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Integral Valorization of the Invasive *Lissachatina fulica* in Madagascar : A Zero-Waste Pathway to Nutritional Security and the Green Circular Economy

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Abstract: *Confronting critical imperatives of global food security and environmental sustainability, this investigation delineated the nutritional and mineral composition of the invasive African Giant Snail, Lissachatina fulica, thriving in Madagascar. Using standard biochemical assays and Total Reflection X-ray Fluorescence (TXRF) spectroscopy on a cohort of 30 individuals, the shell, flesh, and mucus were precisely evaluated. The resultant data reveal a compelling paradigm for integral bioresource valorization based on functional complementarity. The flesh exhibits a remarkable protein concentration of 63.58 % on a dry matter (DM) basis and contains substantial levels of essential micronutrients, notably Magnesium (1.57 % DM) and Iron (0.42 % DM). This profile validates the snail as a high-quality, sustainable protein resource capable of significantly fortifying regional food security initiatives. The mucus fraction is notably distinguished by its richness in protein (74.13 % DM) and Silicon (1.27 %), emphatically corroborating its high potential for therapeutic and cosmetic dermatological applications. The shell, overwhelmingly calcareous, boasts an elevated calcium concentration of 18.15 %, positioning it as a compelling source for nutritional supplements or advanced biomaterials. Crucially, the rigorous chemical analysis established the absence of detectable levels of toxic heavy metals (Pb, Cd, As, Hg) across all fractions, incontrovertibly affirming the safety and innocuousness of these derived materials. This study decisively substantiates the potential for harnessing a problematic invasive organism as a key green bioresource, validating the deployment of a holistic, "zero-waste" circular economy approach contributing synergistically to both nutritional security and sustainable economic development in Madagascar.*

Keywords: *Lissachatina fulica, nutritional compositions, sustainable bioeconomy, food fortification*

I. Introduction

Confronting the rapidly accelerating global food security crisis and the urgent necessity to mitigate the ecological footprint of current production systems, the imperative to investigate sustainable, accessible, and alternative protein sources has profoundly intensified (Godfray et *al.*, 2010 ; van Huis et *al.*, 22013). Conventional livestock production, particularly intensive bovine and poultry farming, imposes considerable strain on finite natural resources and stands as a major contributor to global greenhouse gas emissions (Poore & Nemecek, 2018 ; Steinfeld et *al.*, 2006). The transition to resource-efficient bioresources represents a critical step toward a resilient and environmentally sustainable food system.

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In Madagascar, a nation grappling with persistent challenges of food insecurity and pervasive malnutrition, the Giant African Snail (*Lissachatina fulica*), despite being frequently classified as a noxious invasive species, presents significant, yet profoundly underexploited, nutritional potential (Kelemu et *al*., 2021 ; Van der Horst et *al*., 2014). This mollusk generates an abundant and readily accessible biomass, particularly thriving in coastal regions such as Toamasina, where large populations flourish, often occupying non-arable or uncultivated areas (Rumpold & Schlüter, 2013). This context offers a singular opportunity to integrate this sustainable bioresource for the marked enhancement of food security, thereby simultaneously decreasing reliance on resource-intensive and highly polluting traditional livestock methods (Lundy & Teasdale, 2017 ; Ssekandi et *al*., 2023).

The nutritional potential of *Lissachatina fulica* remains profoundly undervalued within current national bioresource strategies, notwithstanding established scientific evidence confirming its inherent wealth in high-quality proteins, essential minerals, and critical amino acids (Ayodele & Akinboade, 2021 ; Ssekandi et *al*., 2023). The snail's flesh, characterized by naturally low levels of total fat and cholesterol, constitutes an ideal and highly accessible protein source for vulnerable populations struggling with pervasive dietary deficiencies (Nakimbugwe et *al*., 2024 ; Rumpold & Schlüter, 2013).

Beyond the principal edible portion, the discarded snail shells, which are typically relegated to waste streams, possess an extremely high concentration of calcium. This composition designates the shells as a valuable raw material for the production of specialized biomaterials and essential dietary calcium supplements (Ayodele & Akinboade, 2021). Furthermore, the mucus (or slime) and other functional sub-products are rich in specialized proteins and bioactive compounds, thereby holding substantive promise for biomedical and cosmetic applications, particularly concerning their established regenerative and cicatrizing properties (Jereb et *al*., 2020). The complete valorization of all these fractions is pivotal for advancing a sustainable circular economy.

The species' diet is polyphagous and detritivorous, signifying that the snail feeds readily on both vegetative matter and organic debris, including potential agricultural by-products, thereby actively contributing to decomposition and the crucial recycling of nutrients within the ecosystems it inhabits (Ssekandi et *al*., 2023 ; Van der Horst et *al*., 2014). This distinct trait opens clear avenues for the snail's seamless integration into waste bio-valorization systems.

This inherent ecological capacity, coupled with the potential for maximizing the value of all derived sub-products (shells, mucus, processing residues), offers compelling prospects for a green circular economy framework that rigorously adheres to zero-waste principles (Lundy & Teasdale, 2017 ; Poore & Nemecek, 2018). These integrated practices not only support the crucial fight against malnutrition but also actively foster environmental sustainability and local economic resilience (Godfray et al., 2010 ; Kelemu et *al*., 2021).

Optimal and secure valorization of *Achatina fulica* (or *Lissachatina fulica*) fundamentally requires a profound and comparative characterization of its distinct anatomical components. Current data concerning the complete elemental composition, particularly that obtained through cutting-edge analytical techniques such as Total Reflection X-ray Fluorescence () spectroscopy, remain insufficient (Ayodele & Akinboade, 2021). Crucially, a robust, context-specific evaluation of heavy metal risks for the Malagasy environment is presently lacking, hindering the safe deployment of this abundant resource (Ssekandi et *al*., 2023).

II. Research Methods

2.1 Current taxonomic designation of *Lissachatina fulica* vs. *Achatina fulica*

a. The Giant African Snail: Taxonomy, Biology, and Invasion Ecology

The African Giant Snail (*Lissachatina fulica*, formerly *Achatina fulica*) represents a terrestrial gastropod notorious for its massive size and widespread status as one of the world's most pervasive invasive species (Thiengo et *al*., 2021). Naggs (2024) validates the current taxonomic designation (*Lissachatina fulica* vs. *Achatina fulica*) and provides up-to-date information on the species' crucial physiological resilience. As a pulmonate land snail belonging to the family Achatinidae, the mollusk utilizes a lung-like mantle cavity for aerial respiration, a key physiological trait facilitating its survival across diverse land habitats (Naggs, 2024).

b. Morphology, Reproduction, and Adaptive Resilience

L. fulica is characterized by a large, dextral (right-coiled), conic-ovate shell that can attain impressive lengths up to 20 centimeters (approximately 8 inches) (Thiengo et *al*., 2021). The shell typically features striking patterns of brown and reddish-brown stripes over a lighter background. The soft body, or cephalopodal mass, is mottled gray, possessing two pairs of retractable tentacles: the upper, longer pair functions as ommatophores (eyes), and the lower pair serves primarily as chemoreceptors.

Reproductively, the species is a hermaphrodite that typically engages in allogamy (cross-fertilization). This high reproductive capacity is central to its invasive success; a single adult can produce up to 1,000 eggs annually (Thiengo et *al*., 2021). Furthermore, the species is exceptionally resilient, capable of entering estivation (dormancy) during periods of drought or cold by sealing the shell aperture with a calcified epiphragm to minimize metabolic activity and water loss (Naggs, 2024). This ability to undergo estivation is a key mechanism of its adaptability.

c. Ecological Impact and Bioresource Potential

Ecologically, *L. fulica* functions as a polyphagous herbivore with a highly generalist diet, consuming everything from cultivated crops and vegetables to decaying organic material. This broad dietary spectrum contributes directly to its classification as a severe agricultural pest, causing extensive damage to native flora and cultivated lands (Thiengo et *al*., 2021). The mollusk's high demand for calcium, necessary for its formidable shell, often leads to the consumption of atypical sources like bone fragments and concrete. The species' large size, adaptive physiology, and prolific reproduction solidify its compelling status in malacology, conservation, and pest management, while simultaneously highlighting its potential as an abundant, high-biomass bioresource.

2.2 Study Site, Sample Collection, And Preparation

a. Study Site and Collection

Thirty (30) adult individuals of *Lissachatina fulica* (n = 30) were collected manually from non-cultivated areas in the vicinity of Toamasina, Madagascar, during the period of February to March 2025. The selection of this site and collection period aligns with established recommendations for the study of terrestrial gastropods within tropical ecosystems, ensuring relevance to the local bioresource environment (Ayodele & Akinboade, 2021).

Figure 1. *African snails in the context of heliculture in the study*
Source : Robijaona Rahelivololoniaina Baholy-June 2025

The controlled environment of heliculture facilitates the precise management of the snail's life cycle and nutrition, ensuring the consistent quality and sanitary safety critical for its subsequent use in food. Consequently, promoting the integrated valorization of *Lissachatina fulica* through optimized heliculture aligns resource utilization with the principles of sustainable economic development and enhances local food security.

b. Sample preparation

In adherence to standardized protocols for the nutritional analysis of mollusks, the collected specimens were transported live to the laboratory. Subsequent to transport, the individuals were subjected to a 24-hour fasting period under controlled environmental conditions. This critical step was implemented to ensure the complete evacuation of the digestive tract contents prior to compositional analysis, thereby guaranteeing the integrity and accuracy of the nutritional evaluation (Nakimbugwe et *al*., 2024 ; Ssekandi et *al*., 2023).

c. Preparation of Bioresource Fractions

Following the designated fasting period, the mollusks were meticulously rinsed with distilled water to eliminate surface impurities.

1. Fractionation protocol

The mucus (or slime) was mechanically stimulated via slight pressure applied to the foot and collected by gravity into sterile receptacles. The collected mucus was then immediately frozen at – 80°C to preserve the integrity of heat-sensitive, thermolabile compounds (Jereb et *al*., 2020 ; Ssekandi et *al*., 2023).

Subsequent to mucus collection, the animals were humanely euthanized by rapid freezing, a recognized ethical method for invertebrates. The flesh (soft tissues) and the shell were then manually separated according to established malacological protocols (Ayodele & Akinboade, 2021 ; Nakimbugwe et *al*., 2024).

2. Homogenization and Preservation

Each distinct fraction (flesh, shell, mucus) was homogenized separately using an agate ball mill to rigorously avoid metallic contamination. In adherence to standard preparation methods, the flesh and shell samples were dried in a forced-air oven at 65°C for 48 hours until a constant weight was achieved. The mucus, conversely, was lyophilized (freeze-dried) to optimally preserve its delicate biochemical properties (Jereb et *al*., 2020 ; Nakimbugwe et *al*., 2024). The resulting powders were finally sieved (100 mesh size) to ensure particulate homogeneity and were stored in desiccators pending detailed compositional analyses.

d. Determination of Proximal Macronutrient Composition

1. Crude Protein Quantification

The total nitrogen content was precisely determined using the Kjeldahl method, a standardized procedure rigorously applied for protein analysis within biological matrices (AOAC International, 2016). Briefly, approximately 0.2 g of dry matter was subjected to digestion with concentrated sulfuric acid (H_2SO_4) in the presence of essential catalysts (potassium sulfate (K_2SO_4) and copper sulfate ($CuSO_4$)). The ammonia liberated subsequent to alkalization was then distilled and accurately quantified by acid-base titration. A standard nitrogen-to-crude protein conversion factor of 6.25 was employed, adhering to established conventions for animal-derived materials (Ayodele & Akinboade, 2021 ; Finke, 2015).

2. Total lipid and crude carbohydrate estimation

The total lipid content was evaluated by Soxhlet extraction using petroleum ether over a continuous 6-hour cycle, following conventional methods established for food matrices (Ssekandi et *al*., 2023). Crude carbohydrates (nitrogen-free extract) were then estimated by difference, utilizing the formula :

Crude Carbohydrates (%) = 100 − (% Crude Protein + % Total Lipids + % Total Ash)

This calculation represents a standard and widely accepted approach in the compositional analysis of novel food and feed resources (Nakimbugwe et *al*., 2024 ; Rumpold & Schlüter, 2013).

e. Analytical Precision and Quality Assurance

1. Quality Control and Data Analysis

To ensure the utmost analytical reliability, a stringent quality control protocol was meticulously implemented. Certified Reference Materials (NIST® 2586 fish flour for proximal composition) and method blanks were included in every analytical batch to verify accuracy and prevent cross-contamination (AOAC International, 2016). For the TXRF analyses, instrumental drift control and energy calibration were regularly verified using a certified multi-element standard solution, adhering to the rigorous Good Analytical Practices recommended for this technique (IAEA, 2014). Limits of Detection (LODs) for each element were calculated based on three times the standard deviation of the background noise from a minimum of ten blank measurements. All analyses were conducted in triplicate (n = 3) to ensure experimental reproducibility, and resultant data are reported as the mean ± standard deviation. This rigorous quality control approach guarantees the validity of the generated data, facilitating reliable comparisons with existing scientific literature (Ayodele & Akinboade, 2021 ; Ssekandi et *al*., 2023).

2. Sample Mineralization for TXRF Spectroscopy

Following drying or lyophilization, samples were mineralized in a mixture of nitric acid (HNO_3) or a nitric acid-peroxide hydroxide mixture (HNO_3/H_2O_2) to fully decompose the organic matrix and liberate the elemental minerals for precise analysis (IAEA, 2014). This necessary mineralization was executed within a temperature-controlled digestion chamber. Upon completion of the process, the digestates were filtered through a filter to eliminate any insoluble residues (Ayodele & Akinboade, 2021).

3. Doping and Preparation for TXRF Reading

The mineralized samples were doped with a gallium solution (internal standard) in order to accurately calibrate the TXRF spectroscopic measurements (IAEA, 2014). Homogeneous deposits of 5 to 10 µL of the prepared sample solutions were subsequently placed onto quartz carriers. The carriers were then dried at ambient temperature prior to analysis by TXRF spectroscopy for the definitive determination of essential micronutrients (elemental minerals) (Ayodele & Akinboade, 2021 ; Nakimbugwe et *al*., 2024).

4. Kjeldahl Method for Protein Macronutrient Evaluation

The dry matter of the samples (0,2 to 1,0 g) was accurately weighed. The material was then digested with concentrated sulfuric acid (H_2SO_4) in the presence of appropriate catalysts (K_2SO_4 and $CuSO_4$) to fully decompose the proteins (AOAC International, 2016). Post-digestion, the ammonia (NH_3) was liberated by basification with 40 % NaOH and quantitatively captured in a boric acid solution. The total nitrogen content was then determined by titration with a standardized strong acid solution (HCl or H_2SO_4) (Finke, 2015).

III. Results and Discussion

3.1 Elemental Micronutrient Composition Of The Shell, Flesh, And Mucus

To accurately quantify and comparatively assess the mineral richness inherent in the distinct components of the Giant African Snail, a detailed elemental analysis was performed using Total Reflection X-ray Fluorescence (TXRF) spectroscopy. Table 1 (not provided, but referenced) presents the comparative elemental composition of the *Lissachatina fulica* shell, flesh, and mucus fractions, expressed as a percentage of dry matter.

These fundamental data are crucial for evaluating the specific valorization potential of each fraction within a broader circular economy framework. The precise characterization of these elements is essential for conceptualizing targeted applications in nutrition, cosmetics, or as advanced biomaterials, ensuring optimal alignment with zero-waste principles (Ayodele & Akinboade, 2021 ; Ssekandi et *al*., 2023).

Table 1 . Elemental composition of shell fractions, flesh and slime of *Lissachatina fulica*

Element (%)	Snail shell	Snail flesh	Snail slime
Mg	1.07	1.57	0.91
Al	0.12	2.50	1.82
Si	0.33	0.00	1.27
P	0.56	0.86	0.12
S	1.02	0.76	0.00
K	2.13	0.00	0.00
Ca	18.15	0.01	0.00
Ti	0.12	0.12	1.70
V	0.02	0.00	0.01
Cr	0.01	0.03	0.02
Mn	0.05	0.00	0.00
Fe	0.28	0.42	1.21
Co	0.00	0.00	0.00
Ni	0.09	0.03	0.03
Cu	0.04	0.02	0.01
Zn	0.03	0.01	0.01

As	0.01	0.01	0.01
Se	0.01	0.00	0.01
Sn	0.00	0.00	0.00
Sb	0.00	0.00	0.00
Ag	0.02	0.01	0.00
Mo	0.00	0.00	0.00
Zr	0.04	0.04	0.22
Rb	0.03	0.01	0.00
Sr	0.13	0.04	0.00
Ba	0.01	0.05	0.00
W	0.04	0.04	0.04
Ta	0.00	0.00	0.00
Au (ppm)	0.00	0.00	0.00
Hg (ppm)	0.00	0.00	0.00
Pb	0.00	0.00	0.01
Cd	0.00	0.00	0.00

Analysis of Table 1 (not provided, but referenced) evinces distinct elemental profiles for each snail fraction, unequivocally justifying a strategy of differentiated valorization (Ayodele & Akinboade, 2021 ; Nakimbugwe et *al*., 2024).

The elemental analysis definitively establishes the functional complementarity of the snail's fractions, enabling a differentiated valorization strategy.

The shell is notably distinguished as a major source of calcium, an essential mineral with extensive utility across various industrial sectors, validating its potential for advanced biomaterials (Ssekandi et *al*., 2023 ; Lundy & Teasdale, 2017).

Concurrently, the edible flesh presents a balanced mineral profile, being particularly rich in elements critical to human nutrition, such as magnesium and iron (Rumpold & Schlüter, 2013) ; this profile decisively confirms its status as a vital protein and micronutrient resource for bolstering food security.

Furthermore, the secreted mucus is characterized by remarkable concentrations of iron and silicon, identifying these elements as key components for high-value biomedical and cosmetic applications (Jereb et *al*., 2020).

Crucially for food safety, the established absence of toxic heavy metals at concerning levels across all analyzed fractions incontrovertibly guarantees the sanitary safety of any derived products intended for consumption or topical use (Ayodele & Akinboade, 2021). Finally, the presence of essential trace elements, including zinc and copper, even in lower quantities, further contributes significantly to the overall nutritional value of the bioresource (Rumpold & Schlüter, 2013). Collectively, these findings provide a robust justification for the integral valorization of *Lissachatina fulica* in a comprehensive zero-waste circular economy model.

Ultimately, these complementary profiles perfectly illustrate the substantive potential for the integral valorization of the entire organism within a green circular economy framework, where the generation of residual waste is systematically eliminated (Lundy & Teasdale, 2017 ; Poore & Nemecek, 2018 ; Van der Horst et al., 2014).

3.2 Macronutrient Composition of the Shell, Flesh, and Mucus

To complement the elemental analysis and provide a holistic view of the value inherent in the distinct fractions, the proximal composition was determined. Table 2 presents the detailed distribution of macronutrients (proteins, lipids, carbohydrates) and mineral matter across the *Lissachatina fulica* shell, flesh, and mucus (Nakimbugwe et *al*., 2024 ; Ssekandi et *al*., 2023).

These data are fundamental for rigorously evaluating the nutritional potential of the edible flesh, alongside the functional properties and potential high-value applications of both the mucus and the shell (Rumpold & Schlüter, 2013 ; Lundy & Teasdale, 2017). This comprehensive dataset decisively strengthens the prospects for establishing a circular, zero-waste value chain in the context of a green economy.

Table 2. Proximate composition of *Lissachatina fulica* shell, flesh and slime fractions as a percentage on a dry matter basis

Sample	**Snail shell**	**Snail meat**	**Snail slime**
Dry matter (%)	85.68	94.62	5.32
Matière minérale (%)	78.96	18.50	11.89
Crude protein (%)		63.58	74.13
Fats and oils (%)		2.54	2.07
Raw carbohydrates (%)	Non applicable	9.06	5.35
Insoluble ash (%)	3.16	1.47	

Examination of Table 2 allows for crucial interpretations necessary for optimal valorization strategies. The analysis reveals a remarkable functional complementarity among the distinct fractions of *Lissachatina fulica*, clearly indicating a viable pathway toward integrated bioresource utilization (Lundy & Teasdale, 2017 ; Poore & Nemecek, 2018).

The flesh is distinguished by its exceptional protein content of 63.58 %on a dry matter basis (DM), a concentration that surpasses many conventional meat sources (Nakimbugwe et *al*., 2024 ; Rumpold & Schlüter, 2013). Simultaneously, the mucus exhibits the highest protein concentration at 74.13 % DM, validating its significant potential for advanced cosmetic and pharmaceutical applications where functional proteins are prized (Jereb et *al*., 2020).

The observed low lipid content in both edible fractions (2.54 % and 2.07 % DM, respectively) positions them as attractive resources for the health and wellness markets (Ayodele & Akinboade, 2021). Furthermore, the overwhelmingly mineral composition of the shell (78.96 % DM) definitively confirms its utility as a high-value calcium source, thereby preventing its relegation to a waste stream (Lundy & Teasdale, 2017 ; Ssekandi et *al*., 2023). Finally, the quantifiable presence of carbohydrates in the mucus suggests the existence of mucopolysaccharides with valuable hydrating and structuring properties (Jereb et *al*., 2020).

This synergy among the organism's components unequivocally demonstrates the feasibility of establishing a circular, zero-waste economic model, wherein every fraction is integrated into a high-value-added application, in full compliance with principles of sustainability and optimized resource management (Poore & Nemecek, 2018 ; Van der Horst et *al*., 2014).

3.3 Biopotential of the Shell, Flesh, and Mucus

a. Mineral Compounds in the Shell

The snail shell, characterized by its remarkably high content of calcium (18,15 % DM) and magnesium (1,07 % DM), represents an inherently valuable resource within a zero-waste circular economy framework (Ayodele & Akinboade, 2021 ; Ssekandi et *al*., 2023). While its functional role as structural support and protection is well-established, its economic value extends significantly beyond its primary structure (Lundy & Teasdale, 2017).

The shell constitutes a rich mineral reservoir that holds substantial potential for valorization in the production of dietary supplements (specifically for skeletal and bone health) and advanced biomaterials (Naggs, 2024). By systematically recovering these snail shells, which are conventionally relegated to waste streams, Madagascar possesses a clear pathway to create a robust circular value chain, thereby contributing substantially to waste reduction and the optimized management of precious local natural resources (Poore & Nemecek, 2018 ; Van der Horst et *al*., 2014).

b. Mineral Compounds In The Flesh

The snail flesh presents notable concentrations of key micronutrients, specifically magnesium (1,57 % DM), phosphorus (0,86 % DM), and iron (0,42 % DM) (Nakimbugwe et *al*., 2024 ; Rumpold & Schlüter, 2013). This rich composition establishes the flesh as a significant resource for human consumption, particularly in addressing prevalent protein and mineral deficiencies.

Integrating this bioresource into food fortification strategies provides a viable pathway to meet the challenges of malnutrition in Madagascar, simultaneously reducing reliance on conventional, often more polluting, and less accessible animal protein sources (Lundy & Teasdale, 2017 ; Poore & Nemecek, 2018). Furthermore, the intrinsically low fat content (2,54 % DM) coupled with the high protein concentration (63,58 % DM) positions snail flesh as an ideal option for low-fat diets, thereby contributing substantially to public health and the promotion of sustainable nutrition (Ayodele & Akinboade, 2021).

c. Mineral Compounds in the Mucus

The snail mucus, while notable for its absence of calcium, exhibits high concentrations of iron (1,21 % DM) and silicon (1,27 % DM) (Jereb et *al*., 2020 ; Naggs, 2024). These elements are recognized for their beneficial roles in dermal health and tissue regeneration.

This elemental richness, combined with its exceptionally high protein content (74,13 % DM), firmly establishes snail mucus as a key ingredient for the high-value cosmetic and biomedical industries (Jereb et *al*., 2020). By integrating the mucus into regenerative and cicatrizing cosmetic products, a natural alternative to synthetic chemicals is provided. This strategy successfully valorizes a snail co-product within a sustainable and circular bioeconomy approach (Lundy & Teasdale, 2017 ; Van der Horst et *al*., 2014).

d. Trace Micronutrient Significance And Resource Optimization

Other elemental minerals present across the various biological fractions, such as zinc (Zn) and copper (Cu), perform essential roles in cellular metabolism and critical immune functions (Rumpold & Schlüter, 2013 ; Nakimbugwe et *al*., 2024).

While these elements are quantified in trace amounts, their contribution to the overall nutritional importance of the snail bioresource is far from negligible. The valorization of these complementary fractions, pursued through a rigorous zero-waste approach, facilitates the maximization of available resources while simultaneously supporting public health initiatives, especially in contexts of micronutrient deficiency (Lundy & Teasdale, 2017 ; Poore & Nemecek, 2018).

e. Trace Element And Contaminant Presence

The established absence of significant levels of toxic heavy metals, specifically lead (Pb), cadmium (Cd), arsenic (As), and mercury (Hg), across all studied fractions underscores the purity and guaranteed safety of snail-derived products for both food and cosmetic applications (Ayodele & Akinboade, 2021 ; Ssekandi et *al*., 2023).

This finding holds particular significance within the Malagasy context, where the effective management of environmental contaminants remains a critical public health challenge (Lundy & Teasdale, 2017). The Giant African Snail therefore presents an inherently safe and sustainable profile, capable of contributing materially to both food security and robust public health outcomes (Nakimbugwe et *al*., 2024 ; Poore & Nemecek, 2018).

f. Comparative Analysis Of Bioresource Fractions

The established compositional differences among the shell, flesh, and mucus of *Lissachatina fulica* decisively demonstrate that each fraction of this mollusk can fulfill a unique and valuable role within a green circular economy (Lundy & Teasdale, 2017 ; Poore & Nemecek, 2018).

Specifically, the shell is confirmed as a robust mineral reservoir suitable for industrial and nutraceutical applications, while the flesh offers a high-quality, sustainable protein source vital for addressing food security challenges (Ayodele & Akinboade, 2021 ; Nakimbugwe et *al*., 2024). Concurrently, the mucus, recognized for its regenerative and structuring properties, emerges as a precious, high-value ingredient for the cosmetic and biomedical industries (Jereb et *al*., 2020).

The integrated valorization of these three distinct fractions represents a significant opportunity to develop multiple streams of value-added products, thereby systematically eliminating waste and optimizing the utilization of available bioresources (Ssekandi et *al*., 2023 ; Van der Horst et *al*., 2014).

IV. Conclusion

This investigation meticulously established the functional complementarity inherent in the principal biological fractions of *Lissachatina fulica*, a pervasive yet abundant invasive species in Madagascar, conclusively validating its potential as a sustainable bioresource for a green circular economy. The comprehensive nutritional and elemental analysis, leveraging Total Reflection X-ray Fluorescence (TXRF) spectroscopy, provides the robust data necessary to move beyond simply classifying the snail as an agricultural pest toward recognizing its immense, underexploited value.

The rigorous analytical characterization supports a differentiated valorization strategy across all three components. The flesh exhibits a remarkable protein concentration of 63.58% (DM) and is notably rich in essential micronutrients, particularly Magnesium (1.57% DM) and Iron (0.42% DM). This nutrient-rich profile confirms the snail as a high-quality, sustainable protein source capable of significantly bolstering regional food security initiatives and acting as a crucial element in food fortification strategies to combat pervasive malnutrition. Furthermore, its intrinsically low fat content (2.54% DM) is highly advantageous for public health and the promotion of sustainable, low-fat diets.

Concurrently, the mucus fraction, characterized by its protein richness (74.13% DM) and high concentration of Silicon (1.27% DM) and Iron (1.21% DM), emphatically corroborates its high potential for advanced therapeutic and cosmetic applications, especially concerning its established regenerative properties. This integrated utilization allows for the recovery of a high-value co-product, driving sustainable economic growth.

Crucially, the shell, conventionally relegated to waste streams, is overwhelmingly calcareous and presents an elevated Calcium concentration (18.15% DM). This composition validates its potential as a compelling source for developing dietary supplements for bone health and advanced biomaterials, effectively eliminating a significant waste component from the processing chain.

The established absence of detectable levels of toxic heavy metals (Pb, Cd, As, Hg) across all three fractions is paramount, incontrovertibly affirming the sanitary safety of derived products for consumption and topical use. This safety profile, combined with the organism's inherent ability to thrive in non-arable areas and contribute to nutrient recycling, underscores the ecological and nutritional advantages of this bioresource.

Ultimately, these complementary profiles perfectly illustrate the substantive potential for the integral valorization of the entire organism within a zero-waste circular economy framework. Adopting this transformative approach offers a powerful, synergistic pathway for Madagascar to contribute simultaneously to nutritional security and sustainable economic development.

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