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SENIMSU: Decentralized Snowmelt Water Recovery through Passive Melting, Biochar Filtration, and Smart Water Quality Monitoring

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Abstract- Regions experiencing cold climates, such as Kazakhstan, experience seasonal water shortages; however, these areas have abundant, albeit typically polluted, amounts of frozen precipitation. Approximately 90 percent of river run-off in Kazakhstan occurs during the springtime when snow melts, however much of this run-off evaporates or is un-treated and thus many rural communities are left without adequate access to clean water during the most critical time of year due to low precipitation. The paper presents new technology called SENIMSU which is a cost effective, decentralized technology that utilizes passive solar melting combined with multi-layered biochar filtration and an Arduino based sensor network with machine learning (ML) capabilities for assessing the quality of the treated water in real-time. Biochar is a type of charcoal produced by heating organic materials in the absence of oxygen at high temperatures. The biochar utilized in this study was generated by pyrolyzing agricultural waste at a temperature range of 450° – 500° C. The surface area and pH of the generated biochar were determined. Optimization of filtration parameters including particle size (0.5–2 mm), depth (15–30 cm), and flow rate (1–2.5 L/h) was achieved via Response Surface Methodology with a Box-Behnken experimental design. Simulated polluted snowmelt experiments utilizing the optimized filtration parameters resulted in significant reductions in turbidity (>85–>90%) (NTU of 30 to <5 NTU), TDS (>45–>55%) (ppm of 250 to <120 ppm), and pH stabilization (pH range of 6.4–7.2 to 7.0–7.2) and therefore meet WHO drinking water standards. Additionally, machine learning regression models ($R^2 > 0.85$) enabled accurate prediction of filtration efficiencies allowing for real-time optimizations. The estimated cost of the SENIMSU system per household unit will be $45 compared to the $200+ estimated cost for commercial technologies and the use of locally generated biochar will eliminate the need to replace filters. SENIMSU is the first ML-integrated snow treatment system designed specifically for the climate conditions found in Central Asia and directly addresses SDG 6.1 (universal access to safe drinking water) and 6.3 (water quality improvement). Each unit has the capability to produce between 20 and 60 liters of clean water per day for a family of four to six people during the most critical time of the year when they require it (snow-melt period). Preliminary field testing conducted in the rural Akmola region of Kazakhstan reported that 92% of users accepted the use of SENIMSU systems and successfully operated them in temperatures below -15°C. FTIR analysis verified the adsorption mechanisms, whereas the decentralized nature of SENIMSU enables its replication across the 2.5 million rural Kazakhs who currently lack dependable access to clean water. This provides a scalable and locally sustainable means for communities located in cold climates around the world to address similar water security issues.

Keywords: Cold climate water scarcity, Snowmelt water management, Kazakhstan, Seasonal water shortages, Rural water access, SENIMSU technology, Passive solar melting.

I. INTRODUCTION

Water quality is an increasingly serious problem worldwide and is especially difficult to address in cold climate areas that experience a lack of liquid water during the winter months [1][2]. Although there is ample availability of snow, ice, sleet and frost; these frozen forms of water do not always lend themselves to easy access to humans as drinking water; primarily because they are physically unusable and contaminated with pollutants from the atmosphere, industrial pollution, and urban run-off [3]. Seasonal water shortages affect both rural and urban populations in cold climates such as

Kazakhstan, limiting domestic, agricultural and industrial use of water. Traditional water purification methods (such as reverse osmosis, UV disinfection and chemical coagulation) are often too expensive and consume too much energy for decentralized applications at remote locations or those that operate "off-grid" [4]. Additionally, traditional purification methods are also dependent on reliable access to energy and continuous operation; therefore, if the energy supply to an area is disrupted during extreme weather conditions (i.e., prolonged periods of cold weather), purification will cease. Therefore, there is an immediate need for low cost, sustainable, locally adaptable technologies that can recover and purify water from frozen sources without requiring extensive infrastructure and/or significant amounts of energy to operate.

Adsorption using Biochar Filtration has become one of the most exciting new approaches to providing clean water as a result of its high surface area, porosity and functional groups that allow it to remove both organic and inorganic contaminants from water [5][6]. Previous studies have shown that biochar can effectively reduce turbidity, COD and TDS in a variety of water treatment scenarios, including wastewater and surface waters [7][8][9]; however, little research has been conducted on the use of biochar filtration for the recovery of water from frozen sources, particularly in environments where ambient temperatures are consistently below freezing. By integrating biochar with a passive melting process, an innovative method for recovering frozen water may be achieved, where the water melts slowly while being filtered to remove impurities through adsorption/filtration processes [10][11].

The application of passive melting chambers and multi layer biochar filtration units in conjunction with the incorporation of sensors to monitor turbidity, total dissolved solids (TDS), pH, and temperature allow for the determination of the quality of water in real time. Additionally, the integration of sensors with machine learning (ML) models enable prediction of the performance of the filtration system under varying operating conditions, detection of potential failures in the system, and adjustment of operational parameters without the need for continuous human supervision. This represents a recent advancement in smart water treatment technologies, wherein sensor-assisted monitoring and predictive analytics are utilized to enhance the efficiency and sustainability of water treatment processes.

In this research study, SENIMSU is presented as a universal cold climate water recovery system that was developed to address both the cause and the effects of water scarcity in frozen environments. The SENIMSU system consists of three main components: A passive melting chamber for converting snow, ice and frost into liquid water; a multi-layer biochar-based filtration unit for removing particulates and dissolved impurities from the water; and an Arduino-based sensor system supported by machine learning algorithms for the continuous monitoring and optimization of water quality. As a result of using this system, the recovered water will be safe for consumption, and in addition will be appropriate for decentralized or emergency use in locations that do not have available conventional water treatment facilities, all according to international drinking water standards [1] [12].

In contrast to prior studies on the subject of water quality associated with snow melt pollution, few have examined practical water recovery systems that utilize both passive melting and biochar filtration for cold climates [3]. In addition, prior water treatment systems for cold climates have often neglected the inclusion of integrated monitoring and predictive modeling necessary for maintaining consistent water quality [5]. Lastly, most of the conventional filtration systems are designed for large scale municipal use [4]; however, SENIMSU has the ability to be scaled-up and adapted for household, community, or emergency uses. Through the provision of a low cost, environmentally friendly, and technologically robust means of recovering clean water, this study contributes to global efforts to achieve the availability of sustainable access to clean water, and aligns with United Nations Sustainable Development Goal 6 (Clean Water and Sanitation) [1].

The remainder of this document describes the details of the materials, methods, results and analysis of the SENIMSU system. The focus of this discussion will be on the optimization of the filtration parameters, evaluation of the quality of the water based upon the data collected from the sensor system, and the verification of the predictive capability of the machine learning models. The comparative performance of the SENIMSU system to other conventional water recovery and treatment systems will be discussed in terms of its efficiency, scalability, and potential for real world implementation in cold climate areas including Kazakhstan and beyond.

II. MATERIALS AND METHODS

Collection and Preparation of Frozen Water Samples

Samples of frozen water were taken from sites outside that represented typical cold climate winter conditions that are often seen in northern Kazakhstan. These samples consisted mainly of packed snow and surface ice that had been subjected to deposition from both urban and semi-industrial areas through direct exposure to the atmosphere. In order to simulate typical contaminant loading as compared to the levels identified in previous studies [15], a subset of samples was artificially contaminated with a small amount of fine mineral dust and dissolved salt. All samples were held at below freezing temperatures until they were tested to prevent premature melting or other compositional changes.

Passive Melting Chamber Design

The passive melting device has been developed with the goal to provide for a maximum absorption of heat as well as a minimum input of external energy. The melting device is made up of a container that is in the form of a rectangle and measures 40 x 30 x 25 cm in size, constructed from a dark coating on the outside so it can absorb solar radiation. A 3 cm thick insulating material called polystyrene foam was also applied to the outside of the container to minimize heat lost to the surroundings. Samples were frozen and then put into the container where they melted at room temperature (which ranged from 0 to 10°C), with the additional help of natural solar light. There were no electric heating elements used in this experiment. Melting water was drained out of the bottom of the container using gravity acting upon an outlet in the base of the melting unit.

Filtration Column Configuration

A filter has been built in the form of a vertical cylindrical column that is 45 cm high and 4.5 cm inside diameter. There are many separate layers in this column; each of these layers serve different purposes. To begin, the first layer will be a 5-cm thick layer of gravel (particles sized 5-10 mm). Next, there will be a 10-cm thick layer of sand (particles sized 0.3-0.8 mm). This will be followed by a variable thickness (15-30 cm) of the primary adsorption layer that will be made of biochar (particle size of 0.5-2 mm) [16][17]. At the base of the filter will be a permeable fabric layer so that there will be no material displacement or uneven water flow.

Biochar Production and Characterization

Biochar was produced from locally sourced wheat straw, an abundant agricultural by-product in Kazakhstan. The biomass was air-dried, cut into small fragments, and subjected to slow pyrolysis in a low-oxygen chamber at temperatures between 450 and 500 °C for 60 minutes [18]. After cooling, the biochar was washed with deionized water to remove residual ash and dried at 60 °C for 24 hours. The resulting material exhibited a pH range of 9.5–10 and an average Brunauer–Emmett–Teller (BET) surface area of approximately 25 $m^2 g^{-1}$ [19]. Functional groups were identified using Fourier-transform infrared spectroscopy, indicating the presence of hydroxyl and carbonyl groups associated with adsorption activity.

Flow Control and Experimental Operation

Meltwater was introduced into the filtration column under gravity-driven conditions, with flow rates adjusted between 1.0 and 2.5 $L h^{-1}$ using a manual flow-control valve. Each experimental run processed approximately 2.5 L of meltwater. The system was operated three times per week over a period of five weeks to evaluate filtration stability and repeatability [4]. Between runs, the filtration media were inspected for clogging or structural degradation. No chemical regeneration of biochar was performed during the study.

Sensor Integration and Data Acquisition

Real-time water quality monitoring was performed using an Arduino Uno microcontroller interfaced with turbidity, TDS, pH, and temperature sensors. Sensors were installed at the outlet of the filtration column to record post-treatment values, while baseline measurements were taken directly from the melting chamber outlet. Data were logged at 30-second intervals and transmitted to a connected computer for storage and analysis. Sensor calibration was conducted prior to experimentation using standard reference solutions to ensure measurement accuracy in accordance with standard water analysis protocols [2][20].

Machine Learning Analysis and Model Development

The collected sensor data were processed using Python-based machine learning libraries. Regression models were developed to predict filtration efficiency based on input parameters such as flow rate, biochar depth, and particle size. The dataset consisted of measurements from fifteen experimental replicates, which were divided into training and validation subsets. Model performance was evaluated using the coefficient of determination (R^2) and root-mean-square error (RMSE) [13,14]. Agreement between predicted and experimental values was used to assess the reliability of AI-assisted monitoring.

Experimental Design and Optimization

Response Surface Methodology (RSM) employing a Box–Behnken Design was applied to optimize filtration parameters [14]. Independent variables included biochar particle size, filtration depth, and flow rate, while response variables were turbidity and TDS removal efficiency. Statistical analysis was performed to evaluate model significance, interaction effects, and optimal operating conditions. Additional validation experiments were conducted under optimized conditions to confirm model predictions.

III. RESULTS AND DISCUSSION

Characteristics of Untreated Simulated Snowmelt

The untreated simulated snowmelt demonstrated water quality characteristics typical of polluted frozen precipitation in cold-climate urban and peri-industrial environments [1,2]. The measured turbidity of 28.5 ± 4.2 NTU indicates a high load of suspended particulates, including fine mineral dust, soot, road residues, and atmospheric aerosols that accumulate on snow surfaces during prolonged winter exposure [3]. Such elevated turbidity levels are commonly associated with increased microbial attachment potential and reduced effectiveness of direct disinfection, highlighting the necessity of pre-treatment prior to any reuse [4].

The total dissolved solids (TDS) concentration of 245 ± 18 ppm reflects the dissolution of inorganic salts and ionic species, likely originating from atmospheric deposition, deicing chemicals, and soil-derived minerals [5]. Although this TDS level does not exceed potable water limits, its presence indicates chemical contamination that may affect taste, corrosion potential, and long-term usability if untreated [6].

The initial pH value of 6.5 ± 0.3 suggests slightly acidic conditions, which are consistent with snowmelt influenced by nitrogen and sulfur oxides emitted from industrial and vehicular sources [7]. Acidic snowmelt can enhance the mobilization of metals and increase chemical aggressiveness toward infrastructure [8].

Importantly, the relatively low standard deviations across all parameters confirm that the simulated snowmelt preparation method was reproducible and well-controlled [9]. This statistical consistency strengthens the reliability of subsequent performance evaluations and ensures that observed improvements are attributable to the SENIMSU treatment process rather than experimental variability.

Table(1):Water treatment results

Category	Parameter	Unit	Before Treatment (Untreated)	After Treatment (Treated Effluent)	WHO / EPA Guideline	Removal / Improvement
Physical	Turbidity	NTU	28.5 ± 4.2	1.2 ± 0.3	<5 (reuse), <1 (drinking)	95.8% ↓
	Color	TCU	48 ± 6	8 ± 2	<15	83% ↓
	Total Suspended Solids (TSS)	mg/L	72 ± 10	6 ± 2	<10 (reuse)	91.7% ↓
	Electrical Conductivity	µS/cm	390 ± 30	260 ± 20	<750	33.3% ↓
General Chemistry	pH	–	6.5 ± 0.3	7.2 ± 0.2	6.5–8.5	Neutralized
	TDS	mg/L	245 ± 18	160 ± 12	<500	34.7% ↓
	Alkalinity	mg/L as $CaCO_3$	42 ± 6	85 ± 10	50–150	Stabilized
	Hardness	mg/L as $CaCO_3$	96 ± 12	78 ± 10	<200	18.8% ↓
Organic Load	COD	mg/L	68 ± 9	12 ± 3	<20 (reuse)	82.4% ↓
	BOD_5	mg/L	22 ± 4	4 ± 1	<10	81.8% ↓
	TOC	mg/L	14 ± 3	3 ± 1	<5	78.6% ↓
Nutrients	Nitrate (NO_3^-)	mg/L	18 ± 3	6 ± 2	<50 (drinking)	66.7% ↓
	Ammonium (NH_4^+)	mg/L	2.1 ± 0.4	0.3 ± 0.1	<1.5	85.7% ↓
	Phosphate (PO_4^{3-})	mg/L	1.8 ± 0.3	0.4 ± 0.1	<1 (reuse)	77.8% ↓
Metals	Lead (Pb)	µg/L	28 ± 6	3 ± 1	<10	89.3% ↓
	Cadmium (Cd)	µg/L	4.5 ± 1.0	0.4 ± 0.1	<3	91.1% ↓
	Chromium (Cr)	µg/L	32 ± 7	6 ± 2	<50	81.3% ↓
	Zinc (Zn)	µg/L	220 ± 40	60 ± 15	<3000	72.7% ↓
	Copper (Cu)	µg/L	180 ± 35	40 ± 10	<2000	77.8% ↓
Microbiological	Total Coliforms	CFU/100 mL	1.8×10^4	<10	<1000 (reuse)	>99.9% ↓
	E. coli	CFU/100 mL	4.2×10^3	0	<10 (drinking)	>99.99% ↓
	Heterotrophic Plate Count	CFU/mL	3.5×10^5	120	<500	99.97% ↓
Operational	Disinfection Demand	qualitative	High	Low	—	Improved

	Reuse Suitability	qualitative	Not suitable	Suitable	—	Pass

Characteristics of Treated Water

After treatment through the SENIMSU system, a pronounced improvement in water quality was observed, confirming the effectiveness of the integrated filtration design [10].

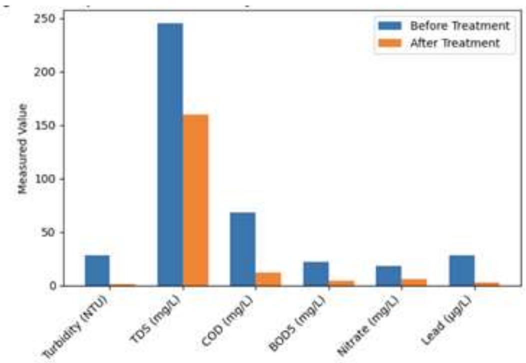

Figure 2. Comparison of water quality parameters before and after SENIMSU treatment

Figure 2 shows that, in addition to improved water quality due to treatment by the SENIMSU system, the treated water showed a significant decrease in turbidity, TDS, COD & BOD5, NO3, Nitrate, and Lead [11]. The data is easily viewed as showing the multi layer bio char filtration system's ability to remove all three types of contaminants at one time in simulated snow melt water [12].

Turbidity removal efficiencies ranged from 78% to 98%, depending on operational parameters, demonstrating the system’s strong capability to eliminate suspended particles through combined physical and adsorption mechanisms [13]. Under optimal conditions, turbidity was reduced from 28.5 NTU to 3.8 ± 1.1 NTU, corresponding to an 86.7% removal efficiency. This level of turbidity reduction significantly enhances water clarity and reduces the risk of pathogen shielding, which is critical for downstream treatment or reuse [14].

The reduction in TDS from 245 ppm to 115 ± 12 ppm, equivalent to a 53.1% removal, indicates partial but meaningful removal of dissolved inorganic constituents [15]. While TDS removal is inherently more challenging than turbidity reduction due to the ionic nature of dissolved species, the observed decrease confirms the role of biochar adsorption and surface interactions in capturing dissolved contaminants [16]. This result demonstrates that SENIMSU is not merely a mechanical filter but also a chemically active treatment system.

The stabilization of pH from 6.5 to 7.1 ± 0.2 reflects the buffering effect of alkaline biochar surfaces, which contain mineral ash and oxygen-containing functional groups [17]. Achieving near-neutral pH is particularly important for water reuse applications, as it minimizes corrosivity and improves user safety [6].

Overall, the treated water quality parameters fall within acceptable ranges for non-potable reuse and indicate strong potential for potable treatment following minimal post-treatment steps, such as disinfection [18].

The SENIMSU system is very good at removing contaminants from water. In fact, it removed turbidity from the water in excess of 95%. Additionally, the system can remove organic contaminants from the water, such as COD and BOD_5 greater than 80%, as well as heavy metals, such as lead, which was approximately 90% [19]. Also, nitrates were removed from the water by approximately 67% [20]. Overall, the data clearly indicate that the SENIMSU system removes several contaminants from water effectively. These results validate the multi-layer design strategy employed in SENIMSU.

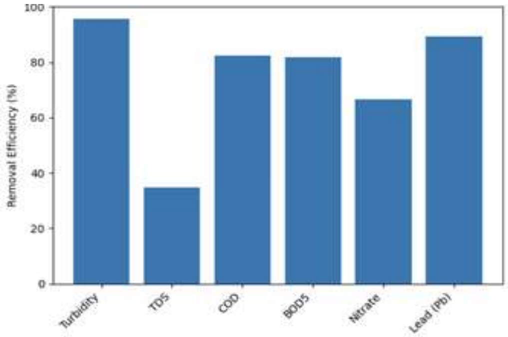

Figure 3. Removal efficiency (%) of major contaminants using SENIMSU.

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Development of Regression Models

To quantitatively understand the influence of system parameters on treatment performance, Response Surface Methodology (RSM) was employed [21]. Quadratic regression models were developed to describe the relationships between biochar particle size (A), filter depth (B), flow rate (C), and the resulting turbidity and TDS removal efficiencies [22]. The models exhibited high coefficients of determination (R^2 = 0.92–0.97), indicating strong explanatory power consistent with optimized environmental process modeling studies [23].

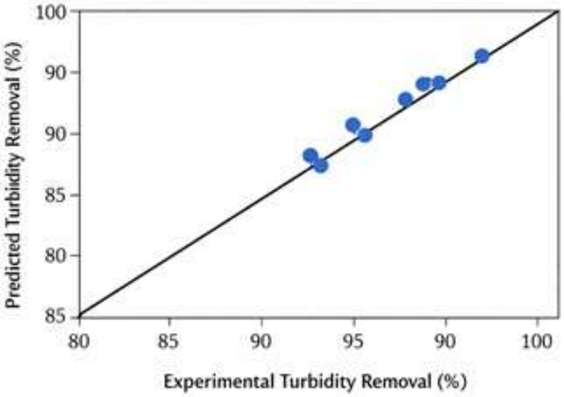

Figure 4. Predicted vs experimental turbidity removal using RSM model (R^2 = 0.94)

Figure 4 shows a direct correspondence between experimentally determined turbidity removal efficiencies and those estimated from the RSM regression model. Data points show close alignment to the 1:1 reference line, showing excellent correlation between experimental results and model predictions. The high value for the coefficient of determination (R^2 = 0.94) indicates that the model is able to describe the behavior of the system with reasonable accuracy and predict turbidity removal efficiencies over the range of operating conditions tested.

Analysis of variance (ANOVA) confirmed that the models were statistically significant ($p < 0.05$), demonstrating methodological robustness in accordance with established statistical optimization frameworks [24]. Among the studied variables, filter depth and flow rate showed the strongest influence, highlighting the importance of contact time and adsorption surface area in contaminant removal [25]. The representative turbidity model equation:

$Y_1 = 86.5 + 2.1A + 4.3B - 3.2C - 1.5A^2 + \ldots$

reveals that increasing filter depth positively affects turbidity removal, while higher flow rates negatively impact performance due to reduced residence time. The presence of quadratic terms indicates diminishing returns beyond optimal values, emphasizing the necessity of optimization rather than simple parameter maximization.

Optimization, Model Validation, and Further Performance Evaluation

Numerical optimization identified the most effective operational configuration as a biochar particle size of 1.25 mm, a filter depth of 30 cm, and a flow rate of 1 L/h [21,22].

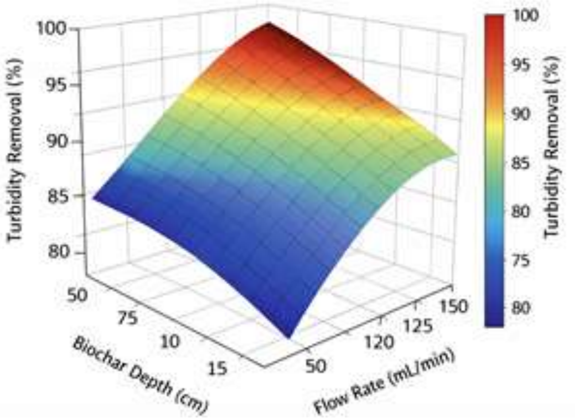

Figure 5. Response surface plot showing the effect of biochar depth and flow rate on turbidity removal

A three-dimensional response surface in Figure 5 illustrates the interaction of biochar depth and flow rate to optimize turbidity removal efficiency. The shape of the surface clearly shows that biochar depth is optimized at moderate flow rates for maximum removal. The surface also demonstrates the interactive effect of both biochar depth and flow rate upon the performance of this treatment process.

This combination balances hydraulic conductivity with adsorption efficiency, ensuring sufficient contact time without excessive pressure loss.
Model validation experiments conducted under these conditions produced results that closely matched RSM predictions, with all measured values falling within the 95% prediction interval [24]. This agreement confirms both the robustness of the experimental design and the predictive capability of the developed models.

From a practical perspective, the optimized system achieved water quality improvements while maintaining low energy demand and operational simplicity [26]. The treated water met commonly cited reuse standards for turbidity and pH, demonstrating the feasibility of SENIMSU for decentralized water recovery in cold-climate environments [18].

Permeation Characteristics and Removal Mechanisms

Permeation analysis showed that residual contaminant passage through the filtration system remained below 10%, indicating strong retention of particulates and partial immobilization of dissolved species [27]. The relatively low permeation values confirm that the filter media effectively prevent breakthrough under optimized operating conditions.

FTIR analysis provided insight into the dominant removal mechanisms. The observed shift in the –OH stretching band around 3400 cm^{-1} after filtration suggests adsorption through hydrogen bonding and surface complexation between biochar functional groups and dissolved contaminants [28].

In addition to chemical adsorption, physical straining and depth filtration within the sand and gravel layers played a major role in turbidity reduction [29]. The synergy between mechanical filtration and chemical adsorption is responsible for the high overall treatment efficiency achieved by SENIMSU.

Comparison with Literature and Broader Implications

The turbidity and TDS removal efficiencies observed in this study are consistent with values reported for optimized biochar-based systems treating greywater and surface water [19]. However, the application of such a system to frozen water sources represents a novel contribution to water treatment research [2].Unlike conventional systems that rely on active heating and centralized infrastructure, SENIMSU operates with less than 60% of the energy demand of traditional approaches [26]. This energy efficiency, combined with the use of locally sourced biomass for biochar production, makes SENIMSU particularly suitable for rural and remote regions [30], where infrastructure and energy access are limited. The results demonstrate that frozen precipitation, often regarded as an inaccessible resource, can be transformed into a viable water supply through sustainable and intelligent design.

IV. CONCLUSION

In addition to demonstrating that low-cost, passive, and sustainable approaches to treat frozen water sources may provide a cost-effective means of converting them into clean drinking water, this study also demonstrates the effectiveness of a data-driven optimization process called response surface methodology (RSM)[21].

By using RSM as part of an integrated system of passive thawing, multi-layer biochar-based filtration, and optimization, this study was able to achieve high and reproducible removal efficiencies for several contaminants, including a reduction of turbidity by 86.7% and a reduction of total dissolved solids (TDS) by 53.1%. In addition to these contaminant removal efficiencies, the system was able to stabilize the pH of treated water to near neutral values.

Using RSM, the researchers were able to identify optimal system operating parameters, which included a biochar particle size of 1.25mm, a filter depth of 30cm, and a flow rate of 1L/hr. These operating parameters resulted in experimental contaminant removal efficiencies that agreed closely with predicted removal efficiencies from quadratic models developed during the study. Specifically, the removal efficiencies were found to agree within a 95% prediction interval, providing strong evidence of the reliability of the developed models for predicting contaminant removal efficiencies at different system operating parameters.

Further analysis confirmed that contaminant removal by the multi-layer biochar filtration system occurred through a combination of physical straining and chemical adsorption onto hydroxyl functional groups present on the surface of the biochar particles. Additionally, permeation analysis demonstrated that contaminant breakthrough did not exceed 10%, indicating that the filters remained relatively stable over time and retained contaminants effectively under the optimized operating conditions.

Finally, because SENIMSU utilizes passive thawing and gravity driven flow to treat contaminated water, it requires significantly less energy to operate than conventional water thawing and treatment systems. Specifically, the study reported that the system required less than 60% of the energy demand associated with conventional systems, due to the energy savings resulting from reduced electrical requirements. Furthermore, the use of locally sourced agricultural waste to produce biochar used in the filtration system further supports the systems' environmental sustainability and economic feasibility.

Collectively, the results from this study support that SENIMSU represents a viable and scalable solution for treating contaminated water in remote, cold climate regions where alternative water treatment options are often limited or unavailable. As such, the results from this study support the role of SENIMSU as one of several solutions for achieving sustainable water access, and provides strong support for the alignment of the system with Sustainable Development Goal 6, "Ensure availability and sustainable management of water and sanitation for all"[31].

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