CONCEPTUAL FRAMEWORK PAPER

From Invasive Biomass to Circular Soil Inputs:

A Waste Free ‘23 Circular Valorization Framework for Water Hyacinth

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Abstract

Water hyacinth (Eichhornia crassipes) is a rapidly proliferating aquatic plant that forms dense mats capable of obstructing waterways, irrigation canals, transport routes, fisheries, and infrastructure. Harvesting removes the biomass from affected water bodies but simultaneously creates a wet biomass-management problem. Water hyacinth also contains organic matter and mineral nutrients and has accordingly been investigated for liquid fertilizer, biochar, biological conversion, and other valorization routes.

This paper proposes the Waste Free ‘23 (WF23) Circular Valorization Framework: a conceptual, safety-aware, and decision-based model for converting harvested water hyacinth into multiple agricultural and biological products. The core pathway consists of source screening, washing, size reduction and dewatering, mechanical fractionation into liquid and solid fractions, optional controlled fermentation of the liquid fraction, pyrolysis of the solid fraction into biochar, and optional nutrient charging of the biochar using the recovered liquid fraction. A separate biological branch allows appropriately screened biomass to be evaluated for black soldier fly larvae (BSFL; Hermetia illucens) bioconversion.

The framework is intentionally not presented as a demonstrated Waste Free ‘23 technology. Existing studies provide evidence for individual conversion routes, but the integrated system has not yet been experimentally validated. Principal research gaps include nutrient recovery efficiency, liquid-fertilizer stability, nutrient charging compatibility, contaminant fate during processing, mass balance, economics, life-cycle impacts, and field crop performance. The framework therefore defines a five-phase validation roadmap spanning feedstock characterization, product development, nutrient-charging trials, agronomic validation, and full systems analysis.

Keywords: *water hyacinth; Eichhornia crassipes; circular economy; liquid organic fertilizer; biochar; nutrient-charged biochar; black soldier fly larvae; biomass valorization; contaminant screening; soil fertility*

1 Introduction

Water hyacinth (Eichhornia crassipes) is among the world's most problematic invasive aquatic plants. Its ability to double its biomass in as little as two weeks under favorable conditions enables it to form dense surface mats that reduce light penetration, deplete dissolved oxygen, obstruct waterways, impede irrigation, damage fishing livelihoods, and degrade aquatic biodiversity [1,2]. Across sub-Saharan Africa, South and Southeast Asia, and parts of Latin America, water hyacinth management imposes substantial costs on governments, farming communities, and water utilities.

Harvesting alone does not solve the entire management problem. Removing dense mats transfers a large volume of wet biomass — typically containing 90–95% moisture by mass — from the aquatic environment to a terrestrial handling system. Transport, dewatering, storage, and final disposal can become significant logistical and economic burdens in their own right. Coupling biomass removal with safe and productive valorization is therefore an important component of a genuinely circular management strategy.

Existing studies have investigated water hyacinth across several conversion routes, including liquid organic fertilizer production, composting, anaerobic digestion, biochar, phytoremediation, and insect bioconversion [1–3]. Recent literature has also examined water-hyacinth-derived biochar and biochar-based fertilizer concepts, while black soldier fly larva (BSFL) research has explored water hyacinth as a biological conversion substrate [3,4].

The available evidence, however, remains fragmented. Individual studies typically optimize or characterize a single product rather than an integrated system that determines how harvested biomass should be fractionated, routed, and evaluated according to feedstock quality, contamination status, target product, and local economic context.

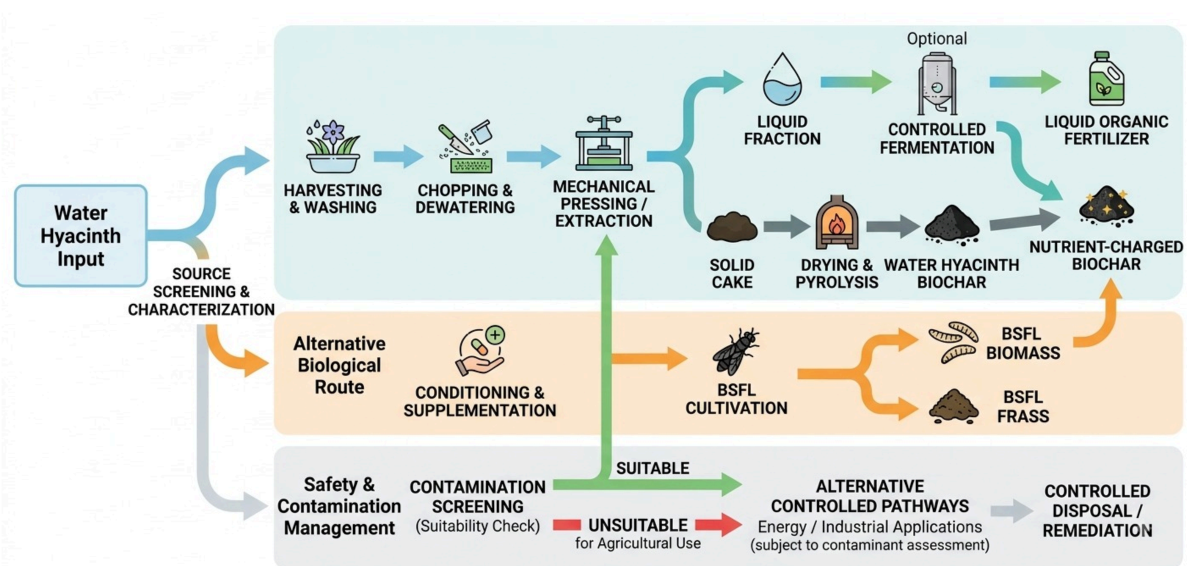
A further and critical complication is that water hyacinth can bioaccumulate heavy metals and other contaminants from polluted water bodies through its well-documented phytoremediation capacity [5,6]. This creates a circular-economy paradox: the same uptake capability that makes the plant valuable for water cleanup can render harvested biomass unsafe for direct agricultural reuse. Contaminant status must therefore be established before any valorization pathway is pursued.

This paper synthesizes current evidence on water-hyacinth-derived liquid fertilizer, biochar, and BSFL conversion, and proposes the WF23 Circular Valorization Framework: a conceptual model linking biomass harvesting, source screening, mechanical fractionation, liquid nutrient recovery, biochar production, optional nutrient charging, optional insect bioconversion, and soil-fertility application. The framework is explicitly prospective; it does not claim experimental performance data by WF23 and defines the research program required before field deployment.

2 Conceptual Basis and Scope

The WF23 framework was developed as a perspective and process-model paper rather than a systematic review or experimental study. The literature base is organized by conversion function and by the role each pathway can play within an integrated biomass-management system. The central distinction maintained throughout is between established evidence for individual pathways drawn from published research and the proposed integration of those pathways within the WF23 system, for which experimental validation is still required.

Figure 1. Schematic representation of the proposed Hyacinth Valorization Framework, detailing core pathways.



The model contains two distinct process routes. The core route is an integrated liquid-fertilizer and biochar pathway in which mechanical pressing of prepared biomass generates both a liquid fraction rich in soluble nutrients and a solid cake suitable for thermal conversion. The second is an optional biological branch for selected, appropriately screened biomass and BSFL bioconversion. These routes are alternatives or decision branches rather than sequential operations; the same solid cake cannot simultaneously be pyrolyzed into biochar and used as a BSFL substrate. Route selection is therefore a deliberate decision governed by feedstock quality, contamination status, economics, and intended product.

3 Water Hyacinth as a Variable-Quality Biomass Resource

Water hyacinth combines rapid biomass production with very high moisture content, typically 90–95% on a fresh-weight basis. Moisture dominates the economics and logistics of collection, transport, storage, pressing, and thermal conversion. Feedstock composition also varies substantially with geographic location, season, plant age, plant part, and the quality of the water body from which the plant is harvested [1,2,3].

The biomass contains organic carbon and a range of plant-available mineral nutrients including nitrogen, phosphorus, potassium, calcium, and magnesium. However, the presence of nutrients does not by itself establish fertilizer or amendment value. Nutrient form, availability, soil pH, electrical conductivity, organic compound composition, microbial community characteristics, application rate, and broader soil and crop context all influence whether and how nutrients become available to plants.

Feedstock quality is treated in the WF23 framework as a variable input rather than a fixed property. Source screening precedes any processing decision, and the intended product route is selected only after moisture content, nutrient profile, and contamination status have been characterized. This prevents the circular-economy objective from substituting for the feedstock quality assessment that safety and agronomic performance require.

Key Feedstock Variable

Moisture content of fresh water hyacinth is typically 90–95%, meaning that 1 tonne of fresh biomass yields approximately 50–100 kg of dry material. All yields, product quantities, and mass balances must be expressed on a dry-weight basis to be meaningful and comparable across sites and seasons.

4 Contamination and Source Screening

Water hyacinth has been extensively studied for phytoremediation because it can take up heavy metals including lead, cadmium, chromium, arsenic, and mercury from contaminated aquatic systems [5,6]. Bioaccumulation factors can be substantial, and metal concentrations in plant tissue can exceed regulatory thresholds for soil amendments and fertilizers even when water-column concentrations appear moderate.

This creates the central circular-economy paradox: the same uptake capacity that makes water hyacinth useful for water cleanup can make harvested biomass unsuitable for agricultural reuse. A management program that removes contaminated biomass and then applies it to farmland may simply transfer pollutants from the water to the food system.

The WF23 framework therefore places source screening before all processing decisions. Biomass from relatively low-risk, uncontaminated water bodies may proceed to agricultural valorization after contaminant characterization confirms compliance with applicable standards. Biomass from uncertain sources requires detailed assessment before any route is selected. Biomass known to carry contaminants above applicable thresholds must be excluded from agricultural fertilizer, soil-amendment, and BSFL routes unless processing is demonstrated to reduce contaminant concentrations and leachability to safe levels under an appropriate regulatory framework.

Important Clarification on Pyrolysis

Pyrolysis should not be assumed to be a universal decontamination step. Depending on contaminant chemistry and process conditions, some metals may be retained in or concentrated in the solid biochar and ash fraction rather than volatilized. Biochar from contaminated water-hyacinth feedstocks therefore requires independent contaminant analysis before agricultural application. Water-hyacinth biochar research has accordingly included metal characterization as a standard component [3,6,7].

5 Literature Review by Conversion Function

5.1 Liquid Organic Fertilizer

Water-hyacinth-derived liquid fertilizers have been investigated using maceration, extraction, and fermentation approaches. Studies have evaluated microbial inoculation, water-to-biomass ratios, fermentation duration, and combinations with other organic materials. Reported characterization typically includes pH, electrical conductivity (EC), nitrogen, phosphorus, potassium, soluble organic carbon, and microbial community properties.

Harbi et al. reported crop yield responses to a liquid fertilizer produced from a 50:50 mixture of water hyacinth and Siam weed (Chromolaena odorata) applied to Taiwan Napier grass [8]. Because the feedstock was a blend rather than pure water hyacinth, the result provides evidence for a water-hyacinth-containing fertilizer rather than proof that an equivalent fertilizer can be reliably produced from water hyacinth alone. Feedstock interaction effects cannot be excluded.

A more recent study evaluated a water-hyacinth-based organic-phosphate liquid fertilizer on strawberry grown across contrasting soil types, reporting effects on plant growth, yield, and fruit quality [9]. Such work supports the agronomic plausibility of liquid fertilizer application but does not establish a universal formulation, processing protocol, or contaminant safety profile applicable to all production contexts.

Fermentation may stabilize or beneficially transform the liquid fraction through pH reduction, pathogen suppression, and nutrient solubilization. However, the WF23 framework does not treat fermentation as an obligatory step. The proposed sequence is mechanical extraction followed by characterization; controlled fermentation is an optional downstream operation if experimental evidence demonstrates that it improves stability, safety, or agronomic performance sufficiently to justify the additional process requirements and holding time.

5.2 Water Hyacinth Biochar

Pyrolysis provides a route for converting the solid fraction of water hyacinth into a carbon-rich biochar. Biochar properties are strongly dependent on feedstock composition, pyrolysis temperature, residence time, heating rate, and any post-processing steps [3,7]. Relevant properties for agricultural use include product yield, pH, EC, ash content, fixed carbon, volatile matter, nutrient content, surface area, porosity, and contaminant concentration.

Kassa et al. produced water-hyacinth biochar at 300°C for 40 minutes and reported a 44.6% yield, a pH of approximately 8.11, and an EC of approximately 18.70 mS/cm. The biochar contained measurable N, P, K, Ca, and Mg. A 2,500 kg/ha application produced teff grain yields comparable with selected mineral-fertilizer and mixed-amendment treatments under the experimental conditions evaluated [7]. These results support the agronomic plausibility of a biochar pathway but should not be generalized across feedstocks or processing conditions without validation.

Potential soil functions of water-hyacinth biochar include nutrient retention, improved water-holding capacity, pH buffering in acidic soils, and provision of reactive adsorption surfaces. However, the high EC reported for water-hyacinth biochar in several studies [7] raises salinity concerns at high application rates, particularly in sodic or salt-sensitive soils. WF23 does not specify a universal optimum pyrolysis temperature; the appropriate operating window should be determined for each feedstock and target soil type through systematic experimentation.

5.3 Nutrient Charging of Biochar

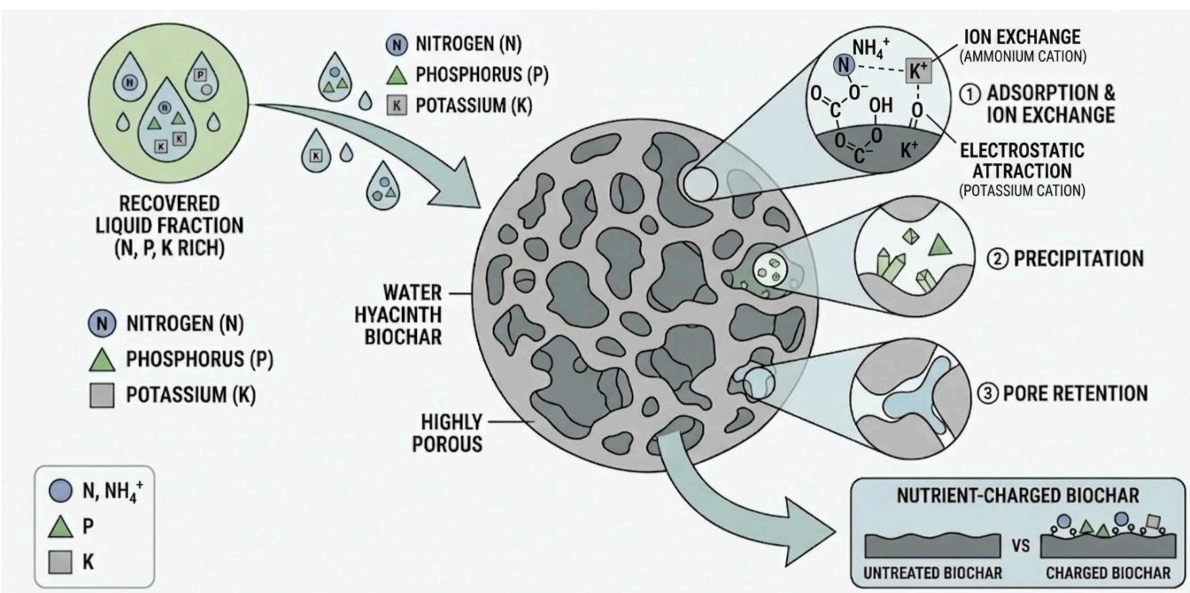


Figure 2. Conceptual loop of biochar nutrient charging using recovered water hyacinth liquid fraction.

Biochar-based fertilizers are increasingly investigated as systems that combine the slow-release nutrient supply with the physicochemical soil functions of biochar. Nutrient-loading approaches include impregnation with nutrient solutions, co-pyrolysis with nutrient-rich materials, encapsulation, and other formulation methods [10,11]. Published results show that loaded biochar can improve nutrient-use efficiency and reduce leaching relative to conventional soluble fertilizers under certain conditions.

The distinctive WF23 hypothesis is to investigate whether the liquid fraction recovered by pressing the same water-hyacinth feedstock can be used to charge the biochar produced from its corresponding solid fraction. Conceptually, the system would recover soluble nutrients — primarily nitrogen, phosphorus, and potassium – into a liquid stream during pressing, convert structural biomass into biochar by pyrolysis, and then combine both streams to form an internally nutrient-charged soil amendment.

This internal nutrient loop is scientifically plausible but remains a hypothesis. Direct experimental evidence for charging water-hyacinth biochar with a water-hyacinth-derived liquid fraction is not yet available. Charging effectiveness will depend on liquid composition (especially pH and EC), biochar surface chemistry, pore structure, contact time, and liquid-to-biochar ratio [10,11]. The compatibility of the specific liquid fraction with the specific biochar produced from the same feedstock must be established experimentally before the concept can be validated.

5.4 BSFL Conversion

Black soldier fly larvae (Hermetia illucens) can efficiently convert organic substrates into larval biomass rich in protein and lipids, and a residual frass that serves as a soil amendment. Water hyacinth has been investigated as a BSFL substrate in several studies examining inclusion levels, co-substrates, substrate reduction efficiency, and larval growth parameters [4].

Recent work on fermented water hyacinth demonstrated that substrate formulation and nutritional supplementation significantly influence the biomass composition of developmental stages, and explicitly emphasized the need to assess contaminant transfer into larvae and frass [4]. This is a critical finding: if the water-hyacinth feedstock carries heavy metals or persistent organic compounds, those contaminants may accumulate in larval tissue and frass at concentrations that render them unsafe for use as animal feed or soil inputs.

Within the WF23 framework, BSFL conversion is therefore an optional biological branch rather than a mandatory or parallel stage. Appropriately screened and conditioned biomass may be routed to BSFL where substrate suitability, nutritional adequacy, and contaminant safety are demonstrated. The solid cake generated by the core pressing route is not simultaneously designated as both BSFL feedstock and pyrolysis feedstock.

5.5 Summary of Evidence Gaps

Table 1. Evidence status and principal uncertainties by conversion route within the WF23 framework.

Route	Established Evidence	Main Product	Principal Uncertainties
Liquid extraction / fermentation	Crop-response and fertilizer studies exist [8,9]	Liquid fertilizer	Nutrient consistency, microbial safety, contaminant fate, storage stability
Pyrolysis to biochar	Biochar characterization and soil studies exist [3,7]	Biochar	Feedstock variability, salinity / high EC, contaminant behavior, yield optimization
Nutrient charging	Biochar-fertilizer literature supports loading concepts [10,11]	Nutrient-charged biochar	Specific compatibility of water-hyacinth liquid with water-hyacinth biochar

BSFL bioconversion	Substrate and larval-growth studies exist [4]	Larvae and frass	Nutritional balance, contaminant transfer, product safety for feed and soil use
Integrated WF23 system	Limited or absent direct evidence	Multiple products	Mass balance, process compatibility, economics, life-cycle impacts

6 The WF23 Circular Valorization Framework

The WF23 model is defined as a decision-based circular system rather than a single fixed processing recipe. Its stages proceed as follows:

- Stage 1 – Biomass harvesting: mechanical or manual removal from the water body.
- Stage 2 – Source screening and initial contaminant assessment: water body history, preliminary heavy-metal and agronomic screening.
- Stage 3 – Washing and debris removal: rinse to reduce surface contamination and remove non-biomass material.
- Stage 4 – Size reduction and dewatering: chopping or shredding, followed by gravity or mechanical dewatering to reduce moisture content.
- Stage 5 – Mechanical pressing: separation into a liquid fraction (plant sap and soluble nutrients) and a solid cake (structural biomass).
- Stage 6 – Liquid fraction management: characterization; optional controlled fermentation if demonstrated to improve safety, stability, or agronomic value.
- Stage 7 – Solid fraction stabilization and pyrolysis: drying of the solid cake to suitable moisture content; conversion to biochar in a TLUD or retort-style reactor.
- Stage 8 – Optional nutrient charging: investigation of using the liquid fraction as a charging medium for the produced biochar.
- Stage 9 – Product quality and safety testing: contaminant analysis, phytotoxicity testing, and compliance with applicable standards before any agricultural application.
- Stage 10 – Agricultural application and monitoring: soil or foliar application under controlled or farmer-managed conditions with monitoring of nutrient uptake, contaminant transfer, and soil health indicators.

Core Process Pathway

> *Water hyacinth → source screening → washing → chopping and dewatering → mechanical pressing → [liquid fraction + solid cake] → liquid characterization / optional fermentation AND solid drying / pyrolysis → biochar → optional nutrient charging → product quality testing → agricultural application → monitoring.*

Optional Biological Branch

> *Screened and conditioned biomass → route-selection decision based on contamination, nutritional suitability, and economics → BSFL conversion → larvae and frass/residue → separate product-quality and contaminant assessment → feed or soil-amendment application.*

Route selection between the core pathway and the biological branch – or between sub-options within the core pathway – is governed by feedstock moisture content, nutrient and contaminant characterization results, available infrastructure, local market context for products, and regulatory requirements. The two primary routes are mutually exclusive for a given solid-fraction batch: the same solid material cannot simultaneously be pyrolyzed and fed to BSFL.

7 Proposed Product Portfolio

The WF23 framework can generate up to four product categories from a single biomass input, subject to feedstock suitability and validation:

- Core Product 1 – Water-hyacinth-derived liquid organic fertilizer: the liquid fraction recovered by mechanical pressing, with fermentation treated as an optional stabilization and formulation step rather than a requirement.
- Core Product 2 – Water-hyacinth biochar: produced from the suitable solid fraction by pyrolysis in a low-cost reactor (TLUD or retort-style), with properties adjusted according to feedstock and target soil type.
- Core Product 3 – Nutrient-charged water-hyacinth biochar: an internally produced soil amendment combining the carrier function of the biochar with the soluble nutrient content of the liquid fraction, contingent on nutrient-loading experiments demonstrating adequate loading efficiency, stability, and release behavior.
- Optional Biological Products – BSFL larvae and BSFL frass: insect biomass for animal feed and frass as a soil amendment, available from the biological branch where substrate suitability and contaminant safety are independently demonstrated.

8 Research Hypotheses and Validation Objectives

The WF23 framework generates seven specific, testable hypotheses that define the validation program:

- H1: Controlled fermentation of water hyacinth produces a liquid fraction containing measurable soluble N, P, K, organic carbon, and microbial metabolites at concentrations relevant to plant nutrition.
- H2: Liquid-fraction composition varies predictably with biomass-to-water ratio, fermentation duration, inoculum source, and plant part, and these variables can be optimized for target nutrient profiles.
- H3: Water-hyacinth biochar improves soil water retention, pH buffering, nutrient retention, or selected soil-fertility indicators relative to an unamended control under experimental conditions.

- H4: Nutrient charging of water-hyacinth biochar using the corresponding liquid fraction increases its measurable nutrient content and nutrient-release capacity compared with uncharged biochar.
- H5: Combined liquid-fertilizer and biochar treatment produces greater plant growth or nutrient-use efficiency than either product used separately, at equivalent total nutrient inputs.
- H6: Contaminant concentrations and phytotoxicity in all products remain below applicable regulatory thresholds for soil amendments and fertilizers after full processing.
- H7: The integrated multi-product pathway achieves greater nutrient recovery from the feedstock and lower residual-waste generation than any single-route conversion process.

9 Validation Methodology

9.1 Feedstock Characterization

Any source intended for agricultural valorization must be characterized for the following parameters before processing begins:

- Moisture content and ash
- Total organic carbon (TOC)
- Total N, P, and K; C/N ratio
- pH and electrical conductivity (EC)
- Ca, Mg, S, and relevant micronutrients
- Pb, Cd, Cr, Hg, As, Ni, and other locally regulated contaminants
- Microbial indicators where agricultural application is intended

9.2 Liquid Fraction Analysis

The recovered liquid fraction should be characterized for:

- pH, EC, and total dissolved solids (TDS)
- Total and soluble N, P, and K; ammonium and nitrate separately
- Dissolved organic carbon and BOD/COD where the fraction is wastewater-like
- Phytotoxicity index or seed-germination index at relevant dilutions
- Microbial load and pathogen indicators
- Heavy metals at relevant detection limits
- Storage stability and odor development over time

9.3 Biochar Characterization

Biochar produced from water hyacinth should be analyzed for:

- Product yield and mass balance
- pH, EC, ash content, fixed carbon, and volatile matter
- Total and plant-available nutrients; C/N ratio

- Surface area and pore characteristics (where feasible)
- FTIR and SEM characterization (where available)
- Heavy metals: total concentration and leachability under standard extraction protocols
- Nutrient-release kinetics and water-retention tests

9.4 Plant Validation – Factorial Design

A factorial experiment is strongly preferable to unrelated pairwise comparisons because it allows main effects and interactions to be estimated. The proposed six-treatment design is:

Table 2. Proposed factorial plant validation treatments.

Treatment	Description	Liquid Fertilizer	Biochar	Notes
C	Unamended control	No	No	Baseline
L	Liquid fertilizer only	Yes	No	...
B	Biochar only	No	Yes	...
LB	Liquid fertilizer + biochar	Yes	Yes	Combined
CF	Commercial fertilizer	Reference rate	No	...
CF+B	Commercial fertilizer + biochar	Reference rate	Yes	...

Liquid and biochar doses must be normalized on the basis of actual measured nutrient input rather than only volume or mass. Without nutrient-normalized dosing, combined treatments cannot be compared fairly with single-product or commercial-fertilizer treatments. Measured outcome variables should include: germination rate, plant height, leaf number, above- and below-ground biomass, chlorophyll content or equivalent physiological indicators, nutrient uptake, and – critically – soil pH, EC, available N/P/K, water retention, and contaminant concentrations at the end of the trial.

9.5 BSFL Branch Evaluation

Where the biological route is pursued, the following parameters should be measured in addition to standard larval growth metrics:

- Larval survival, weight gain, substrate-reduction efficiency, and bioconversion rate
- Feed conversion ratio and larval protein and lipid content
- Residue / frass NPK profile and agronomic characterization
- Heavy metals in both larvae and frass at relevant detection limits
- Pathogen and microbial safety indicators in larvae and frass

10 Mass-Balance and Nutrient-Recovery Framework

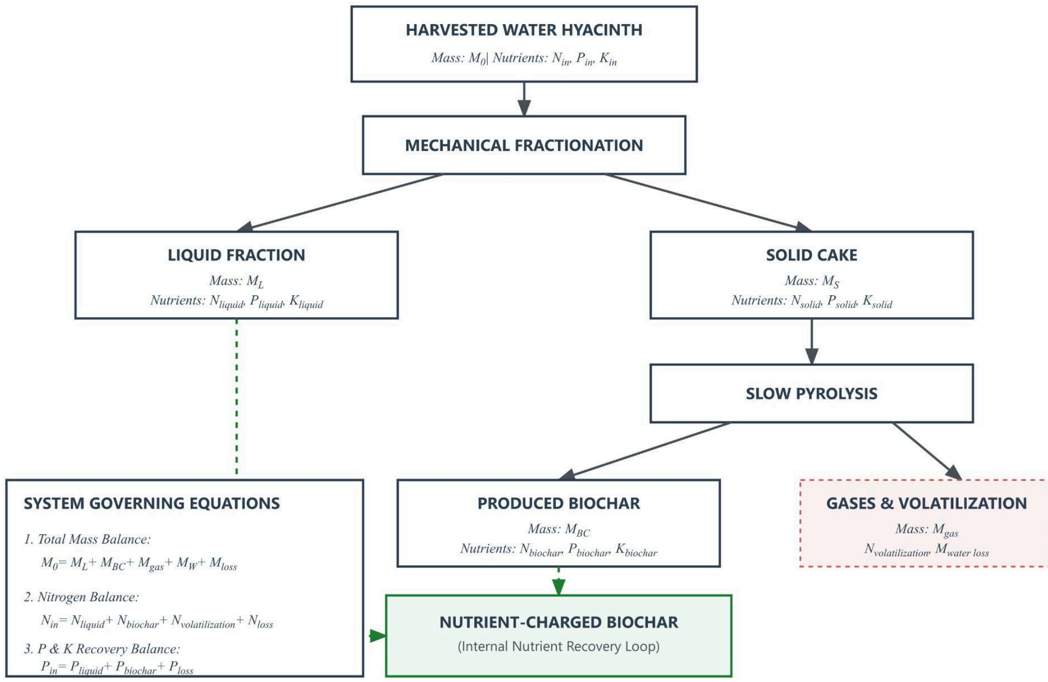


Figure 3. Mass balance and nutrient tracking framework (N, P, K) across fractionation, pyrolysis, and conversion streams.

A central validation requirement for the integrated WF23 system is an experimentally measured mass balance. Without it, claims of circular nutrient recovery remain conceptual. For a fresh biomass input M_0, the primary fractionation step can be represented as:

$$M_0 = M_L + M_S + M_W + M_{loss}$$

where M_L is the recovered liquid fraction, M_S is the recovered solid fraction, M_W is water removed during dewatering or drying, and M_loss represents processing losses. The solid fraction subsequently undergoes pyrolysis:

$$M_S = M_{BC} + M_{gas} + M_{loss,pyrolysis}$$

where M_BC is biochar mass, M_gas represents volatilized gases including syngas and water vapor, and M_loss,pyrolysis represents unrecovered process losses.

Independent nutrient balances must track N, P, and K through the entire system. For nitrogen as an example:

$$N_{input} = N_{liquid} + N_{biochar} + N_{gas} + N_{loss}$$

Equivalent balances should be developed for phosphorus and potassium. These balances will determine the actual nutrient recovery efficiency of the integrated process – that is, how much of the feedstock nutrient resource is genuinely captured into usable products versus lost to the atmosphere, process effluent, or unrecovered residues. Reporting nutrient balances is a prerequisite for any life-cycle or environmental impact assessment.

11 Techno-Economic Considerations

Economic feasibility will depend on local conditions across the full process chain: harvesting and transport costs, labor availability, infrastructure for washing, dewatering, pressing, fermentation, pyrolysis, quality testing, and product storage. Potential revenue streams may include liquid fertilizer, biochar, nutrient-charged biochar, BSFL larval biomass, and frass. Avoided biomass-disposal costs or avoided waterway-management expenditure may also contribute measurable economic value.

An integrated multi-product system could have a profitability advantage over a single-product pathway if multiple revenue streams can be generated from the same feedstock without proportionally increasing fixed costs. However, profitability cannot be assumed. Local feedstock availability and seasonality, product yields per tonne of fresh biomass, energy requirements for drying and pyrolysis, labor intensity, market prices for competing products, and quality-testing costs must all be measured at realistic scale before economic conclusions can be drawn.

A preliminary techno-economic analysis should accompany Phase V of the validation roadmap (Section 15) and should be scenario-based, covering at minimum a conservative, moderate, and optimistic case for key input costs and product prices. Sensitivity analysis should identify which variables most strongly determine economic viability and therefore deserve the most attention during experimental design.

12 Life-Cycle Considerations

A circular designation does not automatically establish environmental superiority over conventional disposal or single-route conversion. A future life-cycle assessment (LCA) must quantify energy inputs across all process stages – harvesting, transport, washing, dewatering, drying, fermentation, pyrolysis, and product distribution – as well as the environmental credits attributable to fertilizer displacement, carbon retention in biochar, avoided biomass disposal, and avoided waterway management.

At minimum, the integrated WF23 system should be compared against: (1) conventional mechanical removal and landfill or composting disposal; and (2) individual single-route conversion pathways (liquid fertilizer only, biochar only, BSFL only). The comparison should be conducted on a common functional unit – most appropriately, per tonne of fresh water hyacinth biomass managed from the water body.

Key LCA indicators should include greenhouse-gas emissions (including carbon permanence in biochar), net energy demand, water consumption, eutrophication potential, acidification potential, recovered nutrient mass, and any contaminant-management burden. Identifying the process stages that dominate environmental impact will guide both engineering optimization and the prioritization of future research investment.

13 Safety and Product-Quality Framework

Safety is positioned in the WF23 framework as a process gate applied at multiple sequential decision points, not as a final-stage check added once products have been generated. The proposed sequence is:

> *Source screening → feedstock contaminant analysis → route selection → product contaminant analysis → leachability and phytotoxicity testing → regulatory compliance review → agricultural application → post-application monitoring of soil and crop.*

The specific regulatory thresholds applicable to each product category – liquid fertilizer, biochar, soil amendment, animal feed ingredient, and BSFL frass – vary by jurisdiction. The framework deliberately avoids specifying universal numeric limits, because appropriate standards must be selected according to the country of production, the intended application, and the crop or livestock system concerned. Experimental teams should identify applicable fertilizer, soil-amendment, and biochar standards for their specific jurisdiction before commencing any product-quality assessment.

For the BSFL branch, the same principle applies with additional specificity: contaminant transfer into larval tissue and frass must be measured rather than assumed to be negligible [4]. Published evidence indicates that certain heavy metals can accumulate in BSFL tissue depending on substrate composition and larval development stage. This makes feedstock contaminant screening even more critical when the biological route is intended to produce feed-grade larval meal.

14 Discussion

The principal contribution of the WF23 framework is the shift from single-product water-hyacinth valorization toward an integrated, decision-based circular biomass system. Existing literature demonstrates that water hyacinth can support several independent conversion pathways [1–4,7–9]. The WF23 model links these pathways through a common fractionation step – mechanical pressing – and a common contamination-screening logic that governs route selection.

The most scientifically distinctive proposed relationship is the coupling of liquid nutrient recovery from pressing with solid-fraction biochar production by pyrolysis, followed by nutrient charging of the biochar using the recovered liquid. This creates a potential internal resource loop in which one feedstock supplies both a liquid nutrient carrier and a carbon-rich porous matrix, and both are combined into a single soil amendment. The concept is supported by the broader biochar-based fertilizer literature [10,11], but its specific application to paired water-hyacinth fractions produced from the same feedstock and in the same processing cycle remains unvalidated.

The framework also makes contamination a central design criterion at every stage rather than an ancillary consideration. Because water hyacinth bioaccumulates contaminants [5,6], biomass quality must determine whether agricultural, biological, energy, or controlled-disposal pathways are appropriate for any given source. This prevents the circular-economy objective from overriding environmental safety, which is a genuine risk when valorization programs are implemented rapidly without adequate feedstock characterization.

The evidence base for individual components is uneven. Liquid fertilizer and biochar have reasonable literature support, though much of the liquid-fertilizer evidence involves mixed feedstocks or limited characterization [8,9]. Nutrient charging remains conceptual for this specific application [10,11]. The BSFL branch has emerging support but requires attention to contaminant transfer and substrate nutritional adequacy [4]. The fully integrated, multi-product WF23 system has no direct published evidence as of the time of writing.

The integrated model generates a clear and sequential research agenda: determine fractionation yields and nutrient partitioning; characterize the liquid fraction in detail; establish whether controlled fermentation adds sufficient value to justify the added process complexity; determine biochar properties as a function of pyrolysis conditions; quantify nutrient-loading efficiency and release kinetics; assess factorial crop response under nutrient-normalized dosing; track contaminants through all product streams; and then determine mass balance, economics, and life-cycle performance at pilot scale.

15 Research Roadmap

The validation program required before field deployment is organized into five sequential phases:

Phase I – Feedstock Characterization

Source mapping; site-specific moisture, nutrient, and contaminant profiling across multiple water bodies and seasons; establishment of source-screening criteria for route selection. Output: a feedstock characterization protocol and source-risk classification for target sites.

Phase II – Fractionation and Product Development

Washing, chopping, and pressing trials; optimization of liquid-extraction efficiency; liquid fraction characterization and fermentation trials; solid fraction drying; pyrolysis trials at multiple temperatures with property characterization at each condition. Output: liquid fraction specification and biochar production protocol for the selected feedstock.

Phase III – Nutrient Charging

Systematic investigation of liquid-to-biochar ratios, charging duration, and pH adjustment effects on loading efficiency; measurement of nutrient-release kinetics and stability; determination of how charging alters EC, pH, and surface chemistry. Output: nutrient-charging protocol or evidence-based decision not to proceed.

Phase IV – Biological and Agronomic Validation

BSFL experiments where feedstock screening indicates appropriateness; germination index testing for all liquid and blended products; factorial greenhouse crop trials using the treatment design in Section 9.4 with nutrient-normalized dosing; contaminant tracking in all plant and soil samples. Output: crop trial data and contaminant safety assessment for each product.

Phase V – Systems Analysis

Experimentally grounded mass balance across all process stages; nutrient-recovery efficiency calculation; scenario-based techno-economic analysis; comparative life-cycle assessment against single-route and conventional disposal baselines; pilot-scale evaluation under field conditions. Output: systems-level evidence base for deployment decisions.

16 Limitations

The following limitations of the present framework and the current evidence base should be acknowledged:

- The WF23 integrated system has not yet been experimentally demonstrated as a complete process; all integration claims are prospective and hypothesis-based.
- Published evidence for individual pathways comes from different countries, feedstock sources, crop species, processing conditions, and experimental scales, limiting direct transferability.
- Several liquid-fertilizer studies use blended feedstocks rather than water hyacinth alone, making it difficult to attribute observed crop responses solely to water hyacinth components.
- Biochar properties – particularly pH, EC, and nutrient content – are highly sensitive to pyrolysis temperature and residence time, and cannot be assumed to be consistent across reactor types or operational conditions.
- Mechanical pressing alone may recover soluble nutrients in the liquid fraction but may not produce a microbiologically stable fertilizer without controlled fermentation, pasteurization, or other preservation treatment.
- Nutrient charging may alter biochar pH, EC, and microbial characteristics in ways that affect both soil compatibility and regulatory classification of the resulting product.
- Pyrolysis may concentrate rather than destroy certain heavy metals in the solid biochar fraction; post-pyrolysis contaminant testing is therefore required for any contaminated feedstock.
- Crop responses cannot be reliably predicted from nutrient composition alone; interactions with soil type, existing fertility status, crop variety, climate, and management practice all influence outcomes.
- The model currently lacks demonstrated mass balance, life-cycle assessment, techno-economic analysis, and field-scale or farmer-level evidence. These gaps define the research program rather than the deployment readiness of the system.

17 Conclusion

Water hyacinth should be regarded not as a weed requiring disposal but as a variable-quality biomass feedstock with potential to support multiple valorization routes. Existing studies provide preliminary support for liquid organic fertilizer production, biochar synthesis, and BSFL bioconversion as individual pathways, but they do not yet demonstrate the WF23 framework as an integrated, validated process [1–4,7–9].

The principal contribution of this paper is the formulation of a testable, safety-aware circular framework that links biomass harvesting, source screening, mechanical fractionation, liquid nutrient recovery, biochar production, optional nutrient charging, optional insect bioconversion, and soil-fertility application into a coherent decision-based system. The framework explicitly and consistently separates established literature evidence from proposed WF23 hypotheses, and makes that distinction visible at every stage.

Experimental validation across all five research phases – feedstock characterization, fractionation and product development, nutrient charging, agronomic validation, and systems analysis – is required before the integrated system can be assessed for agricultural deployment. Contaminant assessment, mass-balance analysis, techno-economic evaluation, and life-cycle assessment are not optional extensions; they are prerequisites for responsible circular-economy implementation.

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Appendix A. Proposed WF23 Process Logic Summary

Core Route

> *Harvest → source screening → washing / debris removal → size reduction / dewatering → mechanical pressing → liquid fraction + solid cake → liquid characterization / optional controlled fermentation → solid stabilization → pyrolysis → biochar → optional nutrient charging → product quality and safety testing → agricultural application → monitoring.*

Optional Biological Branch

> *Screened and conditioned biomass → route-selection decision (contamination, nutritional suitability, economics) → BSFL conversion → larvae + frass/residue → independent product-quality and contaminant assessment → feed or soil-amendment application.*

Route Selection Criteria

Route selection between the core pathway and the biological branch, and between sub-options within each route, should be governed by: feedstock moisture content; nutrient and contaminant characterization results; available processing infrastructure; local market conditions and product prices; and applicable regulatory standards for each product category in the production jurisdiction.

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