Integration of the RANAS and UCD Models in the Development of a Filter to Improve Water Treatment in the Valle De Mezquital

Maya Bautista Jukari[1]*, Navarro Ordoñez Diana Mariel[1], Rivera Escalante Daniel[1]

Industrial Engineering, Instituto Tecnológico de Pachuca, Pachuca de Soto, Mexico.

DOI: https://doi.org/10.47772/IJRISS.2026.102500011

Received: 22 October 2026; Accepted: 27 October 2026; Published: 14 November 2026

ABSTRACT

Water pollution in the Tula River basin and the proliferation of water hyacinth (Eichhornia crassipes) in the Endhó Dam, Mexico, represent two related environmental problems: the deterioration of water quality and the large volumes of invasive biomass removed during restoration activities. This study proposes the development of a magnetic biochar derived from local water hyacinth as an adsorbent for specific contaminants, initially As(V), and integrates the User-Centered Design (UCD) approach of ISO 9241-210:2019 with the RANAS behavior change model (Risk, Attitude, Norm, Ability and Self-regulation) to align the technical development with the needs of riverside communities. The manuscript is presented as an exploratory simulation of filter performance and a proposed research framework; it does not report validated experimental measurements. A mixed exploratory-experimental design was organized in nine sequential phases, beginning with a PRISMA 2020 systematic review of 28 studies that defined four design requirements: iron modification, evaluation with real water, magnetic recovery and reuse, and safe disposal of the spent adsorbent. As a pilot test, a 500-run Monte Carlo simulation of As(V) removal was performed, with explicit input distributions derived from previous studies. Under an initial concentration of 0.100 mg/L, a pH close to 7, an adsorbent dose of 2 g/L and a contact time of approximately 60 min, the simulation estimated a mean final concentration of 0.0082 mg/L, a mean removal efficiency of 91.84 % and an adsorption capacity of 0.046 mg/g; the 95 % interval of the efficiency ranged from 86.05 to 95.53 %, and 19.6 % of the runs exceeded 0.01 mg/L. A sensitivity analysis showed that this efficiency would keep the final concentration below the World Health Organization guideline value of 0.01 mg/L only for initial concentrations up to approximately 0.1225 mg/L. In addition, ten user requirements, a 19-item RANAS questionnaire, a UCD protocol and an IBM SPSS Statistics 19 analysis plan were developed for the community validation stage, with a sample size of 379 participants preceded by a pilot application to 38; the application has not yet begun, since it requires ethics committee approval and the measured results of the controlled laboratory test. The values obtained are model estimates rather than measurements. A preliminary trial with water from the area was not analyzed with validated analytical instrumentation and is not reported as evidence; a controlled laboratory test under strict analytical standards is under way, while column trials, evaluation with real water, safe disposal of the spent adsorbent and ethical community trials constitute the next steps of the research.

Keywords: water hyacinth, magnetic biochar, arsenic removal, user-centered design, RANAS model

INTRODUCTION

Water pollution is a global problem that goes beyond the degradation of ecosystems and directly affects the health, dignity and development opportunities of communities. According to the World Health Organization (WHO, 2026), at least 1.4 million deaths per year are related to unsafe water, sanitation and hygiene conditions; likewise, 2.1 billion people lack safely managed drinking water and 3.4 billion do not have safely managed sanitation services. Although these indicators do not exclusively measure the pollution of water bodies, they make it possible to gauge the inequalities associated with exposure to water-related risks. For this reason, the WHO strategy for 2026–2035 places water, sanitation, hygiene and waste management as components of public health protection, with particular importance for the most deprived populations.

In Mexico, the problem manifests itself in simultaneous pressure on the availability and quality of the resource.

CMDA (2026) states that 157 of the country's 653 aquifers are overexploited and estimates that 60 % of the monitored surface water shows some degree of pollution; these figures correspond to what was reported by that publication and should be interpreted according to its own sources and scope. For his part, Benet (2025) states that approximately 70 % of the country's basins and water bodies show serious signs of degradation; since it comes from an opinion source and uses a different indicator, this percentage is not directly comparable with the previous one.

Furthermore, in the state of Hidalgo, the Tula River basin represents a particularly relevant case due to the convergence of wastewater discharges, alteration of receiving water bodies and impacts expressed by the communities. Sánchez (2026) documented the allocation of more than 900 million pesos in 2026 for the sanitation of the Tula River, including about 38 kilometers of drainage collectors in the metropolitan area of Tula, Atotonilco and Atitalaquia, water-quality monitoring and the cleanup of the Endhó Dam. Likewise, Juárez (2026) reported that the federal recovery program covers 74 kilometers of the Tula River and that its first stage was 62 % complete as of July 16, 2026; the program includes the Endhó Dam, located between Tula de Allende and Tepetitlán. These measures recognize that water recovery requires comprehensive and sustained actions, not merely the removal of visible waste.

With regard to the Valle de Mezquital, the problem takes on a concrete social dimension for those who live next to the Endhó Dam. A report by Villaseñor (2026) in La Jornada states that around 27,000 people live in 27 riverside communities and describes how the proliferation of mosquitoes, odors and the presence of water hyacinth have changed domestic, productive and recreational activities. Testimonies from San Mateo la Curva, San Pedro Nextlalpan and La Ermita show the continuous use of mosquito nets, repellents and smoke to cope with the insects. In turn, López Castillo (2026), drawing on a journalistic investigation by The New York Times, presents community concerns regarding illness and the quality of well water.

In addition to pollution, there is the proliferation of water hyacinth (Eichhornia crassipes), whose accumulation hinders the environmental management of the dam and generates large volumes of biomass after its removal. Based on information attributed to the Ministry of Environment and Natural Resources (SEMARNAT, 2025), it is recorded that in January 2025 the water hyacinth covered approximately 986 hectares, equivalent to 78 % of the dam's surface, and that more than 32,000 tons were removed during that year. These figures are included as documented background in the project file and not as data directly verified in the nine consulted links. As a result of this situation, the coexistence of polluted water and invasive biomass offers an opportunity to investigate complementary treatment alternatives that, in addition to responding to an environmental need, can provide useful knowledge for the affected localities.

Although public interventions prioritize the sanitation of discharges, the control of water hyacinth and the rehabilitation of the basin, an applied research gap remains: the performance of a magnetic adsorbent material made from local water hyacinth has not been demonstrated for the specific conditions of the selected water in the area of the Tula River and the Endhó Dam, nor have its recovery and possible reuse been sufficiently defined. Therefore, this gap does not imply that magnetic biochar is an unprecedented technology, but rather that its performance under the physicochemical characteristics and needs of the study area is unknown. Thus, it is necessary to move from the technical possibility described in the literature to a local experimental evaluation.

Based on the above, the following hypothesis is proposed: magnetic biochar made from water hyacinth collected in the area of influence of the Tula River and the Endhó Dam will show an effectiveness in removing specific contaminants, initially As(V), that will depend on the composition of the local raw material and the physicochemical characteristics of the water to be treated, and may therefore differ from that reported in the literature for equivalent materials. To test it, three scenarios are considered: (H_0) the material achieves an effectiveness comparable to that reported for magnetic water hyacinth biochars evaluated in controlled solutions, with removal efficiencies above 90 %; (H_1) the material shows a lower effectiveness, as a consequence of the variability of the local biomass or the presence of competing ions and organic matter in the water of the study area, which occupy the adsorption sites; and (H_2) the material shows a higher effectiveness, attributable to particular properties of the local biomass, such as the minerals that water hyacinth can

accumulate from the environment, which favor the incorporation of iron and the formation of active adsorption sites.

In this context, the general objective of the study is to develop and evaluate, at laboratory scale, a magnetic biochar obtained from water hyacinth collected in the area of influence of the Tula River and the Endhó Dam, in order to determine its adsorption capacity and removal efficiency for specific contaminants present in the water. Specifically, the study seeks to: characterize the water hyacinth and the study water; produce the biochar and modify it magnetically; identify its physicochemical and magnetic properties; and evaluate its adsorption capacity, removal efficiency, recovery and reuse under different experimental conditions. The analysis of contaminants must correspond to the characterization results and the available analytical capabilities, without extrapolating the laboratory results to drinking water production or to the comprehensive treatment of the basin. This manuscript reports the first stage of that objective: it constitutes an exploratory simulation of the expected performance of the filter and a proposed research framework, while the experimental evaluation is reported as work in progress, as specified in the research design.

Therefore, the expected contribution consists of generating experimental evidence on the valorization of a problematic biomass as a possible adsorbent material and establishing technical bases for assessing a complementary treatment system. From a social perspective, its relevance lies in orienting technological development toward needs expressed by the communities of the Valle de Mezquital, contributing to the search for environmental recovery alternatives and providing verifiable information for future research and sanitation decisions. The study does not replace public obligations regarding wastewater treatment, health care or the guarantee of the human right to water; it aims to be a localized scientific contribution that can later be evaluated with the participation of the potentially benefiting population.

METHODOLOGY

Research design

The study adopted a mixed exploratory-experimental design, developed at laboratory scale and organized into nine sequential phases (Figure 1). The first phase consisted of a systematic literature review conducted in accordance with the PRISMA 2020 statement (Page et al., 2021), whose purpose was to gather the available evidence on adsorbents derived from water hyacinth and iron-modified biochars, and to identify the limitations that condition their application in small-scale treatment systems. The subsequent phases correspond to the experimental development of the magnetic biochar, from the conditioning of the biomass to its evaluation with real water and, conditionally, in a column test.

In order for technological development to respond to the needs of the communities of the Valle de Mezquital and not only to chemical performance criteria, the sequence was structured under the User-Centered Design (UCD) approach. The ISO 9241-210:2019 standard describes this approach as an iterative process comprising four activities: understanding and specifying the context of use, specifying user requirements, producing design solutions and evaluating them against those requirements (International Organization for Standardization [ISO], 2019). Although the standard was formulated for interactive systems, its principles were adopted to guide the design of the filter: the literature review and the contextual background defined the requirements (Phase 1); the preparation of the material constituted the design solution (Phases 2 to 4); and the characterization and performance tests served as the evaluation against the requirements (Phases 5 to 9). When the evaluation results do not satisfy a requirement, the preparation conditions are adjusted and the cycle is repeated.

In a complementary manner, the RANAS model was used, an acronym for the factors Risk, Attitude, Norm, Ability and Self-regulation, proposed by Mosler (2012) to systematically design behavior change interventions in water, sanitation and hygiene. While UCD organizes the design process, RANAS provides the psychosocial factors that determine whether a water treatment technology is adopted and used in a sustained manner: the perception of the risk associated with polluted water, the assessment of the costs and benefits of the technology, the social norms of the community, people's confidence in their ability to operate and maintain it,

and the self-regulation needed to continue its use over time (Mosler and Contzen, 2016). In this study, both models were used as a framework to translate the findings of the literature into design requirements and to define the criterion with which each experimental phase was evaluated (Table 2).

The laboratory phases do not involve human participants. The application of the RANAS-based instrument with inhabitants of the riverside communities of the Endhó Dam constitutes a separate stage that has not yet begun, for the reasons explained in the section on the RANAS instrument; it will address the five factors of the model and, in particular, the norm factor, which depends on the social acceptance of the filter and cannot be assessed in the laboratory.

Status of the study

To avoid ambiguity about what has been completed and what remains to be done, the activities of the project are classified into four states, and this classification is maintained throughout the manuscript. **(i) Completed and reported here:** the systematic review (Phase 1); the collection and conditioning of the biomass (Phase 2); the Monte Carlo simulation of As(V) removal, referred to as the pilot test by simulation, and its sensitivity analysis; the specification of the user requirements; and the design of the RANAS questionnaire, the UCD protocol and the analysis plan. **(ii) Completed but not reported as evidence:** a preliminary exploratory trial with water collected in the study area. Because the arsenic concentrations of that trial were not determined with adequate, validated analytical instrumentation, its results are subject to a measurement bias and are not used to support any result or conclusion of this manuscript. **(iii) In progress:** a controlled laboratory test conducted under strict analytical standards (analytical-grade reagents, calibrated equipment, procedural blanks, independent replicates and arsenic quantification by a validated instrumental technique), which follows the protocol of Phases 3 to 7. **(iv) Planned:** the application of the RANAS questionnaire (pilot with 38 participants and final sample of 379), the evaluation with characterized real water (Phase 8), the column test (Phase 9), the assessment of the safe disposal of the spent adsorbent and the community trials of the prototype.

Accordingly, the procedures of Phases 3 to 9 are described below as the protocol of the study, and none of their results is reported in this manuscript. The main result presented here therefore derives from the simulation of the behavior of the filter, whose parameters were estimated from the treated-water conditions reported in the consulted literature; this is not sufficient to establish the performance or the safety of the filter under local conditions, which is the purpose of the experimental stages in progress and planned.

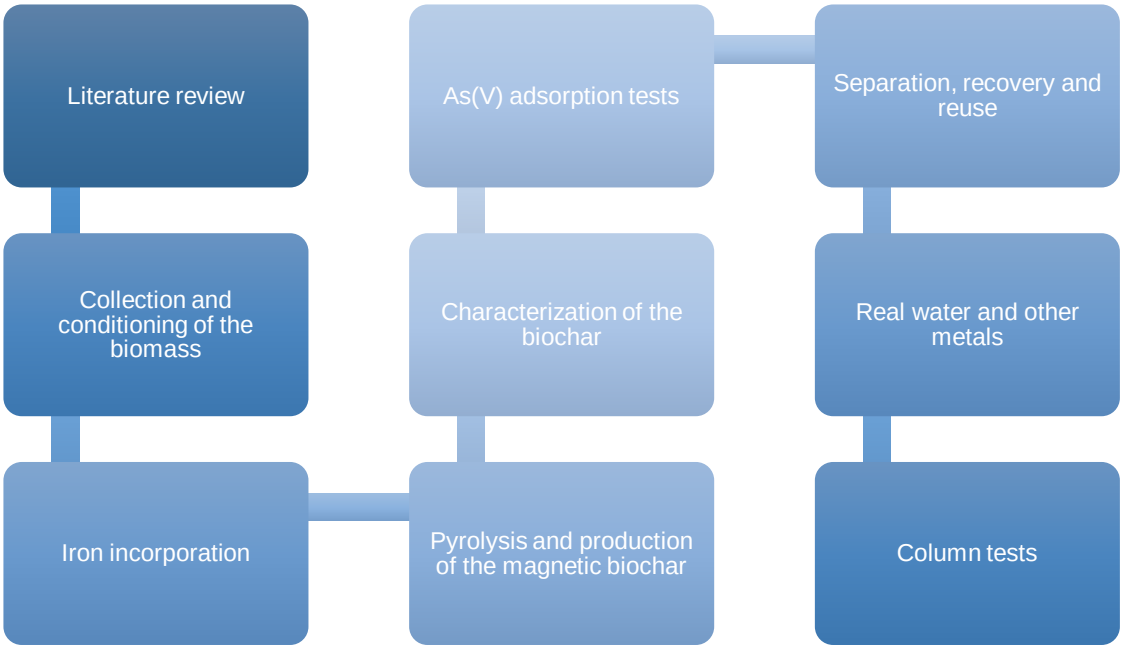


Figure 1. Methodological phases of the study

Source: Prepared by the authors, adapted from ISO (2019) and Mosler (2012)

Procedure

Phase 1. Systematic literature review

Review question. The review was guided by the question: what evidence exists on the performance of adsorbents derived from *Eichhornia crassipes* and iron-modified biochars for the removal of arsenic and heavy metals from water, and what limitations condition their application in small-scale treatment systems? From the outset, the question incorporated the UCD perspective by considering not only the efficiency of the material, but also its context of use.

Sources and search strategy. The search was carried out in the Scopus, ScienceDirect, Web of Science and Google Scholar databases, and was complemented by reviewing the references of the selected articles. Terms in English and Spanish were combined using Boolean operators; the main search strings were: ("water hyacinth" OR "Eichhornia crassipes") AND (biochar OR adsorbent) AND (arsenic OR "heavy metals"); (biochar) AND (magnetic OR "iron-modified") AND (arsenic); and ("household filter" OR "small-scale treatment") AND (arsenic) AND (groundwater). The search covered publications from 2016 to 2026.

Eligibility criteria. Peer-reviewed experimental or review articles in English or Spanish were included that addressed at least one of the following topics: (a) adsorbents or biochars obtained from water hyacinth; (b) magnetic or iron-modified biochars for arsenic removal; and (c) household- or community-scale arsenic treatment systems. In addition, they had to report performance indicators (adsorption capacity, removal efficiency or operating conditions) or a critical analysis of these technologies. Duplicate records, documents without full-text access, non-peer-reviewed works and studies aimed exclusively at soils were excluded.

Study selection. The process followed the identification, screening, eligibility and inclusion stages established by PRISMA 2020 (Page et al., 2021), and the number of records at each stage was as follows. *Identification:* 45 records were retrieved from the four databases and from the review of the reference lists of the selected articles. *Deduplication:* 15 duplicate records were removed, leaving 30 unique records. *Screening:* two authors independently reviewed the titles and abstracts of the 30 records; all of them addressed at least one of the topics defined in the eligibility criteria, so none was excluded at this stage and the 30 were retrieved in full text. *Eligibility:* in the full-text assessment, 2 documents were excluded because their publication date was earlier than the 2016–2026 window; both had been located through the review of reference lists, a route that is not restricted by date. *Inclusion:* 28 studies were included in the qualitative synthesis (Table 1). No meta-analysis was performed, since the studies used heterogeneous materials, contaminants and operating conditions. Discrepancies between the two reviewers at any stage were resolved by consensus with the third author.

Data extraction and synthesis. For each included study, the year, authors, objective, main limitation and most relevant results were recorded (Table 1). To integrate the UCD approach, each study was also classified according to the context of use evaluated (solution prepared in the laboratory, real water or filter in household operation) and, in accordance with RANAS, the limitations were related to the behavioral factor they could affect in a community implementation; for example, the complexity of preparation or maintenance was associated with the ability factor, and the need for regeneration and monitoring with the self-regulation factor.

The synthesis made it possible to establish four design requirements. First, iron modification was adopted as a condition of the material, since unmodified biochar shows low affinity for arsenic; Sun et al. (2022) report an increase from 0.017 to 6.80 mg/g in As(V) adsorption capacity after Fe modification, in agreement with Amen et al. (2020) and Zoroufchi Benis et al. (2020). Second, most studies were carried out with solutions prepared under controlled conditions (Ho et al., 2024; Li et al., 2018; Zhang et al., 2016), so evaluation with real water from the area was defined as a context-of-use requirement. Third, household arsenic treatment systems present failures associated with maintenance, monitoring and costs (Duong et al., 2021), aspects linked to the ability and self-regulation factors of RANAS; hence magnetic recovery, simple operation and reuse were established as requirements. Fourth, the spent adsorbent retains the contaminant and requires safe handling (Nguyen et al., 2021; Shakoor et al., 2016), which was incorporated as a disposal requirement. Likewise, the loss of efficiency

in the presence of bicarbonate and organic matter, and after regeneration cycles (Liao et al., 2024), justified evaluating the material with real water and in successive cycles.

Table 1. Synthesis of the studies included in the systematic review

Year	Author	Objective	Limitation	Results
2016	Ding et al.	To analyze the adsorption of Cd^{2+} and Pb^{2+} by water hyacinth biochars obtained at 300, 450 and 600 °C and the competition between both metals.	Focuses on Cd and Pb; does not evaluate arsenic removal.	The biochars removed Cd^{2+} and Pb^{2+} in single and binary systems, with competition between both metals for adsorption sites.
2016	Shakoor et al.	To analyze the use of agricultural residues as arsenic biosorbents and the alternatives for their safe disposal.	Variable composition of residues; dependence on pH, temperature, time and dose; the loaded biosorbent requires safe disposal.	Agricultural residues remove arsenic by biosorption and are an economical and sustainable option compared with conventional methods.
2016	Zhang, F., Wang et al.	To develop a magnetite-modified water hyacinth biochar and evaluate its capacity to remove As(V).	Demonstrated at laboratory scale; does not evaluate a low-cost household filter for rural communities.	Maximum capacity of 7.41 mg/g; efficiency >90 % between pH 3 and 10; included a column test.
2018	Li, Q. et al.	To investigate biochars from long roots of E. crassipes (200–500 °C) to remove Pb, Zn, Cu and Cd.	Uses prepared solutions; does not evaluate a filtration system with real water.	All four biochars adsorbed the metals, with differences according to production temperature and metal.
2018	Lin, S., Yang et al.	To improve arsenic adsorption by immobilizing FeOOH on E. crassipes root powder.	Requires a specific particle size and modification and regeneration reagents; sensitive to pH and temperature.	Equilibrium in 50 min; 8.67–9.43 mg/g for As(V) and 5.21–5.65 mg/g for As(III); optimum pH 9.0; retained its capacity after 6 cycles.
2018	Niazi et al.	To evaluate perilla leaf biochar (300 and 700 °C) for As(III) and As(V) in solution and groundwater, and its mechanisms.	Raw material other than water hyacinth; does not develop a continuous-flow filter.	Capacities of 3.85–11.01 mg/g (Langmuir); BC700 removed more As(III), especially at pH 7–9.
2018	Zhu et al.	To develop a biochar column and bioreactor system with periphytic biofilm to remove As(III).	The biofilm only developed with As(III) <5.0 mg/L; the biological component adds complexity.	With 2.0 mg/L and 1.0 mL/min, total removal was 90.2–95.4 %; about 60 % was retained in the biochar.
2019	Saning et al.	To convert water hyacinth through hydrothermal carbonization into magnetic carbonaceous materials and evaluate them as adsorbents.	Evaluated dyes and tetracycline, not arsenic.	Capacities of 524.20 mg/g (methylene blue), 425.15 mg/g (methyl orange) and 294.24 mg/g (tetracycline).
2020	Amen et al.	To critically analyze pristine and modified biochars for arsenic removal, considering modification and redox reactions.	Data from heterogeneous, non-comparable conditions; little evidence of long-term operation, regeneration, costs and real systems.	Unmodified biochar has low affinity for As; the incorporation of Fe, Mn and other materials markedly increases its capacity.
2020	Lin, S., Huang et al.	To produce oxidized biochar from E. crassipes residues to remove heavy metals.	No explicit limitation is reported in the information consulted.	Equilibrium in 30 min; 0.57 (Pb^{2+}), 0.41 (Cu^{2+}), 0.44 (Cd^{2+}) and 0.48 (Zn^{2+}) mmol/g; regenerable with HCl for 10 cycles.
2020	Liu, B. et al.	To review and compare functional sorbents for the	Performance depends on pH, temperature,	Novel materials outperform conventional ones;

		removal of As(III) and As(V) using performance metrics.	concentration and ionic strength; spent sorbents require regeneration and disposal.	$ZrO(OH)_2$/CNTs maintained desorption >90 % after three cycles.
2020	Zoroufchi Benis et al.	To systematically review biochar modification methods that increase arsenic adsorption.	Lack of standardized conditions; batch tests with prepared solutions predominate.	Metal oxides, especially Fe oxides, increase capacity; there is no single value, as it depends on biomass, modification and pH.
2021	Duong et al.	To analyze small-scale treatment systems for arsenic in groundwater from technological, economic and social perspectives.	Limited community resources; costly arsenic analysis; lack of maintenance and monitoring.	Household systems present problems of maintenance, monitoring, costs and variable effectiveness; community systems are proposed.
2021	Nguyen et al.	To analyze natural laterite as a household filter medium to remove arsenic from groundwater.	Adsorbent other than water hyacinth biochar; the spent material requires stabilization.	In four households, arsenic was reduced to <0.01 mg/L during seven months of continuous operation.
2021	Qu et al.	To develop a microwave-assisted porous magnetic water hyacinth biochar to remove Cr(VI) and tetracycline.	Does not evaluate arsenic; the microwave process is technologically more complex.	Surface area of 2097.50 m^2/g; 202.61 mg/g for Cr(VI) and 202.62 mg/g for tetracycline; stable after three cycles.
2022	Rodríguez-Lara et al.	To review the characteristics of water hyacinth and its effects on the ecosystem.	Documentary review; does not validate its efficiency as an arsenic adsorbent.	Identifies potential for phytoremediation, compost, biofuels and other products.
2022	Siddiq et al.	To technically evaluate biochar as an alternative for removing arsenic from groundwater.	Laboratory studies predominate; tests with real water, continuous operation, regeneration and economic analysis are lacking.	Fe, Zn, Mn and magnetic modification increase removal, with values >90 % under optimal conditions.
2022	Srivastav et al.	To review the production and modification of biochar for removing arsenic from water.	Removal of organic arsenic remains a challenge; capacities come from different conditions.	Municipal solid waste biochars reached 24.49 mg/g and KOH-treated ones 30.98 mg/g.
2022	Sun et al.	To analyze biochar-based materials for remediating arsenic-contaminated water and soil.	Challenges of cost, regeneration and practical application; real matrices modify efficiency.	The capacity for As(V) increased from 0.017 mg/g unmodified to 6.80 mg/g with Fe (≈400 times).
2023	Ma et al.	To remove and detoxify As(III) at the microgram level in the presence of micromolar H_2O_2 and Fe(II).	Controlled conditions: 25 °C, specific concentrations and batch reactors.	The oxidant:As(III) molar ratio was decisive; oxidation ranged from 7.9 to 60.3 % with H_2O_2 and from 22.2 to 46.6 % with Fe(II).
2024	Corbera-Rubio et al.	To analyze the role of biological processes in sand filters for drinking water production.	Complex simultaneous reactions; difficult access to the biofilm; backwashing alters the steady state of the filter.	Biological Fe oxidation improves performance; the biological contribution to Mn and As oxidation is probably underestimated.
2024	Ho et al.	To evaluate activated water hyacinth biochar to remove As(V) at low concentrations and the effect of NO_3^-.	Low-concentration aqueous solution; does not evaluate a household filter or well water from Hidalgo.	Capacity of 0.203 mg/g at pH 7; good performance between pH 3 and 10; equilibrium in 1 h; reusable three times.
2024	Li, T. et al.	To develop a cellulose-confined ferrihydrite	Complex preparation; nanoconfinement may	Capacity of 169.25 mg/g; in column it exceeded 4000 bed

		nanocomposite to remove As(III).	hinder application and raise costs.	volumes and passed the leaching test.
2024	Liao et al.	To evaluate Fe-impregnated henequen biochar for As(V), with columns, regeneration and life cycle assessment.	Bicarbonate, high pH and organic matter reduced removal to as low as 62 %; after three cycles it dropped to 37–57 %.	Capacity of 7.30–8.98 mg/g; treated 8792 mL of groundwater (24.10 µg/L) before exceeding 10 µg/L.
2024	Ullah and Rahman	To review water hyacinth, its biochar and modified biochar as heavy metal adsorbents.	More studies are needed on the effect of the functional groups of modified biochars.	Identifies electrostatic attraction, ion exchange, complexation and precipitation; modification improves surface area, pores and magnetism.
2025	Hamid et al.	To review the synthesis, properties and application of magnetic biochar for arsenic removal.	Pending issues: cost reduction, production techniques and fate of the retained arsenic.	Magnetic biochar can exceed 90 % removal under optimal conditions.
2025	Morales-Amaya et al.	To review immobilized nanostructured systems for arsenic removal.	Need to stabilize nanomaterials; modification raises costs.	They improve the removal of As(III) and As(V); highlights the importance of regeneration and stabilization.
2026	Du et al.	To synthesize, solvent-free, iron oxide nanoparticles from Fe-containing waste to remove As(III) and As(V).	Requires 180 °C, 48 h and control of the C/Fe ratio; depends on waste availability.	Chemical adsorption through As–O–Fe complexes, with maximum performance at pH 4.

Note: Studies ordered by year of publication.
Source: Prepared by the authors based on the included studies.

Phase 2. Collection and conditioning of the biomass

Approximately 3 kg of fresh water hyacinth were collected in the study area. Biomass without advanced decomposition was selected, washed with tap water to remove sediments and debris and, finally, rinsed with deionized water. Its mass was then recorded, and it was cut into fragments and dried in a laboratory oven until reaching an approximately constant mass. The dry biomass was ground and sieved to obtain homogeneous particles that would favor contact with the iron reagents; the final size depended on the available equipment. From the UCD perspective and the RANAS attitude factor, the use of a local, abundant biomass that is currently removed as waste responds to the requirement of a low-cost material linked to the problem perceived by the communities.

Phase 3. Iron incorporation

The dry biomass is placed in contact with analytical-grade Fe^{2+} and Fe^{3+} solutions, under controlled stirring and pH, following the co-precipitation procedure used by Zhang et al. (2016) to obtain magnetic water hyacinth biochar for As(V) removal. The salt concentrations, the iron-to-biomass ratio and the other conditions are defined based on the complete experimental method and the laboratory's capacity. No recycled metallic materials or materials of unknown composition are used.

Phase 4. Pyrolysis and production of the magnetic biochar

The modified biomass is subjected to pyrolysis in a tube furnace or other equipment that allowed working at a controlled temperature with limited oxygen availability. As an initial reference condition, a temperature of 550 °C for 2 h, used by Ho et al. (2024), is evaluated; this condition is not considered optimal until its performance is experimentally verified. The initial mass, temperature, treatment time, final mass and yield are recorded. After cooling, the biochar is ground, sieved, identified by batch and stored in airtight containers.

Phase 5. Characterization of the biochar

The magnetic response of the material is verified by the external application of a magnet, a check that corresponds to the simple-recovery requirement derived from Phase 1. When institutional availability or support from another laboratory exists, the characterization is complemented with physicochemical techniques that identify the properties related to its behavior as an adsorbent.

Phase 6. Batch As(V) adsorption tests

The first experiments are carried out in batch mode, with a known volume of As(V) solution and a given mass of adsorbent. Three groups are considered: As(V) solution without adsorbent, As(V) solution with unmodified biochar and As(V) solution with magnetic biochar. This comparison makes it possible to identify the removal attributable to the adsorbent and the effect of the iron modification.

Four variables are evaluated progressively: contact time, with periods of around one hour, considering the equilibrium reported by Ho et al. (2024); pH, given that it influences the chemical form of arsenic and the surface charge of the adsorbent, taking as reference the range of 3 to 10 in which Zhang et al. (2016) obtained good results; the adsorbent dose per volume of solution; and the initial concentration, to analyze the behavior of the material and estimate its adsorption capacity. The tests are performed with independent replicates, keeping constant the variables that were not under evaluation. In RANAS terms, the reduction in arsenic concentration is linked to the risk factor, as it constitutes the benefit that the technology must demonstrate in relation to the exposure perceived by the population.

Phase 7. Separation, recovery and reuse

At the end of each test, the biochar is separated by means of an external magnetic field and, when necessary, the separation is complemented with filtration or centrifugation. The initial and final arsenic concentrations are determined by a validated analytical technique, available at the Institute or in a specialized laboratory; no dyes, mobile applications or visual assessments are used as substitutes for chemical analysis; the absence of this type of analysis is precisely the reason why the preliminary trial with water from the area is not considered evidence. With the results, the removal efficiency (Equation 1) and the adsorption capacity (Equation 2) are calculated:

$$E\ (\%) = [(C_0 - C_f) / C_0] \times 100 \qquad (1)$$

$$q = [(C_0 - C_f) \times V] / m \qquad (2)$$

where E is the removal efficiency, C_0 and C_f are the initial and final concentrations of As(V) (mg/L), q is the adsorption capacity (mg/g), V is the volume of solution (L) and m is the mass of adsorbent (g).

The recovered biochar is subjected to additional cycles to evaluate the retention of its efficiency, taking as an initial reference the three reuse cycles reported by Ho et al. (2024). This stage responds to the ability and self-regulation factors of RANAS, since separation with a magnet and the possibility of reusing the material reduce the complexity of operation and maintenance that, according to Duong et al. (2021), limits the continuity of household systems. The arsenic-loaded adsorbent and the solutions used are treated as hazardous chemical waste, because magnetic recovery does not eliminate the retained contaminant; their regeneration and final disposal are carried out in accordance with institutional safety measures (Zoroufchi Benis et al., 2020).

Phase 8. Evaluation with real water and other contaminants

Once the operating conditions have been established with controlled solutions, the biochar will be evaluated with a representative water sample from the study area, whose physicochemical parameters and concentrations of contaminants of interest will be previously determined. This phase corresponds to the evaluation in the real context of use proposed by UCD, since the simultaneous presence of other ions and organic matter may modify the performance observed in the laboratory (Liao et al., 2024). Based on these results and on the

available analytical capacity, the tests will be extended to Pb, Cd, Cu, Zn or other relevant contaminants (Ding et al., 2016; Li et al., 2018).

Phase 9. Column test

The construction of an experimental column is considered only if the biochar shows satisfactory results in the batch tests. In this phase, the bed height, flow rate and treated volume will be evaluated in order to obtain the breakthrough curve indicating the moment at which the adsorbent must be replaced or regenerated. This sequence matches that of Zhang et al. (2016), who evaluated their material first through adsorption tests and later in a column. Within the UCD cycle, the column represents the first functional prototype of the filter and the basis for its future evaluation with the user population.

Table 2. Integration of the methodological phases with the UCD activities and the RANAS factors

Phase	UCD activity	RANAS factor	Requirement or evaluation criterion
F1. Literature review	Understand the context of use and specify requirements	Risk, attitude, ability and self-regulation	Design requirements derived from the evidence: Fe modification, real water, simple recovery and safe disposal.
F2. Collection and conditioning	Produce the design solution	Attitude	Local, abundant and low-cost material.
F3. Iron incorporation	Produce the design solution	Risk	Greater affinity for arsenic compared with unmodified biochar.
F4. Pyrolysis	Produce the design solution	Attitude	Reproducible production conditions and recorded yield.
F5. Characterization	Evaluate against the requirements	Ability	Magnetic response verifiable with a magnet.
F6. As(V) adsorption	Evaluate against the requirements	Risk	Removal efficiency and adsorption capacity.
F7. Recovery and reuse	Evaluate against the requirements	Ability and self-regulation	Magnetic separation, efficiency over successive cycles and safe handling of the waste.
F8. Real water and other metals	Evaluate in the context of use	Risk	Performance with water from the study area.
F9. Column test	Evaluate the prototype	Ability and self-regulation	Treated volume and time of adsorbent replacement.

Note. UCD = User-Centered Design (ISO, 2019); RANAS = Risk, Attitude, Norm, Ability and Self-regulation (Mosler, 2012).

Source: Prepared by the authors.

RANAS instrument and UCD protocol

As indicated in the research design, user evaluation constitutes the UCD activity in which the filter is contrasted with the needs of the potentially benefiting population, while the RANAS model provides the factors that must be measured to anticipate its adoption and sustained use (Mosler, 2012). Therefore, in parallel with the experimental phases, a RANAS-based questionnaire and a UCD application protocol were developed, whose purpose is to specify the user requirements of the filter and estimate the psychosocial factors that favor or limit its use. Since its application with inhabitants of the riverside communities has not yet begun, this section describes the planned application: the population, sample size, structure of the instrument, validity and reliability criteria, and the data processing procedure in IBM SPSS Statistics 19.

Population, sample and sampling

The study population corresponds to the inhabitants of the 27 riverside communities of the Endhó Dam, where, as stated in the introduction, around 27,000 people reside. The unit of analysis was defined as the person over 18 years of age responsible or co-responsible for the supply, storage or use of water in the household, since this is the person who would make the decision to adopt the filter and who would carry out its daily operation. To estimate the sample size, the formula for finite populations was used (Cochran, 1977), expressed in Equation 3:

$$n = [N \cdot Z^2 \cdot p \cdot q] / [e^2 \cdot (N - 1) + Z^2 \cdot p \cdot q] \qquad (3)$$

where n is the sample size, N the population size (27,000), Z the critical value for a 95 % confidence level (1.96), p and q the expected proportions (0.5 each, as this is the assumption of maximum variability) and e the margin of error (0.05). With these values, n = 378.78 was obtained, which was rounded to 379 participants. Because N includes the total population and not only adults, the calculated size is conservative, since a smaller population would produce a slightly smaller sample.

Sampling will be stratified probabilistic with proportional allocation, in which each community constitutes a stratum and the number of questionnaires assigned will be calculated from its population as recorded in the census data for each locality. Within each stratum, households will be selected systematically from a random starting point and one person per household will be interviewed. Prior to the final application, a pilot application will be carried out with 38 participants. This size was adopted for two reasons: it is equivalent to 10 % of the calculated sample, the proportion recommended for pilot studies by Connelly (2008), and it exceeds the minimum of 30 participants recommended for obtaining stable preliminary estimates of internal consistency in scale development (Johanson and Brooks, 2010). The pilot participants will be selected with the same unit of analysis and the same household selection procedure as the final sample, distributed across the strata in proportion to their population, so that the conditions of comprehension and application are representative of the final survey; they will not be included in the final sample. The purpose of the pilot is to verify the comprehension of the items, the application time and the preliminary reliability of each factor.

Timing of the application. The application of the questionnaire, both in the pilot and in the final sample, has not yet begun, for three reasons. First, because it involves human participants from a population exposed to an environmental health problem, it requires the prior approval of an ethics committee, which will be requested together with the informed consent form (Appendix D). Second, the content validity of the instrument must be assessed by the expert panel before any field application, so that the pilot evaluates an already reviewed version.

Third, the questionnaire presents to the participants a brief description of the filter before section B; presenting it before the controlled laboratory test provides measured results would risk generating expectations about a technology whose performance and safety have not yet been verified, which contradicts the criterion that the information provided to the community must be based exclusively on measured results. For these reasons, the pilot application (n = 38) is scheduled once the ethical approval and the results of the controlled laboratory test are available, and the final application (n = 379) after the adjustments derived from the pilot.

Structure of the questionnaire

The questionnaire was organized into four sections, each linked to a UCD activity. Section A (context of use) gathers eight sociodemographic and household water management variables; section B (RANAS factors) contains 19 items on a five-point Likert-type scale, from 1 (strongly disagree) to 5 (strongly agree); section C (user requirements) includes six multiple-choice questions on the expected characteristics of the filter; and section D (intention to use) contains two Likert items that serve as the dependent variable. Table 3 presents the structure of section B, while the complete instrument is included in Appendix A.

Table 3. Structure of section B of the questionnaire according to the factors and subfactors of the RANAS model

Factor	Subfactor	Code	Item
Risk	Perceived vulnerability	RSK1	I consider it likely that my family or I will get sick from the water we use in my community.
Risk	Perceived severity	RSK2	If we got sick from polluted water, the consequences for our health would be serious.
Risk	Knowledge about pollution	RSK3	I know that the water of the Endhó Dam and the Tula River may contain harmful substances, such as metals or arsenic.
Attitude	Beliefs about costs	ATT1	I would be willing to devote time and money to a filter to treat water.
Attitude	Beliefs about benefits	ATT2	A filter made from water hyacinth could improve the quality of the water I use.
Attitude	Affective beliefs	ATT3	I like the idea of using the water hyacinth removed from the dam to make a filter.
Attitude	Confidence in the technology	ATT4	I would trust a material made from water hyacinth to treat water.
Norm	Descriptive norm	NOR1	Many people in my community use some method to treat water.
Norm	Injunctive norm	NOR2	People who are important to me would approve of my using a filter of this type.
Norm	Personal norm	NOR3	I feel obliged to protect my family by treating the water we use.
Ability	Action knowledge	ABI1	I would know how to operate the filter if I received simple instructions.
Ability	Performance self-efficacy	ABI2	I feel capable of removing the material from the filter with a magnet and putting it back.
Ability	Maintenance self-efficacy	ABI3	I could maintain the filter on a regular basis.
Ability	Recovery self-efficacy	ABI4	If the filter stopped working, I would know whom to turn to in order to fix it.
Self-regulation	Action planning	SRG1	I could plan at what time of day to use and check the filter.
Self-regulation	Action control	SRG2	I could remember when the filter material needs to be replaced.
Self-regulation	Commitment	SRG3	I would commit to using the filter continuously.
Self-regulation	Barrier management	SRG4	I would keep using the filter even if it required additional effort.
Intention to use*	Dependent variable	INT1–INT2	I intend to use a filter of this type if it were available; I would recommend the filter to other people in my community.

Note. Response scale: 1 = strongly disagree, 2 = disagree, 3 = neither agree nor disagree, 4 = agree, 5 = strongly agree. Subfactors adapted from Mosler (2012) and Mosler and Contzen (2016). Source: Prepared by the authors.

The items were written in simple language and technical terms were avoided, considering that the questionnaire will be administered through face-to-face interviews and that the responses will be read aloud when the person requires it. Likewise, before section B, a brief description of the filter will be presented as a technology under development to remove specific contaminants from water, without attributing to it the capacity to make water potable, in order to avoid expectations that do not correspond to the scope of the study.

Validity and reliability of the instrument

Content validity will be assessed through the judgment of a panel of at least three experts in environmental chemistry, environmental health and design, the minimum number recommended by Lynn (1986), who will rate the clarity, relevance and coherence of each item with its factor. Subsequently, with the pilot test data, the internal consistency of each factor will be estimated using Cronbach's alpha coefficient, considering values equal to or greater than 0.70 acceptable (Nunnally, 1978); in addition, items with a corrected item-total correlation below 0.30 will be revised or removed. With the final sample, construct validity will be analyzed through exploratory factor analysis, after verifying sampling adequacy with the Kaiser-Meyer-Olkin index (KMO ≥ 0.60) and Bartlett's test of sphericity ($p < 0.05$), in order to confirm that the items group into the five factors of the model.

UCD application protocol

The UCD protocol translates the four activities of the ISO 9241-210:2019 standard into concrete techniques, instruments and products for the development of the filter (International Organization for Standardization [ISO], 2019). As shown in Table 4, the context and requirements activities combine the documentary evidence from Phase 1 with sections A, B and C of the questionnaire; the production of solutions corresponds to the biochar preparation phases and the column prototype; and the evaluation integrates the laboratory tests, the pilot test by simulation and a second application of the questionnaire after a demonstration of the prototype.

Table 4. UCD protocol applied to the development of the magnetic biochar filter

UCD activity	Techniques and instruments	Related filter phases	Expected product
1. Understand and specify the context of use	Systematic review; documentary background on the Endhó Dam; section A of the questionnaire	F1 and F8 (water characterization)	Profile of users and household water management
2. Specify the user requirements	Synthesis of the review; section B (RANAS) and section C (requirements) of the questionnaire	F1	Requirements matrix with acceptance criteria (Table 12)
3. Produce design solutions	Preparation of the magnetic biochar; column prototype	F2, F3, F4 and F9	Adsorbent material and first functional prototype of the filter
4. Evaluate against the requirements	Pilot test by simulation; batch tests; real water; prototype demonstration and second application of the questionnaire	F5, F6, F7, F8 and F9	Report on compliance with requirements and adjustments for the next iteration

Note. Activities according to ISO 9241-210:2019 (ISO, 2019).

Source: Prepared by the authors.

In this way, the cycle will be repeated when the evaluation indicates that a requirement is not met; for example, if the ability factor shows low scores, the procedure for separating and replacing the adsorbent will be simplified before a new evaluation, and if the performance with real water is lower than in controlled solutions, the dose or the contact time will be adjusted.

Data processing in IBM SPSS Statistics 19

The questionnaire data will be entered and analyzed in IBM SPSS Statistics 19 (IBM Corp., 2010). For this purpose, a codebook was prepared with the name, label, values and level of measurement of each variable

(Appendix B), as well as a syntax file that defines the labels and runs the analyses in the established order (Appendix C), which makes it possible to reproduce the processing and document each output. Missing values will be coded as 9 and declared as such; in addition, 10 % of the questionnaires will be entered twice to verify data entry accuracy. The score of each RANAS factor will be calculated as the mean of its items, with a possible range of 1 to 5. Table 5 summarizes the analysis plan, the corresponding menu path in SPSS 19 and the decision criterion for each test.

Table 5. Statistical analysis plan for the questionnaire in IBM SPSS Statistics 19

Purpose of the analysis	Test or statistic	Path in SPSS 19	Decision criterion
Describe the context of use and the requirements	Frequencies and percentages	Analyze > Descriptive Statistics > Frequencies	Description of sections A and C
Assess internal consistency	Cronbach's alpha; item-total correlation	Analyze > Scale > Reliability Analysis	$\alpha \geq 0.70$; item-total $r \geq 0.30$
Verify the factor structure	Exploratory factor analysis; KMO; Bartlett	Analyze > Dimension Reduction > Factor	KMO ≥ 0.60; Bartlett $p < 0.05$
Describe the RANAS factors	Mean, standard deviation and median	Analyze > Descriptive Statistics > Descriptives	Classification: barrier, intermediate or favorable
Verify normality	Kolmogorov-Smirnov	Analyze > Descriptive Statistics > Explore	$p > 0.05$ indicates normality
Relate factors and intention	Spearman correlation	Analyze > Correlate > Bivariate	$p < 0.05$
Compare between communities	Kruskal-Wallis	Analyze > Nonparametric Tests > Legacy Dialogs > K Independent Samples	$p < 0.05$
Estimate the weight of each factor	Multiple linear regression (Equation 4)	Analyze > Regression > Linear	$p < 0.05$; VIF < 10; adjusted R^2

Note. $\alpha = 0.05$ for all hypothesis tests. VIF = variance inflation factor.

Source: Prepared by the authors.

Data analysis

As a pilot test to assess the feasibility of the project and guide the experimental design, the As(V) removal process was simulated by the Monte Carlo method with 500 runs, whose input distributions were derived from previous research (Ho et al., 2024; Zhang et al., 2016). The reference scenario considered a mean initial concentration of 0.100 mg/L, a pH close to 7, a magnetic biochar dose of 2 g/L and an approximate contact time of 60 min; from each run, the final concentration, the removal efficiency and the adsorption capacity were obtained and summarized by means of the mean, the standard deviation and the 2.5–97.5 percentile interval. The equations, parameters, assumptions and the justification of the number of runs are detailed at the end of this section (Table 6). The simulated values are considered estimates and do not replace experimental validation.

The experimental results will be reported as mean ± standard deviation of the independent replicates. Differences among the three groups of Phase 6 will be analyzed by one-way analysis of variance with Tukey's multiple comparison test ($\alpha = 0.05$). The contact time and initial concentration data will be fitted to pseudo-first-order and pseudo-second-order kinetic models, and to the Langmuir and Freundlich isotherms, which are the models most frequently used in the reviewed studies. As a comparative reference, and not as a potability criterion, the final arsenic concentrations will be compared with the guideline value of 0.01 mg/L established by the World Health Organization (2022).

As for the questionnaire data, frequencies and percentages will be obtained for sections A and C, as well as means, standard deviations and medians for the RANAS factors. Since the items are ordinal, the relationship between each factor and intention to use will be assessed with Spearman's correlation coefficient, and

differences between communities with the Kruskal-Wallis test. Finally, the relative weight of the factors on intention to use will be estimated by multiple linear regression (Equation 4), verifying the absence of multicollinearity with VIF values below 10:

$$INT = \beta_0 + \beta_1 R + \beta_2 A + \beta_3 N + \beta_4 Ab + \beta_5 S + \varepsilon \qquad (4)$$

where INT is the intention-to-use score; R, A, N, Ab and S are the mean scores for risk, attitude, norm, ability and self-regulation; β_0 to β_5 are the model coefficients; and ε is the error term. In order to link the statistical analysis with UCD, each factor will be classified according to its mean as a barrier (less than 3.0), intermediate (from 3.0 to 3.99) or favorable (equal to or greater than 4.0), and this classification will determine the corresponding design response.

Specification of the simulation model

The simulation was formulated as a propagation of uncertainty by the Monte Carlo method (Joint Committee for Guides in Metrology [JCGM], 2008): in each run, a value of every input parameter is drawn from its probability distribution and the outputs are computed with the model equations, so that the set of runs approximates the distribution of the outputs. The removal efficiency at the contact time *t* was represented by a first-order approach to equilibrium (Equation 5), from which the final concentration (Equation 6) and the adsorption capacity were derived:

$$E(t) = E_{eq} \cdot [1 - \exp(-k \cdot t)] \qquad (5)$$

$$C_f = C_0 \cdot [1 - E(t)] \qquad (6)$$

where E_{eq} is the fraction of As(V) removed at equilibrium, *k* is the apparent rate constant (min^{-1}) and *t* is the contact time (min). The adsorption capacity of each run was calculated with Equation 2, expressing V/m as the inverse of the dose D, that is, $q = (C_0 - C_f) / D$. Equation 5 was chosen because, with a single kinetic parameter, it reproduces the approach to equilibrium in about one hour reported by Ho et al. (2024), and because the available data do not allow a more complex kinetic model to be parameterized; the pseudo-first-order and pseudo-second-order fits will be performed with the experimental data, as described above.

Assumptions. The model rests on five assumptions: (a) As(V) is the only species competing for the adsorption sites, that is, the matrix is a controlled solution without bicarbonate, phosphate or organic matter; (b) within the scenario conditions (pH close to 7), the efficiency does not depend on pH, since Zhang et al. (2016) reported removals above 90 % between pH 3 and 10, so pH is fixed and not sampled; (c) the initial concentration is far below the saturation of the adsorbent, so E_{eq} does not depend on C_0 within the simulated range, an assumption also adopted in the sensitivity analysis; (d) the input parameters are mutually independent; and (e) the material is used in its first cycle, without regeneration. Assumptions (a) and (e) are the most favorable to the filter; their relaxation is examined through the comparison scenarios of Table 10.

Parameters and distributions. Table 6 lists the parameters, their distributions and their sources. The nominal values reproduce the reference scenario, while the dispersion represents the tolerances of a batch test (preparation of the standard solution, weighing of the adsorbent and timing of the contact) and the batch-to-batch variability of the material. Normal distributions were assigned to the quantities controlled by the operator, a uniform distribution to the contact time, for which only a tolerance range is known, a beta distribution to the equilibrium efficiency because it is bounded between 0 and 1, and a lognormal distribution to the rate constant because it is strictly positive and right-skewed.

Table 6. Parameters, probability distributions and sources of the Monte Carlo simulation model

Parameter	Distribution	Values	Source or justification
Initial concentration, C_0 (mg/L)	Normal	$\mu = 0.100$; $\sigma = 0.005$ (CV = 5 %)	Reference scenario; σ represents an assumed tolerance of ±5 % in the preparation and verification of the

			standard solution
Adsorbent dose, D (g/L)	Normal	$\mu = 2.0$; $\sigma = 0.04$ (CV = 2 %)	Reference scenario; σ represents an assumed weighing and volume tolerance
Contact time, t (min)	Uniform	55 to 65	Equilibrium close to 1 h (Ho et al., 2024); ±5 min operating tolerance
pH	Fixed (not sampled)	7	pH 7 in Ho et al. (2024); no effect within the scenario, assumption (b) (Zhang et al., 2016)
Equilibrium efficiency, E_{eq} (–)	Beta	$\alpha = 152.26$; $\beta = 11.64$ (mean = 0.929; SD = 0.020)	Removal above 90 % reported by Zhang et al. (2016); SD assumed to represent batch-to-batch variability
Rate constant, k (min^{-1})	Lognormal	Median = 0.08; $\sigma_{ln} = 0.25$	95 % of equilibrium reached in ≈ 37 min (central 95 % range: 23–61 min), consistent with equilibrium close to 1 h (Ho et al., 2024)

Note. CV = coefficient of variation; SD = standard deviation. Random number generator: PCG64 (NumPy), seed 726; 500 runs. The α and β parameters of the beta distribution were obtained from its mean and SD by the method of moments.

Source: Prepared by the authors.

Number of runs. The number of runs was determined by the precision required for the main output. The Monte Carlo standard error of the mean efficiency is $s/\sqrt{n}$, where s is the standard deviation of the efficiency among runs and n the number of runs. A maximum 95 % half-width of 0.25 percentage points was set as the criterion, that is, less than one-seventh of the 1.84-point margin above the required minimum identified in the sensitivity analysis, so that the simulation error cannot alter the conclusion about that margin. With s = 2.32 %, the criterion requires $n \geq (1.96 \cdot s / 0.25)^2 \approx 331$ runs; 500 runs were adopted to provide additional margin, which yielded a half-width of 0.20 points. Convergence was verified in two ways: the running mean of the efficiency varied by less than 0.25 points between 100 and 500 runs (from 92.09 to 91.84 %), and an independent run of 10,000 iterations with another seed gave a mean efficiency of 91.65 %, a difference of 0.19 points, within the half-width. With 500 runs, the proportion of runs exceeding 0.01 mg/L is estimated with a standard error of about 1.8 percentage points.

Reported uncertainty. The outputs are reported as mean ± standard deviation and as the 2.5–97.5 percentile interval of the 500 runs, together with the proportion of runs in which C_f exceeds 0.01 mg/L. This uncertainty reflects only the dispersion assigned to the inputs; it does not include the structural uncertainty of the model (assumptions a to e) or the differences between the materials of the literature and the local biochar, which can only be quantified experimentally. The simulation code and the dataset of the 500 runs are available as supplementary material.

RESULTS AND DISCUSSION

The results are presented in the order of the UCD activities. First, the results of the pilot test carried out by simulation and its sensitivity analysis are presented, which correspond to the technical evaluation of the filter; subsequently, these results are contrasted with the user requirements and with the factors of the RANAS model, in order to integrate the development of the material with the conditions necessary for its adoption. All the quantitative results on the performance of the filter in this section derive from the simulation and from calculations with Equations 1 and 2; none corresponds to a measurement of the produced biochar.

Rationale for the simulation as a pilot test

Before starting the controlled laboratory tests, a pilot test was carried out by simulating the As(V) removal process, in order to assess the feasibility of the project and guide the experimental design described in the methodology. This pilot was justified for three reasons. First, it made it possible to estimate the performance of

the material under different operating conditions before allocating reagents, biomass and chemical analyses to each test. Second, by running 500 Monte Carlo runs with explicit input distributions (Table 6), it was possible to incorporate the expected variability of the process instead of relying on a single value. Finally, the simulation is integrated into the iterative UCD cycle, since it constitutes a first evaluation of the design solution against the requirements established in Table 2, whose results guide the adjustments of the subsequent experimental phases.

To build the model, results published in previous research on iron-modified water hyacinth biochars were taken as reference (Ho et al., 2024; Zhang et al., 2016). Consequently, the values presented in this section correspond to estimates derived from the model and not to measurements of the filter; their function is to establish reference values for the design and evaluation of the experimental stages, which still require validation. For the same reason, the preliminary trial with water from the area is not used in this section.

Expected behavior of the magnetic biochar

The model was based on two expected behaviors. On the one hand, the final As(V) concentration was anticipated to decrease as the contact time with the magnetic biochar increases, until it approaches an equilibrium condition. As a reference, Ho et al. (2024) observed an equilibrium close to one hour with their iron-modified water hyacinth biochar and obtained an adsorption capacity of 0.203 mg/g at pH 7; therefore, the simulation scenario considered an approximate contact time of 60 min, which makes it possible to assess whether additional time would produce a relevant decrease under the selected assumptions.

On the other hand, the magnetic modification was expected to contribute to As(V) removal. In this regard, Zhang et al. (2016) obtained, with magnetite-modified water hyacinth biochar, an estimated maximum capacity of 7.41 mg/g and a removal efficiency above 90 % between pH 3 and 10, values that served as a reference for comparing the simulation outputs. However, the difference between the capacities reported by Zhang et al. (2016) and Ho et al. (2024) shows that performance depends on the prepared material and the conditions of each study; consequently, it is not appropriate to set a single capacity as a guaranteed result of the proposed filter.

As(V) removal in the simulated scenario

In the reference scenario of 500 simulated runs, with a mean initial As(V) concentration of 0.100 mg/L, a pH close to 7, a magnetic biochar dose of 2 g/L and an approximate contact time of 60 min, an estimated mean final concentration of 0.0082 mg/L was obtained. This decrease of 0.0918 mg/L is equivalent to a simulated mean removal efficiency of 91.84 % (Equation 1) and a calculated adsorption capacity of 0.046 mg/g (Equation 2) for that concentration and dose. The dispersion among runs was considerable in relation to the margin of the scenario: the efficiency showed a standard deviation of 2.32 percentage points and a 95 % interval of 86.05 to 95.53 %, and the final concentration ranged between 0.0045 and 0.0136 mg/L. Consequently, although the mean final concentration is below 0.01 mg/L, 19.6 % of the runs (98 of 500) exceeded that value. Table 7 summarizes the indicators obtained in the scenario.

Table 7. Results of the simulated scenario for As(V) removal

Indicator	Result	Interpretation
Simulation runs	500	Variations generated by the model
Mean initial concentration, C_0	0.100 mg/L	Selected input condition
Mean final concentration, C_f	0.0082 mg/L	Estimated concentration after contact
Mean decrease in concentration	0.0918 mg/L	Difference between C_0 and C_f
Mean removal efficiency, E	**91.84 %**	Main result of the simulation
Calculated adsorption capacity, q	0.046 mg/g	Value for the selected dose and concentration
Standard deviation of E	2.32 percentage points	Dispersion among the 500 runs

95 % interval of E ($P_{2.5}$–$P_{97.5}$)	86.05–95.53 %	Range containing 95 % of the simulated efficiencies
95 % interval of C_f ($P_{2.5}$–$P_{97.5}$)	0.0045–0.0136 mg/L	Range containing 95 % of the simulated final concentrations
Runs with C_f > 0.01 mg/L	19.6 % (98 of 500)	Proportion of runs above the guideline value under the model assumptions
Approximate pH, dose and time	7; 2 g/L; 60 min	Scenario conditions

Note. The figures are simulated results and not measurements of the filter; intervals correspond to the 2.5 and 97.5 percentiles of the 500 runs (Table 6). C_0 = initial concentration; C_f = final concentration. Source: Prepared by the authors.

In addition, Figure 2 represents the estimated decrease in As(V) concentration from 0.100 to 0.0082 mg/L under the selected conditions. This comparison corresponds to the input and output concentrations of the simulated scenario; therefore, it describes the mean result of the runs and not the evolution of the concentration over the treated volume.

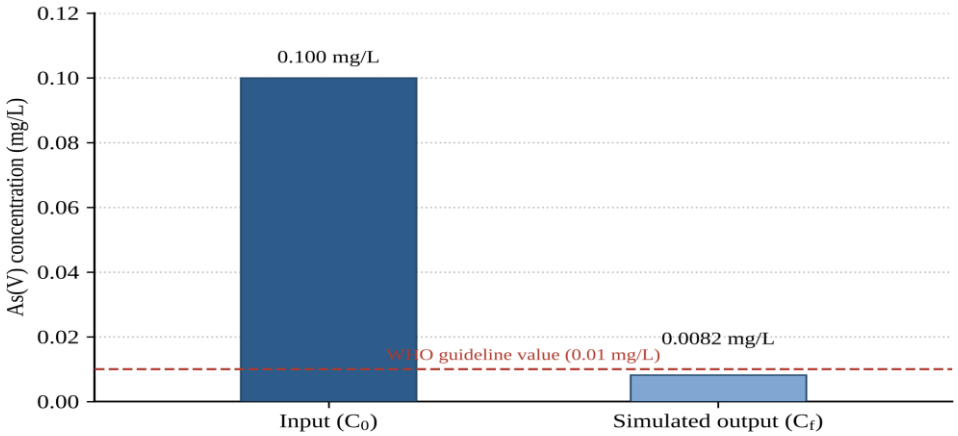


Figure 2. Mean As(V) concentration before and after the simulated treatment

Source: Prepared by the authors with the values of the 500-run simulated scenario. Estimated mean removal: 91.84 %. Reference guideline value: World Health Organization (2022).

In relation to the literature, the simulated efficiency of 91.84 % is comparable with the removals above 90 % published by Zhang et al. (2016) for magnetic water hyacinth biochar. This result therefore falls within the scenario proposed in hypothesis H_0, in which the material achieves an effectiveness comparable to that reported for magnetic water hyacinth biochars evaluated in controlled solutions. However, given that the model parameters come from these prior studies, this agreement should be interpreted as comparative evidence and not as confirmation of the hypothesis, which can only be tested with the biochar produced from the local biomass. Likewise, the calculated adsorption capacity of 0.046 mg/g corresponds only to this low initial concentration scenario and does not represent the maximum capacity of the material. Indeed, according to Equation 2, the capacity depends on the initial concentration and the dose used, so its value is lower than those reported by Ho et al. (2024) and Zhang et al. (2016), whose tests were carried out under different conditions. Therefore, the maximum capacity must be estimated experimentally through tests with different initial concentrations and their fitting to the Langmuir and Freundlich isotherms.

Furthermore, the estimated mean final concentration of 0.0082 mg/L is below the guideline value of 0.01 mg/L established by the World Health Organization (2022) for arsenic in drinking water (Figure 2). This comparison is presented only as a reference, in accordance with what was established in the data analysis, and not as a potability criterion, since the value comes from the simulation model, 19.6 % of the runs exceeded the guideline value, and the result must be verified through chemical analyses and filter tests before being considered an experimental result of the project.

Sensitivity analysis of the simulated scenario

In order to assess the robustness of the main result, Equations 1 and 2 were applied to a range of initial concentrations and adsorbent doses around the reference scenario. This analysis starts from the simplifying assumption that the removal efficiency remains constant at 91.84 %; although in a real system the efficiency varies with the initial concentration and with the dose, the assumption makes it possible to identify the margins within which the simulated scenario remains valid and, consequently, the conditions that should be prioritized in the batch tests. First, based on Equation 1, the minimum efficiency that would be required for the final concentration not to exceed the guideline value of 0.01 mg/L was calculated, as well as the final concentration that would be obtained with the simulated efficiency. The results are presented in Table 8.

Table 8. Minimum required efficiency and estimated final concentration according to the initial As(V) concentration

C_0 (mg/L)	Minimum required efficiency (%)	C_f estimated with E = 91.84 % (mg/L)	Comparison with 0.01 mg/L
0.020	50.00	0.0016	Below
0.050	80.00	0.0041	Below
0.075	86.67	0.0061	Below
0.100	**90.00**	**0.0082**	**Below**
0.1225	91.84	0.0100	At the limit
0.150	93.33	0.0122	Above
0.200	95.00	0.0163	Above
0.300	96.67	0.0245	Above
0.500	98.00	0.0408	Above

Note. Required efficiency = $(1 - 0.01/C_0) \times 100$. C_f estimated with a constant efficiency of 91.84 %. Reference guideline value: 0.01 mg/L (World Health Organization, 2022).

Source: Prepared by the authors based on the simulation results.

As shown in Table 8 and Figure 3, for the initial concentration of the reference scenario (0.100 mg/L) a minimum efficiency of 90.00 % is required, so the simulated efficiency of 91.84 % exceeds that threshold by a margin of only 1.84 percentage points. Similarly, the maximum initial concentration at which an efficiency of 91.84 % would keep the final concentration below 0.01 mg/L is approximately 0.1225 mg/L; above that value, even with the same performance, the final concentration would exceed the reference value. For example, with 0.200 mg/L an efficiency of 95.00 % would be required and the estimated final concentration would be 0.0163 mg/L, while with 0.500 mg/L the required efficiency would increase to 98.00 %.

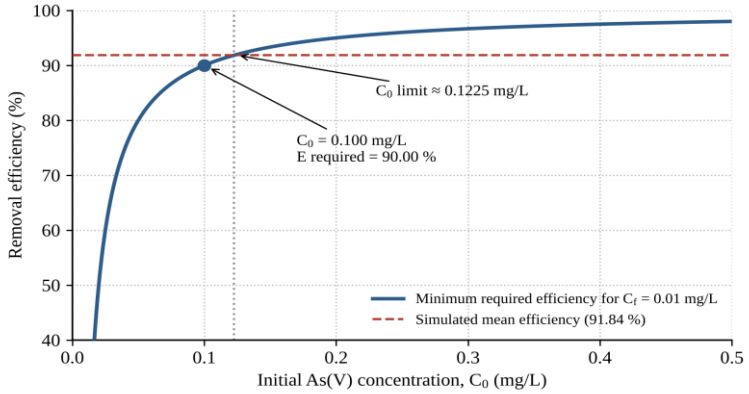


Figure 3. Minimum efficiency required to reach the guideline value according to the initial As(V) concentration

Source: Prepared by the authors based on Equation 1 and the simulated mean efficiency.

This result has two implications for the development of the filter. On the one hand, it confirms that the prior characterization of the water in the study area (Phase 8) is decisive, since compliance with the reference value depends both on the performance of the material and on the incoming arsenic concentration. On the other hand, the narrow margin indicates that a decrease in efficiency greater than 1.84 percentage points, such as could occur due to the presence of competing ions and organic matter in real water (Liao et al., 2024), would be enough for the final concentration to exceed 0.01 mg/L. Consequently, the scenario described in hypothesis H_1 is not only plausible, but would have an immediate practical effect on the performance of the filter, which justifies evaluating higher doses or longer contact times in the batch tests as compensatory measures.

Second, based on Equation 2, the adsorption capacity corresponding to different biochar doses was calculated for the reference initial concentration, together with the mass of adsorbent required and the mass of arsenic that would be retained when treating 1,000 L of water (Table 9).

Table 9. Adsorption capacity, adsorbent mass and retained arsenic according to the magnetic biochar dose

Dose (g/L)	Calculated q (mg/g)	Biochar required per 1,000 L (kg)	As retained per 1,000 L (mg)
0.5	0.184	0.5	91.8
1.0	0.092	1.0	91.8
2.0	**0.046**	**2.0**	**91.8**
3.0	0.031	3.0	91.8
4.0	0.023	4.0	91.8

Note. Calculations for C_0 = 0.100 mg/L and a constant efficiency of 91.84 %. $q = (C_0 - C_f)$ / dose. The row in bold corresponds to the simulated scenario.

Source: Prepared by the authors based on the simulation results.

The values in Table 9 show that, with a constant efficiency, the adsorption capacity is inversely proportional to the dose: by reducing the dose from 2 to 0.5 g/L, the capacity would increase from 0.046 to 0.184 mg/g, while with 4 g/L it would decrease to 0.023 mg/g. However, in a real system a reduction in dose implies fewer available adsorption sites and, therefore, a probable decrease in efficiency, so the optimal dose must be established experimentally as the minimum value that maintains the required efficiency. This relationship also explains why the capacity obtained in the simulated scenario should not be compared directly with that of other studies: as shown in Figure 4, with a dose of 2 g/L the capacity would equal the 0.203 mg/g reported by Ho et al. (2024) only at an initial concentration close to 0.442 mg/L, and would reach the 7.41 mg/g of Zhang et al. (2016) only at a concentration close to 16.1 mg/L, far higher than that of the evaluated scenario.

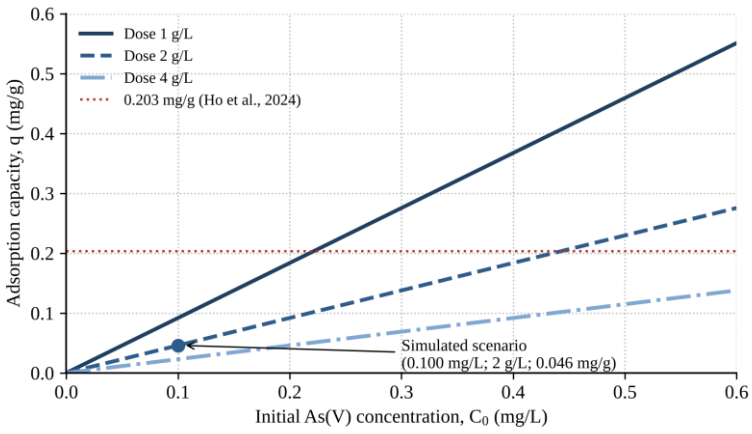


Figure 4. Calculated adsorption capacity as a function of the initial As(V) concentration and the biochar dose

Source: Prepared by the authors based on Equation 2, with a constant efficiency of 91.84 %. Reference: Ho et al. (2024).

Finally, Table 9 provides relevant information for the management of the spent material: with the dose of the simulated scenario, treating 1,000 L of water would require 2 kg of magnetic biochar, which would retain around 91.8 mg of arsenic. Since magnetic separation does not eliminate the contaminant, that mass of adsorbent must be managed as hazardous waste (Zoroufchi Benis et al., 2020). From the UCD perspective, this result suggests that the replacement and disposal of the spent material should not fall exclusively on the users, but on an organized collection scheme, an aspect that is taken up again in the analysis of the RANAS factors.

Third, in order to gauge the effect that a loss of performance such as that described in hypothesis H_1 would have, the final concentration that would be obtained with the reference initial concentration under different efficiencies was calculated. In addition to the simulated value and the 90.00 % threshold, the efficiencies reported in the systematic review for an iron-impregnated biochar evaluated in complex matrices and after regeneration cycles were considered as scenarios; its removal decreased to as low as 62 % in the presence of bicarbonate, high pH and organic matter, and ranged between 37 and 57 % after three cycles (Liao et al., 2024). The results are presented in Table 10.

Table 10. Estimated final As(V) concentration under different removal efficiency scenarios

Scenario	Efficiency (%)	Estimated C_f (mg/L)	C_f / guideline value ratio
Simulated scenario	**91.84**	**0.0082**	**0.82**
Minimum required efficiency for C_0 = 0.100 mg/L	90.00	0.0100	1.00
Complex matrix: bicarbonate, high pH and organic matter	62.00	0.0380	3.80
Third reuse cycle, upper value	57.00	0.0430	4.30
Third reuse cycle, lower value	37.00	0.0630	6.30

Note. C_0 = 0.100 mg/L; $C_f = C_0 \times (1 - E/100)$. The efficiencies of the reference scenarios correspond to another material (Liao et al., 2024) and are used only as comparison scenarios. Guideline value: 0.01 mg/L (World Health Organization, 2022).

Source: Prepared by the authors.

As can be seen in Table 10, if the efficiency of the magnetic biochar in real water decreased to a level similar to that reported for complex matrices (62 %), the estimated final concentration would be 0.0380 mg/L, that is, 3.8 times the reference value; similarly, after three reuse cycles with efficiencies of 57 to 37 %, the final concentration would be between 0.0430 and 0.0630 mg/L, equivalent to 4.3 and 6.3 times that value. In contrast to the margin of 1.84 percentage points identified in the simulated scenario, the difference between the simulated efficiency and the 62 % reported in a complex matrix is 29.84 points, more than 16 times the available margin, which indicates that performance in real water and the retention of efficiency between cycles are the aspects of greatest technical risk for the filter.

These results have direct consequences for the use requirements. On the one hand, reuse of the adsorbent would only be compatible with the reference criterion if the efficiency remains above the required threshold; therefore, should similar losses be verified, the operating strategy should favor replacing the material over regenerating it. On the other hand, from the perspective of the RANAS model, this condition reinforces the importance of the self-regulation factor, since the user would not be able to perceive the decrease in performance with the naked eye and would depend on an external signal to replace the material.

Comparison with the evidence from the systematic review

To situate the results of the pilot test with respect to the evidence gathered in the systematic review (Table 1), Table 11 compares the simulated scenario with the three studies whose material or conditions are closest to the proposed filter.

Table 11. Comparison of the simulated scenario with iron-modified biochars reported in the systematic review

Study	Material	Evaluation conditions	Capacity (mg/g)	Reported performance
Zhang et al. (2016)	Magnetite-modified water hyacinth biochar	Controlled solutions; pH 3 to 10; column test	7.41 (maximum)	Efficiency > 90 % between pH 3 and 10
Ho et al. (2024)	Iron-modified activated water hyacinth biochar	Low As(V) concentration; pH 7	0.203	Equilibrium in 1 h; reusable three times
Liao et al. (2024)	Fe-impregnated henequen biochar	Solutions, columns and groundwater with 24.10 µg/L	7.30–8.98	8,792 mL treated before exceeding 10 µg/L; removal as low as 62 % in a complex matrix
Present study (simulation)	Local water hyacinth magnetic biochar	C_0 = 0.100 mg/L; pH 7; 2 g/L; 60 min; 500 runs	0.046 (scenario)	Efficiency of 91.84 %; C_f = 0.0082 mg/L

Note. The values of the present study correspond to the simulation and not to measurements of the material. Source: Prepared by the authors based on the studies included in Table 1.

The comparison makes it possible to identify three aspects. First, the simulated efficiency matches that reported by Zhang et al. (2016), while the pH and contact time conditions of the scenario correspond to those of Ho et al. (2024); therefore, the scenario reproduces documented conditions, although the dispersion assigned to them is an explicit assumption of the model (Table 6). Second, the adsorption capacities are not comparable with each other, since, as Figure 4 showed, they depend on the initial concentration and the dose of each study. Third, neither of the two water hyacinth studies evaluated their material in real water, while the only work that did so, with a different material, treated 8,792 mL of groundwater with 24.10 µg/L of arsenic before exceeding 10 µg/L (Liao et al., 2024). This difference confirms the gap identified in the introduction and supports Phase 8 and the column test as the main expected experimental contribution of the project.

User requirements and progress of the UCD cycle

Based on the synthesis of the systematic review, the context described for the Endhó Dam and the results of the pilot test, ten user requirements were specified for the filter, which correspond to the product of the second UCD activity. Each requirement was associated with its origin, with a verifiable indicator or acceptance criterion and with its status after the pilot test (Table 12).

Table 12. Matrix of user requirements for the filter and compliance status after the pilot test

RQ	Requirement	Origin	Indicator or acceptance criterion	Status after the pilot test
RQ1	Reduce the As(V) concentration	Phase 1; risk factor	$C_f \leq 0.01$ mg/L as a comparative reference (World Health Organization, 2022)	Estimated favorable: 0.0082 mg/L
RQ2	Efficiency comparable with the literature	Hypothesis H_0	$E \geq 90$ % (Zhang et al., 2016)	Estimated favorable: 91.84 %
RQ3	Simple recovery of the adsorbent	Phase 1; ability factor	Separation with an external magnet, without specialized equipment	Addressed in the design; recovery percentage pending
RQ4	Reuse of the material	Phase 1; self-	At least three cycles as a	Pending

		regulation factor	reference (Ho et al., 2024)	
RQ5	Local, low-cost material	Context; attitude factor	Use of water hyacinth removed from the dam; cost per treated volume	Addressed in the design; cost pending
RQ6	Identifiable replacement time	Self-regulation factor	Breakthrough curve and treated volume per adsorbent load	Pending (Phase 9)
RQ7	Performance with real water	Phase 1; context of use	Removal with water from the Endhó Dam or the Tula River	Pending (Phase 8)
RQ8	Safe handling of the spent material	Phase 1	Disposal procedure as hazardous waste	Addressed in the design
RQ9	Understandable operation	Ability factor	Ability factor mean ≥ 4.0	Pending (questionnaire)
RQ10	Social acceptance	Norm factor	Norm factor mean ≥ 4.0	Pending (questionnaire)

Note. RQ = requirement. Status: estimated favorable = the criterion is met in the simulation; addressed in the design = the criterion was incorporated into the experimental protocol; pending = requires laboratory tests or application of the questionnaire.

Source: Prepared by the authors.

Of all the requirements, two (20 %) were estimated as favorable in the simulation (RQ1 and RQ2), three (30 %) were addressed from the design of the experimental protocol (RQ3, RQ5 and RQ8) and five (50 %) remain pending verification (RQ4, RQ6 and RQ7 in the laboratory, and RQ9 and RQ10 through the planned application of the questionnaire). This distribution shows that the pilot test provides evidence mainly on the technical dimension of removal, while the requirements linked to the long-term operation of the filter, to real water and to acceptance by the population require both the experimental phase and the application of the RANAS questionnaire. In other words, the development of the filter is advancing faster in its chemical component than in its use component, which confirms the relevance of integrating both models from the design stage and not only at the end of the process. Accordingly, Figure 5 summarizes the progress of each UCD activity. The context-of-use and requirements specification activities were completed in their documentary component, but still require community participation; the production of solutions has a defined preparation protocol; and the evaluation began with the pilot test, so the controlled laboratory test, currently under way, and the subsequent application of the questionnaire constitute the next iteration of the cycle.

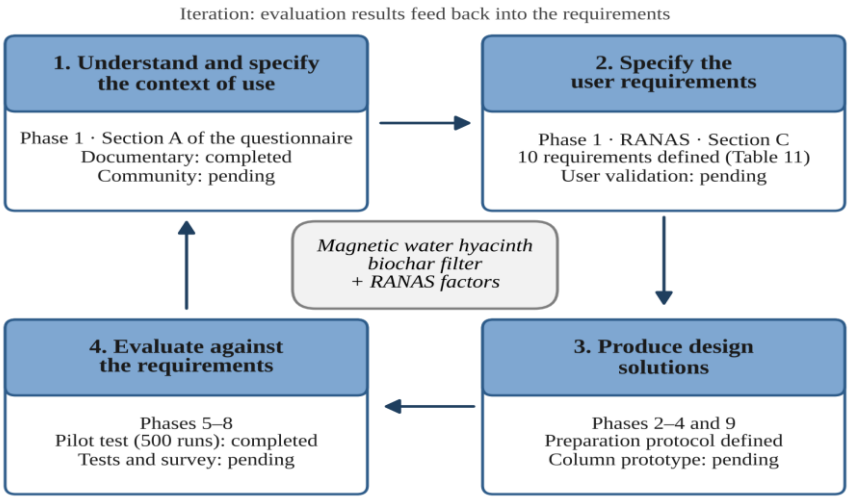


Figure 5. Progress of the UCD cycle in the development of the magnetic biochar filter

Source: Prepared by the authors, adapted from ISO (2019).

Interpretation of the technical results from the RANAS model

Although the RANAS factors can only be quantified once the questionnaire is applied, the available technical results make it possible to anticipate which filter conditions would favor or limit each factor and, therefore, which items of the instrument are critical for design decision-making. Table 13 relates the technical evidence from the pilot test to its implication for adoption and to the items that will measure it.

Table 13. Relationship between the technical evidence from the pilot test and the factors of the RANAS model

RANAS factor	Available technical evidence	Implication for adoption	Items that will measure it
Risk	Estimated reduction from 0.100 to 0.0082 mg/L (91.84 %)	Potential benefit against exposure; can only be communicated after experimental validation	RSK1–RSK3
Attitude	Local biomass currently removed as waste; cost not yet estimated	Favorable assessment due to the use of water hyacinth; cost will be decisive	ATT1–ATT4
Norm	No evidence possible in the laboratory	Depends on community acceptance and use by other people	NOR1–NOR3
Ability	Magnetic separation; 2 kg of adsorbent per 1,000 L with the reference dose	Simple operation, but replacement and disposal require support and clear instructions	ABI1–ABI4
Self-regulation	Up to three cycles as background; margin of 1.84 percentage points; breakthrough curve pending	A clear signal of when to replace and reminders are needed	SRG1–SRG4

Note. Item codes correspond to Table 3.

Source: Prepared by the authors.

For the risk factor, the estimated reduction from 0.100 to 0.0082 mg/L represents the benefit that the technology should demonstrate against the exposure perceived by the population. However, communicating that benefit before its experimental validation could generate unjustified confidence; therefore, the information provided to the community must be based exclusively on measured results. For the attitude factor, the use of a local biomass that is currently removed as waste constitutes a favorable argument, especially considering that more than 32,000 tons of water hyacinth were removed from the dam during 2025 (SEMARNAT, 2025); however, the cost-benefit assessment will depend on the cost per treated volume, which has not yet been estimated.

For its part, the norm factor cannot be inferred from laboratory results, since it depends on the social approval of the filter and the behavior of other people in the community; for this reason, items NOR1 to NOR3 will be the only ones to provide evidence on this factor. In contrast, the ability and self-regulation factors are directly related to technical decisions: magnetic separation simplifies the recovery of the adsorbent, but Table 9 indicates that every 1,000 L treated would involve replacing 2 kg of material with retained arsenic, which requires a clear procedure, an identifiable signal of when to replace it, derived from the breakthrough curve, and a collection scheme for the spent material. In this way, the sensitivity analysis not only informs about chemical performance, but also defines operating requirements that users would have to meet.

To translate the questionnaire results into design decisions, interpretation criteria were established for each factor, based on the classification of means described in the data analysis and on the behavior change techniques that the RANAS approach associates with each factor (Mosler and Contzen, 2016). Table 14 presents these criteria and the planned design response when a factor is identified as a barrier.

Table 14. Interpretation criteria for the RANAS factors and planned design response in the UCD cycle

RANAS factor	Barrier condition	Planned design response in the next UCD iteration
Risk	Mean < 3.0 on RSK1–RSK3	Information on water quality in the area based on measured results and communicated at community meetings
Attitude	Mean < 3.0 on ATT1–ATT4	Prototype demonstration, explanation of the origin of the material and estimate of the cost per treated volume
Norm	Mean < 3.0 on NOR1–NOR3	Participation of community leaders and committees in the presentation and testing of the filter
Ability	Mean < 3.0 on ABI1–ABI4	Simplification of the separation and replacement procedure; illustrated manual and hands-on training
Self-regulation	Mean < 3.0 on SRG1–SRG4	Replacement-time indicator, maintenance schedule and community collection scheme for the spent material

Note. Classification by factor mean: barrier < 3.0; intermediate 3.0–3.99; favorable ≥ 4.0. Design responses adapted from Mosler and Contzen (2016).

Source: Prepared by the authors.

Overall, this integration allows the questionnaire results to become concrete adjustments to the filter and its implementation strategy, instead of merely describing the population's perception. Thus, UCD provides the iterative structure of the process, while RANAS identifies which specific aspect must be modified in each iteration, which responds to the approach set out in the title of the study.

To make the link between the models and specific design decisions explicit, each questionnaire result is associated with a decision about the filter rather than with a general recommendation. **D1. Format of the adsorbent:** if the ability factor is classified as a barrier, or if item ABI2 (handling with a magnet) has a mean below 3.0, the loose adsorbent will be replaced by a closed, interchangeable cartridge that does not require the user to handle the material. **D2. Replacement regime:** if the self-regulation factor is a barrier, regeneration by the user is discarded and replacement is scheduled by treated volume, derived from the breakthrough curve, with collection of the spent material by a community scheme. **D3. Communication of benefits:** if the risk factor is a barrier, community information sessions will be held, using exclusively measured results of water quality and filter performance. **D4. Implementation route:** if the norm factor is a barrier, the prototype trials will begin with community committees and leaders before any household distribution. **D5. Cost target:** if the attitude factor is a barrier and item ATT1 (willingness to devote time and money) has the lowest mean of the factor, the cost per treated volume will be set as a design restriction of the next iteration. When several factors are barriers, the order of attention is defined by the standardized coefficients of the regression model (Equation 4): the factor with the largest significant coefficient is addressed first. Each decision is re-evaluated through the second application of the questionnaire after the demonstration of the prototype (Table 4).

Projection to the filter: breakthrough curve, recovery and reuse

To represent the operation of the filter, the As(V) concentration at the inlet and outlet must be considered as the volume of treated water increases. Under favorable conditions, the outlet concentration is expected to be initially lower than the inlet concentration and to increase gradually as the material loses retention capacity. This breakthrough curve will make it possible to estimate the moment at which operation must be stopped or the adsorbent replaced. However, the simulated scenario only provides the inlet and outlet concentrations, so outlet concentrations associated with different treated volumes will be needed to plot the breakthrough curve. Furthermore, although Zhang et al. (2016) performed a column test with their magnetic water hyacinth biochar, no treated volume or flow rate is available that could be adopted as a result, so those volumes should not be transferred directly to the magnetic water hyacinth biochar filter.

Similarly, the magnetic recovery of the adsorbent and the use of up to three cycles were not simulated (assumption e), but were examined through the comparison scenarios of Table 10, taking as background the reuse studied by Ho et al. (2024). Although these scenarios show a possible decrease in efficiency between cycles, the recovery percentage and the actual retention of capacity must be measured after defining a

regeneration procedure. Considering the margin of 1.84 percentage points identified in the sensitivity analysis, any loss of efficiency between cycles would have a direct effect on the final concentration, so the number of admissible reuses must be defined according to that margin. It should be noted that the retained arsenic remains in the recovered material, because magnetic separation does not eliminate the contaminant; consequently, its subsequent management as hazardous waste must also be considered (Zoroufchi Benis et al., 2020).

Finally, the 500 simulated runs produce a mean and a dispersion band for the final concentration, the removal efficiency and the adsorption capacity, which reflects only the variability assigned to the model inputs (Table 6). Even so, the evaluation with water from the Endhó Dam or the Tula River will be subject to prior knowledge of its arsenic concentration and composition, since the results obtained with prepared solutions do not by themselves describe the behavior of a real sample. This precaution is consistent with the observations of Liao et al. (2024), who recorded lower removal in the presence of bicarbonate, high pH and organic matter, conditions that correspond to the scenario described in hypothesis H_1.

Experimental matrix derived from the pilot test

Based on the sensitivity analysis, the levels of each variable to be evaluated in the Phase 6 batch tests were defined, so that the experimental results allow a direct comparison with the simulation estimates. Thus, the initial concentration levels include values below and above the estimated limit of 0.1225 mg/L, and the dose levels match those in Table 9, in order to compare the calculated capacity with the measured capacity. Table 15 presents the resulting matrix.

Table 15. Experimental matrix of the batch tests defined from the pilot test

Variable evaluated	Levels	Fixed conditions	Groups × replicates	Tests
Contact time	0, 15, 30, 45, 60, 90 and 120 min (7)	C_0 = 0.100 mg/L; pH 7; 2 g/L	3 × 3	63
pH	3, 5, 7, 9 and 10 (5)	C_0 = 0.100 mg/L; 2 g/L; 60 min	3 × 3	45
Adsorbent dose	0.5, 1, 2, 3 and 4 g/L (5)	C_0 = 0.100 mg/L; pH 7; 60 min	2 × 3	30
Initial concentration	0.050, 0.100, 0.150, 0.200 and 0.500 mg/L (5)	pH 7; 2 g/L; 60 min	3 × 3	45
Reuse	3 cycles	Reference conditions	1 × 3	9
Total				**192**

Note. Groups: As(V) solution without adsorbent, with unmodified biochar and with magnetic biochar. For the dose variable, the group without adsorbent is excluded; reuse is evaluated only with the magnetic biochar. Source: Prepared by the authors.

In total, the matrix comprises 192 tests, each of which requires the analytical determination of the final concentration, in addition to verification of the initial concentration of each prepared solution. Of these tests, 63 (32.8 %) correspond to contact time, 45 (23.4 %) to pH, 30 (15.6 %) to dose, 45 (23.4 %) to initial concentration and 9 (4.7 %) to reuse. This distribution prioritizes adsorption kinetics, because the 60 min time of the simulated scenario comes from a previous study and must be confirmed with the local material, and it makes it possible to fit the kinetic models and isotherms described in the data analysis. In this way, the pilot test not only estimated the expected performance, but also defined the scope of the experimental work, which corresponds to the iterative nature of UCD.

Scope of the pilot test and validation requirements

Based on the above, Table 16 contrasts the results of the pilot test with the evaluation criteria defined for each phase in Table 2. As can be seen, the simulation made it possible to estimate the indicators associated with

Phase 6, while the criteria for recovery, evaluation with real water, column testing and user evaluation remain as validation requirements.

Table 16. Scope of the pilot test against the evaluation criteria of the study

Phase	Evaluation criterion	Pilot test result	Requirement for validation
F6. As(V) adsorption	Removal efficiency	91.84 % estimated for C_0 = 0.100 mg/L; margin of 1.84 points above the required minimum	Analytical determination of C_0 and C_f with the produced biochar
F6. As(V) adsorption	Adsorption capacity	0.046 mg/g for 2 g/L; does not represent the maximum capacity	Tests with different initial concentrations and fitting to isotherms
F6. As(V) adsorption	Contact time	60 min, based on the equilibrium close to one hour reported by Ho et al. (2024)	Evolution of the concentration over time and kinetic fitting
F7. Recovery and reuse	Magnetic separation and efficiency over successive cycles	Comparison of up to three cycles as background; no measured recovery percentage	Define the regeneration procedure, measure recovery and manage the retained arsenic
F8. Real water and other metals	Performance with water from the study area	Not evaluated; validity of the scenario limited to $C_0 \leq$ 0.1225 mg/L	Determine the arsenic concentration and composition of the water from the Endhó Dam or the Tula River
F9. Column test	Treated volume and replacement time	Breakthrough curve cannot be plotted with the scenario	Outlet concentrations associated with different treated volumes
User evaluation	RANAS factors and intention to use	Questionnaire, sample (n = 379) and analysis plan defined	Ethical approval, pilot test (n = 38) and application of the questionnaire

Note. The pilot test results correspond to the 500-run simulated scenario. Source: Prepared by the authors.

In summary, the results of the pilot support the relevance of evaluating the material through batch adsorption tests and, if satisfactory performance is obtained, subsequently analyzing its application in a laboratory-scale column filtration system. Likewise, the sensitivity analysis delimited the range of concentrations in which the simulated scenario remains valid, and the integration with UCD and RANAS made it possible to specify the use requirements that must be verified with the population. In this way, the simulation fulfills its function within the UCD cycle: it reduces uncertainty about the operating conditions and defines more precisely what must be measured in each phase, without replacing the physicochemical characterization of the biochar, its experimental validation or the evaluation with users.

CONCLUSION

The pilot test, developed by simulating the As(V) removal process, made it possible to estimate the potential performance of the magnetic biochar obtained from water hyacinth and to establish reference values for the design and evaluation of the subsequent experimental stages. Under the 500-run scenario, with a mean initial concentration of 0.100 mg/L, a pH close to 7, an adsorbent dose of 2 g/L and an approximate contact time of 60 min, a mean removal efficiency of 91.84 % was estimated, with a mean final concentration of 0.0082 mg/L and a calculated adsorption capacity of 0.046 mg/g. The uncertainty of this estimate is not negligible: the 95 % interval of the efficiency ranged from 86.05 to 95.53 %, and 19.6 % of the runs exceeded 0.01 mg/L.

The removal percentage obtained is consistent with the efficiencies above 90 % reported for magnetic biochar materials derived from water hyacinth, so the result falls within the scenario of hypothesis H_0. However, this agreement should be interpreted only as comparative evidence with respect to the literature and not as a validation of the performance of the material that will be produced with the local biomass. Likewise, the estimated adsorption capacity value corresponds specifically to the conditions established in the model and does not represent the maximum adsorption capacity of the material, since, as the sensitivity analysis showed, it depends directly on the initial concentration and the dose.

Furthermore, the sensitivity analysis showed that the performance margin of the scenario is narrow: with 0.100 mg/L, a minimum efficiency of 90.00 % is required so as not to exceed the reference value of 0.01 mg/L, and the simulated efficiency would only guarantee this for initial concentrations of up to 0.1225 mg/L. Consequently, the characterization of the water in the study area and the evaluation of the effect of competing ions and organic matter become decisive conditions for the applicability of the filter, while the adsorbent dose must be optimized experimentally, considering that every 1,000 L treated with 2 g/L would generate 2 kg of material with retained arsenic that requires safe handling. Likewise, if the efficiency decreased to levels such as those reported for complex matrices or after regeneration cycles in other iron-modified biochars, the final concentration could exceed the reference value by 3.8 to 6.3 times; for this reason, an experimental matrix of 192 batch tests was defined that will make it possible to directly verify the estimates of the pilot test.

Regarding the integration of the models, UCD made it possible to organize the development of the filter as an iterative cycle and to specify ten user requirements, of which two were estimated as favorable in the pilot test, three were addressed from the design of the protocol and five remain pending. For its part, the RANAS model was operationalized in a 19-item questionnaire distributed across five factors, accompanied by a sample size of 379 participants, a planned pilot application with 38 participants, reliability and validity criteria, and an analysis plan in IBM SPSS Statistics 19 that links the classification of each factor with a concrete design response. In this way, the integration of both models ensures that the development of the filter is not limited to its chemical performance, but incorporates from the design stage the conditions necessary for its adoption and sustained use.

Among the limitations of the study, it should be emphasized that this manuscript constitutes an exploratory simulation and a proposed research framework: the reported values are estimates derived from the model and from the bibliographic information used; the preliminary trial with water from the area is not considered evidence because it was not analyzed with validated instrumentation; and the RANAS factors have not yet been measured in the population, since the application of the questionnaire will begin once ethical approval and the controlled laboratory results are available. Consequently, this study does not claim that the filter is effective in practice, that it is safe under local conditions or that it will be adopted by the community. Such claims require, in this order: (i) controlled laboratory tests with the produced biochar, which are currently under way; (ii) trials with characterized real water from the Endhó Dam or the Tula River, since the simultaneous presence of other ions, organic matter and different physicochemical conditions may modify the adsorption process with respect to a controlled system; (iii) an assessment of the safe handling and disposal of the spent adsorbent, including the stability of the retained arsenic; and (iv) community trials of the prototype conducted under ethical criteria, with informed consent and without attributing to the filter the capacity to make water potable. These stages will make it possible to test the H_0, H_1 and H_2 scenarios proposed in the hypothesis and to verify the pending user requirements.

In conclusion, the results allow the objective set for this stage of the study to be considered fulfilled, since it was possible to estimate through simulation the potential behavior of the magnetic water hyacinth biochar with respect to As(V), to delimit the conditions under which this behavior is sufficient and to structure, through UCD and the RANAS model, the evaluation of the filter with its potential users. Therefore, as lines of future work, the actual removal efficiency, the adsorption capacity, the service life of the material and the optimal operating conditions must be determined through the physicochemical characterization of the produced biochar and its experimental validation; finally, the application of the questionnaire and the evaluation of the column prototype with the user population will make it possible to complete the UCD cycle and orient the filter toward sustained adoption in the communities of the Valle de Mezquital.

ACKNOWLEDGEMENTS

The authors thank the Instituto Tecnológico de Pachuca and the Industrial Engineering program for the institutional support provided for the development of the project, as well as Mtro. Enrique de Jesús Mohedano Torres for his guidance as technical lead.

Ethical Approval

The laboratory phases of the study do not involve human or animal participants. The application of the questionnaire based on the RANAS model with inhabitants of the riverside communities of the Endhó Dam has not yet begun and will be carried out only after approval by an ethics committee; participation will be voluntary, informed consent will be obtained from each person (Appendix D) and the data will be recorded using ID numbers, without information that could identify the participants.

Conflict Of Interest

The authors declare that there is no conflict of interest in relation to the research, authorship or publication of this article.

Data Availability

The data supporting the results of this study correspond to the values of the simulated scenario and the calculations derived from Equations 1, 2, 5 and 6, which are presented in full in Tables 6 to 11 and Figures 2 to 4; the simulation code (Python, NumPy; seed 726) and the dataset of the 500 runs are available as supplementary material. Likewise, the questionnaire, the codebook and the analysis syntax in IBM SPSS Statistics 19 are included in Appendices A, B and C, and the laboratory record forms in Appendix E. The data generated in the experimental and questionnaire application stages will be available upon reasonable request from the corresponding author once these stages have been completed, safeguarding the confidentiality of the participants at all times.

REFERENCES

1. Amen, R., et al. (2020). A critical review on arsenic removal from water using biochar-based sorbents: The significance of modification and redox reactions. Chemical Engineering Journal, 396, 125195.
2. Benet, R. (2025, April 22). 70% de cuerpos de agua en México con signos graves de degradación [70% of water bodies in Mexico with serious signs of degradation]. IMER Noticias. https://noticias.imer.mx/blog/70-de-cuerpos-de-agua-en-mexico-con-signos-graves-de-degradacion/
3. CMDA. (2026, May 16). Estrés hídrico en México 2026: panorama y soluciones [Water stress in Mexico 2026: Overview and solutions]. https://cmda.com.mx/estres-hidrico-mexico-2026/
4. Cochran, W. G. (1977). Sampling techniques (3rd ed.). John Wiley & Sons.
5. Connelly, L. M. (2008). Pilot studies. Medsurg Nursing, 17(6), 411–412.
6. Corbera-Rubio, F., Goedhart, R., Laureni, M., van Loosdrecht, M. C. M., & van Halem, D. (2024). A biotechnological perspective on sand filtration for drinking water production. Current Opinion in Biotechnology, 90, 103221. https://doi.org/10.1016/j.copbio.2024.103221
7. Ding, Y., Liu, Y., Liu, S., Li, Z., Tan, X., Huang, X., Zeng, G., Zhou, Y., Zheng, B., & Cai, X. (2016). Competitive removal of Cd(II) and Pb(II) by biochars produced from water hyacinths: Performance and mechanism. RSC Advances, 6, 5223–5232.
8. Du, B., Wang, Y., Li, Y., & Zhao, X. (2026). Solvent-free fabrication of coral-like iron oxide nanoparticles from iron-bearing solid waste for the treatment of arsenic-containing wastewater: Synthesis process, adsorption mechanisms and DFT study. Separation and Purification Technology, 391, 137028. https://doi.org/10.1016/j.seppur.2026.137028
9. Duong, H. C., Tran, L. T. T., Vu, M. T., Nguyen, D., Tran, N. T. V., & Nghiem, L. D. (2021). A new perspective on small-scale treatment systems for arsenic affected groundwater. Environmental Technology & Innovation, 23, 101780. https://doi.org/10.1016/j.eti.2021.101780

10. Hamid, Y., Chen, Y., Haris, M., Usman, M., Hussain, B., Rashid, M. S., Ahmed, T., Noman, M., & Yang, X. (2025). Magnetic biochar for the remediation of arsenic contaminated water: A complete guide of science, synthesis, and solutions. Journal of Environmental Chemical Engineering, 13(5), 118348. https://doi.org/10.1016/j.jece.2025.118348
11. Ho, P. N. T., Nguyen, T. B., Dong, C. D., Ho, H. T. T., Phan, C. T., & Lai, T. H. D. (2024). Arsenic adsorption by activated biochar derived from water hyacinth. Case Studies in Chemical and Environmental Engineering, 10, 100907.
12. IBM Corp. (2010). IBM SPSS Statistics for Windows (Version 19.0) [Computer software]. IBM Corp.
13. International Organization for Standardization. (2019). Ergonomics of human-system interaction — Part 210: Human-centred design for interactive systems (ISO Standard No. 9241-210:2019). ISO.
14. Johanson, G. A., & Brooks, G. P. (2010). Initial scale development: Sample size for pilot studies. Educational and Psychological Measurement, 70(3), 394–400. https://doi.org/10.1177/0013164409355692
15. Joint Committee for Guides in Metrology. (2008). Evaluation of measurement data — Supplement 1 to the "Guide to the expression of uncertainty in measurement" — Propagation of distributions using a Monte Carlo method (JCGM 101:2008). BIPM.
16. Juárez, A. (2026, July 17). Sheinbaum incluye presa Endhó en recuperación del río Tula [Sheinbaum includes the Endhó Dam in the recovery of the Tula River]. El Congresista. https://elcongresista.mx/sheinbaum-recuperacion-presa-endho-rio-tula
17. Li, Q., Tang, L., Hu, J., Jiang, M., Shi, X., Zhang, T., Li, Y., & Pan, X. (2018). Removal of toxic metals from aqueous solution by biochars derived from long-root Eichhornia crassipes. Royal Society Open Science, 5(10), 180966. https://doi.org/10.1098/rsos.180966
18. Li, T., Su, H., Ma, H., Luo, S., & Wang, H. (2024). Cellulose confined ferrihydrite nanocomposite beads for efficient As(III) removal. Separation and Purification Technology, 339, 126598. https://doi.org/10.1016/j.seppur.2024.126598
19. Liao, X., Miranda-Avilés, R., Serafin Muñoz, A. H., Rocha-Amador, D. O., Pérez Rodríguez, R. Y., Hernández-Anguiano, J. H., Navarro, C. J., Zha, X., Moncada, D., Puy-Alquiza, M. de J., Kshirsagar, P. V., & Li, Y. (2024). Efficient arsenic removal from water using iron-impregnated low-temperature biochar derived from henequen fibers: Performance, mechanism, and LCA analysis. Scientific Reports, 14, 20769. https://doi.org/10.1038/s41598-024-69769-7
20. Lin, S., Huang, W., Yang, H., & Sun, S. (2020). Recycling application of waste long-root Eichhornia crassipes in the heavy metal removal using oxidized biochar derived as adsorbents. Bioresource Technology, 314, 123749. https://doi.org/10.1016/j.biortech.2020.123749
21. Lin, S., Yang, H., Na, Z., & Lin, K. (2018). A novel biodegradable arsenic adsorbent by immobilization of iron oxyhydroxide (FeOOH) on the root powder of long-root Eichhornia crassipes. Chemosphere, 192, 258–266. https://doi.org/10.1016/j.chemosphere.2017.10.163
22. Liu, B., Kim, K.-H., Kumar, V., & Kim, S. (2020). A review of functional sorbents for adsorptive removal of arsenic ions in aqueous systems. Journal of Hazardous Materials, 388, 121815. https://doi.org/10.1016/j.jhazmat.2019.121815
23. López Castillo, I. (2026, September 20). Cáncer, mosquitos y agua contaminada: así es la vida junto a la presa que recibe las aguas negras de CDMX [Cancer, mosquitoes and polluted water: Life next to the dam that receives Mexico City's wastewater]. Infobae. https://www.infobae.com/mexico/2026/09/20/cancer-mosquitos-y-agua-contaminada-asi-es-la-vida-junto-a-la-presa-que-recibe-las-aguas-negras-de-cdmx/
24. Lynn, M. R. (1986). Determination and quantification of content validity. Nursing Research, 35(6), 382–385.
25. Ma, Y., Yang, C., Shi, Y., Liu, Z., Cao, W., Wen, Q., & Qin, Y. (2023). Simultaneous elimination and detoxification of arsenite in the presence of micromolar hydrogen peroxide and ferrous and its environmental implications. Ecotoxicology and Environmental Safety, 249, 114435. https://doi.org/10.1016/j.ecoenv.2022.114435
26. Morales-Amaya, C. G., Astudillo-Sánchez, P. D., Reynoso-Cuevas, L., Herrera-Mendoza, R., & Lozano Morales, S. A. (2025). Immobilized nanomaterials for arsenic removal in agricultural systems: A brief review. Revista Mexicana de Ciencias Agrícolas, 16(30), e4056. https://doi.org/10.29312/remexca.v16i30.4056

27. Mosler, H.-J. (2012). A systematic approach to behavior change interventions for the water and sanitation sector in developing countries: A conceptual model, a review, and a guideline. International Journal of Environmental Health Research, 22(5), 431–449. https://doi.org/10.1080/09603123.2011.650156
28. Mosler, H.-J., & Contzen, N. (2016). Systematic behavior change in water, sanitation and hygiene: A practical guide using the RANAS approach (Version 1.1). Eawag: Swiss Federal Institute of Aquatic Science and Technology.
29. Nguyen, T. H., Nguyen, A. T., Loganathan, P., Nguyen, T. V., Vigneswaran, S., Nguyen, T. H. H., & Tran, H. N. (2021). Low-cost laterite-laden household filters for removing arsenic from groundwater in Vietnam and waste management. Process Safety and Environmental Protection, 152, 154–163. https://doi.org/10.1016/j.psep.2021.06.002
30. Niazi, N. K., Bibi, I., Shahid, M., Ok, Y. S., Burton, E. D., Wang, H., Shaheen, S. M., Rinklebe, J., & Lüttge, A. (2018). Arsenic removal by perilla leaf biochar in aqueous solutions and groundwater: An integrated spectroscopic and microscopic examination. Environmental Pollution, 232, 31–41. https://doi.org/10.1016/j.envpol.2017.09.051
31. Nunnally, J. C. (1978). Psychometric theory (2nd ed.). McGraw-Hill.
32. Page, M. J., McKenzie, J. E., Bossuyt, P. M., Boutron, I., Hoffmann, T. C., Mulrow, C. D., Shamseer, L., Tetzlaff, J. M., Akl, E. A., Brennan, S. E., Chou, R., Glanville, J., Grimshaw, J. M., Hróbjartsson, A., Lalu, M. M., Li, T., Loder, E. W., Mayo-Wilson, E., McDonald, S., … Moher, D. (2021). The PRISMA 2020 statement: An updated guideline for reporting systematic reviews. BMJ, 372, n71. https://doi.org/10.1136/bmj.n71
33. Qu, J., et al. (2021). Magnetic porous biochar with high specific surface area derived from microwave-assisted hydrothermal and pyrolysis treatments of water hyacinth for Cr(VI) and tetracycline adsorption from water. Bioresource Technology, 340, 125692. https://doi.org/10.1016/j.biortech.2021.125692
34. Rodríguez-Lara, J. W., Cervantes-Ortiz, F., Arámbula-Villa, G., Mariscal-Amaro, L. A., Aguirre-Mancilla, C. L., & Andrio-Enríquez, E. (2022). Lirio acuático (Eichhornia crassipes): una revisión [Water hyacinth (Eichhornia crassipes): A review]. Agronomía Mesoamericana, 33(1), 44201. https://doi.org/10.15517/am.v33i1.44201
35. Sánchez, J. (2026, January 10). Federación y gobierno de Hidalgo invertirán más de 900 mdp en 2026 para el saneamiento del río Tula [Federal and Hidalgo governments will invest more than 900 million pesos in 2026 to clean up the Tula River]. La Jornada Hidalgo. https://lajornadahidalgo.com/federacion-y-gobierno-de-hidalgo-invertiran-mas-de-900-mdp-en-2026-para-el-saneamiento-del-rio-tula/
36. Saning, A., Herou, S., Dechtrirat, D., Ieosakulrat, C., Pakawatpanurut, P., Kaowphong, S., Thanachayanont, C., Titirici, M.-M., & Chuenchom, L. (2019). Green and sustainable zero-waste conversion of water hyacinth (Eichhornia crassipes) into superior magnetic carbon composite adsorbents and supercapacitor electrodes. RSC Advances, 9, 24248–24258. https://doi.org/10.1039/C9RA03873F
37. Secretaría de Medio Ambiente y Recursos Naturales. (2025, November 7). El Gobierno de México avanza en la restauración ecológica de la presa Endhó y control del mosquito Culex [The Government of Mexico advances in the ecological restoration of the Endhó Dam and the control of the Culex mosquito]. Gobierno de México. https://www.gob.mx/semarnat/prensa/el-gobierno-de-mexico-avanza-en-la-restauracion-ecologica-de-la-presa-endho-y-control-del-mosquito-culex?idiom=es-MX
38. Shakoor, M. B., Niazi, N. K., Bibi, I., Murtaza, G., Kunhikrishnan, A., Seshadri, B., Shahid, M., Ali, S., Bolan, N. S., Ok, Y. S., Abid, M., & Ali, F. (2016). Remediation of arsenic-contaminated water using agricultural wastes as biosorbents. Critical Reviews in Environmental Science and Technology, 46(5), 467–499. https://doi.org/10.1080/10643389.2015.1109910
39. Siddiq, O. M., Tawabini, B. S., Soupios, P., & Ntarlagiannis, D. (2022). Removal of arsenic from contaminated groundwater using biochar: A technical review. International Journal of Environmental Science and Technology, 19(1), 651–664. https://doi.org/10.1007/s13762-020-03116-x
40. Srivastav, A. L., et al. (2022). Biochar adsorbents for arsenic removal from water environment: A review. Bulletin of Environmental Contamination and Toxicology, 108(4), 616–628. https://doi.org/10.1007/s00128-021-03374-6

41. Sun, Y., Wang, T., Bai, L., Han, C., & Sun, X. (2022). Application of biochar-based materials for remediation of arsenic contaminated soil and water: Preparation, modification, and mechanisms. Journal of Environmental Chemical Engineering, 10(5), 108292. https://doi.org/10.1016/j.jece.2022.108292
42. Ullah, M. H., & Rahman, M. J. (2024). Adsorptive removal of toxic heavy metals from wastewater using water hyacinth and its biochar: A review. Heliyon, 10, e36869. https://doi.org/10.1016/j.heliyon.2024.e36869
43. Villaseñor, A. (2026, July 20). Aguas negras en la presa Endhó, Hidalgo, foco de contaminación y enfermedades [Wastewater in the Endhó Dam, Hidalgo, a source of pollution and disease]. La Jornada. https://www.jornada.com.mx/noticia/2026/07/20/politica/aguas-negras-en-la-presa-endho-hidalgo-foco-de-contaminacion-y-enfermedades
44. World Health Organization. (2022). Guidelines for drinking-water quality: Fourth edition incorporating the first and second addenda. World Health Organization. https://www.who.int/publications/i/item/9789240045064
45. World Health Organization. (2026). WHO water, sanitation, hygiene and waste strategy 2026–2035 (WHO Reference No. B09661). https://www.who.int/publications/i/item/B09661
46. Zhang, F., Wang, X., Ji, X., & Ma, L. (2016). Efficient arsenate removal by magnetite-modified water hyacinth biochar. Environmental Pollution, 216, 575–583. https://doi.org/10.1016/j.envpol.2016.06.013
47. Zhu, N., Zhang, J., Tang, J., Zhu, Y., & Wu, Y. (2018). Arsenic removal by periphytic biofilm and its application combined with biochar. Bioresource Technology, 248(Pt B), 49–55. https://doi.org/10.1016/j.biortech.2017.07.026
48. Zoroufchi Benis, K., Motalebi Damuchali, A., Soltan, J., & McPhedran, K. N. (2020). Treatment of aqueous arsenic: A review of biochar modification methods. Science of the Total Environment, 739, 139750.

APPENDICES

Appendix A. Questionnaire for the evaluation of the filter with users (UCD–RANAS)

Introduction and consent. Good morning/afternoon. We are students from the Instituto Tecnológico de Pachuca and we are developing a filter made from water hyacinth from the Endhó Dam to remove some contaminants from water. The filter is still at the research stage and is not intended to make water potable. We invite you to answer some questions about water use in your household and your opinion about this filter. The interview is voluntary and anonymous, you may stop it at any time and your answers will be used for academic purposes only. Do you agree to participate? 1. Yes 2. No

Section A. Context of use

Code	Question	Response options
community	A1. In which community do you live?	List of the 27 riverside communities (codes 1 to 27)
age	A2. How old are you (in completed years)?	Number of years
sex	A3. Sex	1. Female 2. Male 3. Prefer not to answer
education	A4. What is your highest level of education?	1. No schooling 2. Primary 3. Lower secondary 4. Upper secondary 5. Higher education
members	A5. How many people live in your household?	Number of people
source	A6. What is the main source of water in your household?	1. Public network 2. Well 3. Water truck 4. Water jug or bottled water 5. Other
treatment	A7. Do you apply any treatment to the water before using it?	1. None 2. Boiling 3. Chlorine 4. Filter 5. Other
use	A8. What do you mainly use the water from that source for?	1. Drinking and cooking 2. Personal hygiene 3. Household cleaning 4. Irrigation or productive activities

Section B. RANAS factors

Instruction: I will now read some statements. Please indicate how much you agree with each one, where 1 means strongly disagree and 5 strongly agree.

Code	Item	1	2	3	4	5
RSK1	I consider it likely that my family or I will get sick from the water we use in my community.	☐	☐	☐	☐	☐
RSK2	If we got sick from polluted water, the consequences for our health would be serious.	☐	☐	☐	☐	☐
RSK3	I know that the water of the Endhó Dam and the Tula River may contain harmful substances, such as metals or arsenic.	☐	☐	☐	☐	☐
ATT1	I would be willing to devote time and money to a filter to treat water.	☐	☐	☐	☐	☐
ATT2	A filter made from water hyacinth could improve the quality of the water I use.	☐	☐	☐	☐	☐
ATT3	I like the idea of using the water hyacinth removed from the dam to make a filter.	☐	☐	☐	☐	☐
ATT4	I would trust a material made from water hyacinth to treat water.	☐	☐	☐	☐	☐
NOR1	Many people in my community use some method to treat water.	☐	☐	☐	☐	☐
NOR2	People who are important to me would approve of my using a filter of this type.	☐	☐	☐	☐	☐

NOR3	I feel obliged to protect my family by treating the water we use.	☐	☐	☐	☐	☐
ABI1	I would know how to operate the filter if I received simple instructions.	☐	☐	☐	☐	☐
ABI2	I feel capable of removing the material from the filter with a magnet and putting it back.	☐	☐	☐	☐	☐
ABI3	I could maintain the filter on a regular basis.	☐	☐	☐	☐	☐
ABI4	If the filter stopped working, I would know whom to turn to in order to fix it.	☐	☐	☐	☐	☐
SRG1	I could plan at what time of day to use and check the filter.	☐	☐	☐	☐	☐
SRG2	I could remember when the filter material needs to be replaced.	☐	☐	☐	☐	☐
SRG3	I would commit to using the filter continuously.	☐	☐	☐	☐	☐
SRG4	I would keep using the filter even if it required additional effort.	☐	☐	☐	☐	☐

Section C. User requirements

Code	Question	Response options
REQ1	C1. How much water would you like to treat per day with the filter?	1. Less than 20 L 2. From 20 to 50 L 3. From 51 to 100 L 4. More than 100 L
REQ2	C2. How often would you be willing to maintain it?	1. Weekly 2. Every two weeks 3. Monthly 4. Less often
REQ3	C3. How much would you be willing to pay for the filter?	1. Nothing 2. Less than $200 3. From $200 to $500 4. More than $500 (MXN)
REQ4	C4. Where would you prefer the filter to be located?	1. In my home 2. At a community point 3. At a school or community center
REQ5	C5. Who should be in charge of replacing the material?	1. Me or my family 2. A community committee 3. The municipality 4. An academic institution
REQ6	C6. How would you prefer to receive information about the filter?	1. Community meeting 2. Brochure 3. Video or social media 4. Home visit

Section D. Intention to use

Code	Item	1	2	3	4	5
INT1	I intend to use a filter of this type if it were available.	☐	☐	☐	☐	☐
INT2	I would recommend the filter to other people in my community.	☐	☐	☐	☐	☐

Appendix B. Codebook for data entry in IBM SPSS Statistics 19

Variable	Label	Values	Measure
id	Questionnaire ID number	Consecutive numeric	Scale
community	Community of residence	1–27; 99 = no response	Nominal
age	Age in completed years	18–99; 999 = no response	Scale
sex	Sex	1 = Female; 2 = Male; 3 = No response	Nominal
education	Highest level of education	1–5; 9 = no response	Ordinal
members	Household members	1–30; 99 = no response	Scale
source	Main water source	1–5; 9 = no response	Nominal
treatment	Household water treatment	1–5; 9 = no response	Nominal
use	Main use of water	1–4; 9 = no response	Nominal

RSK1–RSK3	Risk factor items	1–5 (Likert); 9 = no response	Ordinal
ATT1–ATT4	Attitude factor items	1–5 (Likert); 9 = no response	Ordinal
NOR1–NOR3	Norm factor items	1–5 (Likert); 9 = no response	Ordinal
ABI1–ABI4	Ability factor items	1–5 (Likert); 9 = no response	Ordinal
SRG1–SRG4	Self-regulation factor items	1–5 (Likert); 9 = no response	Ordinal
REQ1–REQ6	User requirements	1–4; 9 = no response	Nominal / ordinal
INT1–INT2	Intention-to-use items	1–5 (Likert); 9 = no response	Ordinal
RISK, ATTITUDE, NORM, ABILITY, SELFREG, INTENTION	Mean score of each factor (computed variables)	1.00–5.00	Scale
C_RISK … C_SELFREG	Classification of each factor (computed variables)	1 = Barrier; 2 = Intermediate; 3 = Favorable	Ordinal

Appendix C. Analysis syntax in IBM SPSS Statistics 19

```
* IBM SPSS Statistics 19 syntax - RANAS / UCD questionnaire.

* Magnetic water hyacinth biochar filter.

 * 1. Variable and value labels.

VARIABLE LABELS community 'Community of residence' /age 'Age'

  /sex 'Sex' /education 'Education' /members 'Household members'

  /source 'Main water source' /treatment 'Water treatment'

  /use 'Main use of water'.

VALUE LABELS sex 1 'Female' 2 'Male' 3 'No response'

  /education 1 'No schooling' 2 'Primary' 3 'Lower secondary'

   4 'Upper secondary' 5 'Higher education'

  /source 1 'Public network' 2 'Well' 3 'Water truck' 4 'Water jug' 5 'Other'

  /treatment 1 'None' 2 'Boiling' 3 'Chlorine' 4 'Filter' 5 'Other'

  /RSK1 TO SRG4 INT1 INT2 1 'Strongly disagree' 2 'Disagree'

   3 'Neither agree nor disagree' 4 'Agree' 5 'Strongly agree'.

MISSING VALUES education source treatment use RSK1 TO SRG4 REQ1 TO REQ6

  INT1 INT2 (9) /community members (99) /age (999).

EXECUTE.

* 2. Frequencies for context of use and requirements (sections A and C).

FREQUENCIES VARIABLES=community sex education source treatment use
```

```
  REQ1 TO REQ6 /ORDER=ANALYSIS.
* 3. Reliability by factor (Cronbach's alpha).
RELIABILITY /VARIABLES=RSK1 RSK2 RSK3 /SCALE('Risk') ALL
  /MODEL=ALPHA /SUMMARY=TOTAL.
RELIABILITY /VARIABLES=ATT1 ATT2 ATT3 ATT4 /SCALE('Attitude') ALL
  /MODEL=ALPHA /SUMMARY=TOTAL.
RELIABILITY /VARIABLES=NOR1 NOR2 NOR3 /SCALE('Norm') ALL
  /MODEL=ALPHA /SUMMARY=TOTAL.
RELIABILITY /VARIABLES=ABI1 ABI2 ABI3 ABI4 /SCALE('Ability') ALL
  /MODEL=ALPHA /SUMMARY=TOTAL.
RELIABILITY /VARIABLES=SRG1 SRG2 SRG3 SRG4 /SCALE('Self-regulation') ALL
  /MODEL=ALPHA /SUMMARY=TOTAL.
* 4. Exploratory factor analysis (KMO and Bartlett).
FACTOR /VARIABLES RSK1 TO SRG4 /PRINT INITIAL KMO EXTRACTION ROTATION
  /CRITERIA FACTORS(5) ITERATE(25) /EXTRACTION PAF /ROTATION VARIMAX.
* 5. Mean scores by factor.
COMPUTE RISK=MEAN(RSK1,RSK2,RSK3).
COMPUTE ATTITUDE=MEAN(ATT1,ATT2,ATT3,ATT4).
COMPUTE NORM=MEAN(NOR1,NOR2,NOR3).
COMPUTE ABILITY=MEAN(ABI1,ABI2,ABI3,ABI4).
COMPUTE SELFREG=MEAN(SRG1,SRG2,SRG3,SRG4).
COMPUTE INTENTION=MEAN(INT1,INT2).
EXECUTE.
* 6. Factor classification: 1 Barrier, 2 Intermediate, 3 Favorable.
RECODE RISK ATTITUDE NORM ABILITY SELFREG
  (LOWEST THRU 2.999=1) (3 THRU 3.999=2) (4 THRU HIGHEST=3)
  INTO C_RISK C_ATTITUDE C_NORM C_ABILITY C_SELFREG.
VALUE LABELS C_RISK TO C_SELFREG 1 'Barrier' 2 'Intermediate' 3 'Favorable'.
EXECUTE.
```

```
* 7. Descriptives and normality.

DESCRIPTIVES VARIABLES=RISK ATTITUDE NORM ABILITY SELFREG INTENTION

  /STATISTICS=MEAN STDDEV MIN MAX.

EXAMINE VARIABLES=RISK ATTITUDE NORM ABILITY SELFREG INTENTION

  /PLOT NPPLOT /STATISTICS DESCRIPTIVES.

FREQUENCIES VARIABLES=C_RISK TO C_SELFREG.

* 8. Spearman correlation between factors and intention to use.

NONPAR CORR /VARIABLES=RISK ATTITUDE NORM ABILITY SELFREG INTENTION

  /PRINT=SPEARMAN TWOTAIL NOSIG /MISSING=PAIRWISE.

 * 9. Comparison between communities (Kruskal-Wallis).

NPAR TESTS /K-W=RISK ATTITUDE NORM ABILITY SELFREG INTENTION

  BY community(1 27).

* 10. Multiple linear regression (Equation 4).

REGRESSION /STATISTICS COEFF OUTS R ANOVA COLLIN TOL

  /DEPENDENT INTENTION

  /METHOD=ENTER RISK ATTITUDE NORM ABILITY SELFREG.
```

Appendix D. Informed consent form

Project: Integration of the RANAS and UCD models in the development of a filter to improve water treatment in the Valle de Mezquital. Institution: Instituto Tecnológico de Pachuca, Industrial Engineering.

Purpose. We invite you to take part in an interview whose objective is to learn how water is used in your household and your opinion about a filter made from water hyacinth from the Endhó Dam that is at the research stage. Your answers will help design the filter according to the needs of the communities.

Procedure. If you agree to participate, a member of the research team will read you the questions in the questionnaire and record your answers. No samples, photographs or recordings will be taken.

Risks and benefits. Participation does not pose any risk to your health. You will not receive payment or any direct benefit; however, the information you provide will contribute to developing a water treatment alternative for the region.

Confidentiality. Your answers will be recorded with an ID number, without your name or any data that could identify you, and will be used for academic purposes only. The results will be presented in aggregate form.

Voluntary participation. You may refuse to participate, decline to answer any question or stop the interview at any time, without any consequence.

Contact. For any questions about the study, you may contact the research team at l23201027@pachuca.tecnm.mx.

I have read, or have had read to me, the information above, I have been able to ask questions and I agree to participate voluntarily.

ID No.: _____ Date: _____ Signature or fingerprint of the participant: _____

Name and signature of the interviewer: _____

Appendix E. Laboratory record forms

Form E1. Magnetic biochar production record by batch

Batch	Initial mass (g)	Temperature (°C)	Time (h)	Final mass (g)	Yield (%)	Magnetic response (yes/no)
B01						
B02						
B03						
B04						
B05						
B06						
B07						
B08						

Form E2. Batch As(V) adsorption test record

Test	Group	Variable and level	C_0 (mg/L)	C_f (mg/L)	V (L)	m (g)	E (%)	q (mg/g)	Replicate
001									
002									
003									
004									
005									
006									
007									
008									
009									
010									
011									
012									
013									
014									
015									

Note for recording: E (%) and q (mg/g) are calculated with Equations 1 and 2. Each test must be identified with the code of the variable evaluated and the corresponding level from Table 15.