20.289 | 17.298 | 398 | 193 | 23.75 | 24.10 | 10.00 | 2.973 |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 4 | 10 | 22.240 | 24.238 | 420 | 340 | 24.00 | 23.90 | 10.00 | 3.045 |
| 5 | 10 | 15.249 | 18.238 | 388 | 243 | 23.99 | 24.14 | 10.00 | 3.215 |
| Average | 10 | 18.755 | 19.861 | 417 | 265 | 24.09 | 24.18 | 10.00 | 3.078 |

At 100% sunlight exposure, MicroXtract achieved the most effective microplastic removal, reducing the final average microplastic mass from 10.00 grams to 3.078 grams, representing approximately 69.2% removal efficiency. Turbidity dropped significantly from an average of 417 NTU to 265 NTU, indicating successful particle filtration. The TDS values fluctuated slightly with an average increase from 18.76 ppm to 19.86 ppm, likely due to changes in ionic concentrations not related to microplastics.

**Table 2**. Results with 90% Sunlight Exposure

| Trials | Water Amount (L) | Initial TDS (ppm) | Final TDS (ppm) | Initial Turbidity (NTU) | Final Turbidity (NTU) | Initial Temperature (°C) | Final Temperature (°C) | Initial Amount of Microplastics in Water (g) | Final Amount of Microplastics in Water (g) |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 10 | 19.242 | 14.893 | 424 | 380 | 24.32 | 23.28 | 10.00 | 4.322 |
| 2 | 10 | 18.092 | 25.982 | 389 | 300 | 23.81 | 24.38 | 10.00 | 3.289 |
| 3 | 10 | 18.289 | 17.239 | 430 | 323 | 23.18 | 24.39 | 10.00 | 4.392 |
| 4 | 10 | 14.928 | 20.829 | 399 | 345 | 24.29 | 23.28 | 10.00 | 4.552 |
| 5 | 10 | 15.280 | 20.190 | 418 | 328 | 24.89 | 23.45 | 10.00 | 4.201 |
| Average | 10 | 17.167 | 19.827 | 412 | 335 | 24.10 | 23.76 | 10.00 | 4.151 |

Under 90% sunlight exposure, filtration efficiency decreased, with an average final microplastic mass of 4.151 grams, equating to 58.5% removal efficiency. Turbidity decreased from 412 NTU to 335 NTU, and water temperature remained stable.

**Table 3**. Results with 80% Sunlight Exposure

| Trials | Water Amount (L) | Initial TDS (ppm) | Final TDS (ppm) | Initial Turbidity (NTU) | Final Turbidity (NTU) | Initial Temperature (°C) | Final Temperature (°C) | Initial Amount of Microplastics in Water (g) | Final Amount of Microplastics in Water (g) |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 10 | 19.574 | 23.329 | 432 | 402 | 24.38 | 23.84 | 10.00 | 5.293 |
| 2 | 10 | 20.195 | 22.295 | 403 | 390 | 23.91 | 22.47 | 10.00 | 5.589 |
| 3 | 10 | 28.250 | 19.497 | 420 | 434 | 24.88 | 25.2 | 10.00 | 4.832 |
| 4 | 10 | 21.489 | 21.428 | 423 | 405 | 24.39 | 24.89 | 10.00 | 5.183 |
| 5 | 10 | 13.280 | 20.497 | 430 | 418 | 23.95 | 24.94 | 10.00 | 5.437 |
| Average | 10 | 20.557 | 21.409 | 422 | 410 | 24.30 | 24.27 | 10.00 | 5.267 |

At 80% sunlight exposure, the device's performance was significantly impacted, with an average final microplastic mass of 5.2668 grams, corresponding to 47.3% removal efficiency. Turbidity reduction was less pronounced, with an average decrease of just 11.8 NTU, and TDS values showed more variability. This drop in efficiency is attributed to the solar panel's limited power output, which affected pump consistency.

In full sunlight, the system ran continuously with a strong, consistent flow. Water passed through the filter efficiently, and microplastics were extracted at a steady rate. However, at 90% sunlight, the system began showing brief interruptions in flow, especially when cloud cover occurred, though filtration still proceeded moderately well. Under 80% sunlight, the solar-powered pump operated intermittently, resulting in slow and inconsistent flow, which visibly impacted microplastic removal—yet even under these conditions, partial microplastic removal was observed.

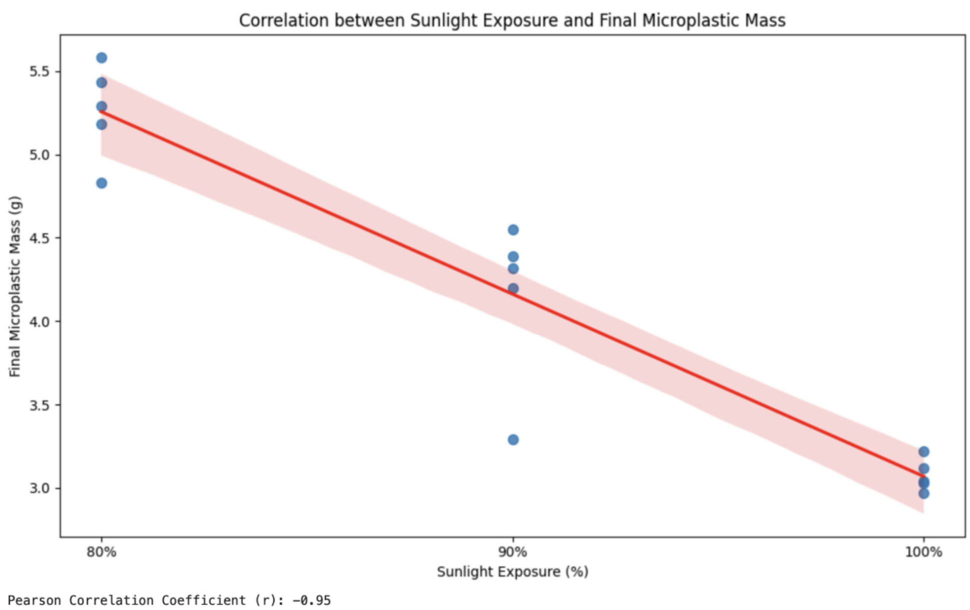


**Figure 14.** Graph of Sunlight Exposure vs. Final Microplastic Mass

After graphing the data points from the experiments, the results show a clear negative correlation between sunlight exposure and final microplastic mass, indicating that greater sunlight exposure improves filtration effectiveness. This relationship is supported by a Pearson correlation coefficient of r = -0.95, confirming a strong inverse correlation between sunlight availability and microplastic levels post-filtration. As solar power is critical to running the pump, reduced sunlight diminished the device's ability to maintain a steady flow and consistent filtration.

With regards to sources of error, while turbidity decreased as expected, TDS readings did not consistently decline, and in some cases increased slightly. This anomaly may be due to the limitations of the TDS sensor, which indirectly measures ion concentration through water conductivity. Since microplastics are non-ionic, their removal has little effect on TDS. Moreover, the turbidity sensor, though capable of detecting suspended solids like microplastics in this controlled experiment, lacks the specificity to distinguish them from other particles, reducing its accuracy in real-world scenarios. These limitations suggest that while the device performs well, more specialized sensors are needed for microplastic-specific monitoring.

These findings highlight the effectiveness of MicroXtract as a solar-powered, autonomous water treatment system, especially in off-grid locations. The system's performance directly depends on solar input, reinforcing the importance of energy availability in remote filtration applications. Although TDS and turbidity sensors provide insight into water quality, the need for low-cost, dedicated microplastic sensors remains critical for improving accuracy. Nonetheless, MicroXtract's modular design and scalable deployment potential position it as a viable, environmentally friendly solution for mitigating microplastic pollution in freshwater ecosystems.

## Conclusion

This study presents MicroXtract, an IoT-enabled solar-powered microplastic filtration system, as an innovative solution to the pressing issue of microplastic pollution in freshwater ecosystems. The device successfully integrated a multi-layer filter with real-time environmental data monitoring, providing both autonomous operation and insightful performance feedback through a connected mobile application. Experimental results demonstrated a clear correlation between solar availability and filtration efficiency, with the strongest performance under full sunlight (removing up to 69.2% of microplastics), confirming that energy input directly impacts removal effectiveness.

MicroXtract offers several advantages over existing methods, including low maintenance, off-grid autonomy, and real-time data tracking—making it especially well-suited for use in remote or under-resourced regions. Its efficient filtration, lack of pretreatment requirements, and simplicity in design offer a practical alternative for widespread application, contributing to the ongoing efforts to mitigate the global impact of microplastics on aquatic ecosystems. MicroXtract's design bridges a critical gap in microplastic mitigation technologies, particularly in freshwater environments, where few solutions exist. As the first of its kind to focus specifically on freshwater microplastic filtration in an affordable and scalable manner, MicroXtract holds significant promise for broader deployment and impact.

Still, several limitations in the project should be addressed for enhanced effectiveness. Firstly, the experimental conditions may not precisely replicate real-world scenarios, potentially impacting the generalizability of findings. The simplistic approach to microplastic introduction and the idealized laboratory environment may oversimplify the complexities of natural water bodies [11]. Additionally, the experiments did not account for potential variations in water quality, which could influence filtration efficiency. Furthermore, the impact of factors like water turbulence, temperature fluctuations, and different microplastic types warrants further investigation [12]. To improve the project, more sophisticated experimental setups mimicking realistic conditions, diverse microplastic sources, and comprehensive water quality assessments could be incorporated. Moreover, refining MicroXtract's design based on detailed analysis of experiment outcomes and conducting long-term field tests in diverse environments would provide valuable insights for optimizing the system's practical applicability. Continued iterations and experimentation would contribute to a more robust, adaptable, and efficient microplastic filtration solution. Future research may focus on developing an affordable microplastic-specific sensor to improve detection accuracy and enable long-term data analysis. With such advancements, MicroXtract could also contribute to identifying pollution hotspots and informing data-driven environmental policy. Additionally, future iterations of the system may incorporate AI-powered analytics to detect abnormalities and predict pollution trends, further expanding its environmental value.

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