

Duckweed-Integrated Bioenergy, Biofertiliser and Feed Production: A Site-Based Feasibility Assessment and Decision Framework for Smallholder Cattle Systems in Laikipia, Kenya

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Duckweed-Integrated Bioenergy, Biofertiliser and Feed Production: A Site-Based Feasibility Assessment and Decision Framework for Smallholder Cattle Systems in Laikipia, Kenya

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Abstract

Rising and volatile prices for conventional protein ingredients constrain smallholder livestock production across Kenya, creating strong incentives for locally produced feed alternatives. This study assesses the feasibility of integrating duckweed (Lemnaceae) cultivation with anaerobic digestion, nutrient recovery and livestock-feed production within a smallholder cattle system at Ngobit, Laikipia County. Four candidate configurations were evaluated: duckweed-tilapia aquaponics, duckweed-integrated swine wastewater treatment, duckweed in poultry waste management and feed production, and duckweed in bioenergy, biofertiliser and feed production (DBBF). A structured synthesis of 110 academic and institutional sources was combined with site observation and a SWOT analysis, then converted into a transparent weighted decision matrix across seven criteria derived from the study objectives and site constraints. DBBF scored highest (4.60 of 5.00) and weakly dominates all alternatives across the criterion set, so its first-ranked position is invariant to the weighting applied. A first-order water and nitrogen balance, developed from published pilot parameters, indicates that the herd's own manure saturates a pond of 500 to 750 m², yielding 8 to 12g of crude protein per head per day. Nitrogen rather than water is therefore limiting at this scale, and the configuration functions as a marginal protein supplement within a joint energy, nutrient and feed product rather than as a substitute for purchased concentrate. A staged implementation framework with explicit decision gates is proposed, and the parameters requiring measurement before deployment are identified. The weighted score is a structured decision-support indicator, not an experimentally measured performance index.

Keywords: Duckweed; Lemnaceae; Livestock feed; Circular bioeconomy; Anaerobic digestion; Digestate; Smallholder systems; Nitrogen/Nutrient recovery.

1. Introduction

1.1 The feed-protein constraint in Kenyan smallholder livestock systems

Livestock production underpins a substantial share of Kenya's agricultural economy, yet the sector's economics are increasingly dictated by the cost and availability of compounded feed (Njehu & Ouma, 2025; Lutta et al., 2026). Analysis of the Kenyan feed sector finds that it depends heavily on imported protein ingredients, with soybean meal drawn principally from Zambia, Malawi and Uganda and sunflower cake from Tanzania, and that the four largest suppliers account for more than half of

commercial feed sales (Munguti et al., 2024; Roberts et al., 2025). Kenyan poultry producers also paid substantially more for feed between 2021 and 2023 than counterparts in Brazil and South Africa, and smaller, non-integrated millers absorbed disproportionately large increases in soymeal prices (Gachuiri et al., 2025; Roberts et al., 2025). For a smallholder with a handful of cows, this translates directly into reduced concentrate feeding and forgone milk yield.

The structural character of this constraint matters for how alternatives should be evaluated. Because the problem originates in import dependence, market concentration and exchange-rate exposure rather than in any single agronomic failure, interventions that merely substitute one purchased ingredient for another purchased ingredient offer limited insulation. Interventions that relocate protein production onto the farm itself, using resources the household already controls, address the constraint more directly.

1.2 Rationale for an on-farm protein pathway

Duckweeds are free-floating aquatic macrophytes of the family Lemnaceae. They grow faster than any other flowering plant, reproduce vegetatively, take nutrients up directly across the frond surface, accumulate crude protein at concentrations comparable to conventional oilseed meals, and can be harvested with a hand net (Baek et al., 2021; Ziegler et al., 2023; Jaimes Prada et al., 2024). They require no arable land, and they will grow on water that is already carrying a nutrient load. Those properties make them an unusually direct answer to the structural problem described above, because they permit protein to be produced on the farm from a waste stream the farm already generates. Section 2 examines the evidence for each of these claims and, more importantly, the conditions under which they fail to hold.

1.3 Research gap and objectives

Published research on duckweed has concentrated on two lines of enquiry. The first characterises the biology, compositional profile and remediation performance of the family (Ekperusi et al., 2019; Xu et al., 2023; Sosa et al., 2024). The second, reports the operational performance of individual production configurations under defined conditions (O'Mahoney et al., 2022; Lambert et al., 2025; Redmond et al., 2025). Comparatively little attention has been directed toward the prior question of how a particular site should select among competing duckweed-integrated configurations. Where feasibility studies including Calicioglu et al. (2021) and Munaro et al. (2025), report a configuration, the grounds on which it was chosen are seldom made explicit, with the consequence that the selection can be neither scrutinised nor transferred to another setting. The question confronting a practitioner at a given location is comparative rather than descriptive, and is bounded by local conditions of water supply, livestock enterprise, labour availability and market access (Munaro et al., 2025).

This study addresses the established gap. Its objectives were to define four duckweed-integrated systems that exemplify circular-economy principles; to evaluate them against the physical and socio-economic constraints of a specific proposed site using a transparent, reproducible decision procedure; and to develop a staged implementation framework for the selected configuration, with explicit validation requirements attached to each stage.

2. Literature review

2.1 Taxonomy, genotype identity and the limits of morphological determination

The family Lemnaceae comprises five genera, *Spirodela*, *Landoltia*, *Lemna*, *Wolffiella* and *Wolffia*, and is conventionally cited as containing thirty-six species, a figure which remains under active revision (Zuki et al., 2022; Zięć et al., 2025). Morphological characters within the family are extremely reduced, and species-level determination on morphology alone is unreliable, particularly within the speciose genera (Bog et al., 2020; Bog et al., 2022). Plastid barcoding, and more recently nuclear tubulin-based polymorphism fingerprinting, have resolved relationships that morphology could not, and have revealed cryptic interspecific hybrids: *Lemna japonica* proved to be a hybrid of *L. minor* and *L. turionifera*, and a further hybrid of *L. minor* and *L. gibba* was described as *Lemna* × *mediterranea* (Braglia et al., 2024; Romano et al., 2025). Genomic work has since shown that triploidy is common in wild *Lemna* populations (Ernst et al., 2025).

The consequence of this taxonomic instability extends well beyond nomenclature. Physiological performance in duckweeds is a property of the clone rather than of the species: growth rate, protein concentration and turion formation all vary substantially between clones of the same nominal species (Ziegler et al., 2023; Mascheretti et al., 2026). A projection of yield or protein content built on published values for a named species therefore carries no guarantee of applying to an unidentified field population. For any deployment intended to supply a feed ingredient with a stated specification, molecular identification of the resident genotype constitutes a precondition for deployment.

2.2 Environmental envelope and cultivation requirements

It is widely established that the growth rate in duckweed is governed principally by temperature, irradiance, pH and nutrient availability, and the operating windows are narrow enough to constitute genuine siting constraints (Pasos-Panqueva et al., 2024; Femeena & Brennan, 2025). A recent meta-analysis conducted by Pasos-Panqueva et al. (2024), synthesising light, temperature and nutrient effects across the published literature confirms strong and interacting influences of all three. Optimum water temperatures for treatment applications fall broadly between 25 and 31 °C, with efficiency declining below about 17 °C and heat stress becoming acute above 35 °C (Stejskal et al., 2022; Coughlan et al., 2023). According to Iqbal (1999) and Morello et al. (2026), optimum pH ranges vary between authors but converge on mildly acidic to neutral conditions; alkaline water shifts the ammonium-ammonia equilibrium toward free ammonia, which is toxic to the plant. Moreover, Yin et al. (2015) and Islam et al. (2025) assert that irradiance shapes both biomass accumulation and starch partitioning, with an optimum near 110 $\mu\text{mol m}^{-2} \text{s}^{-1}$ reported for biomass and starch production in *Lemna aequinoctialis*, and light intensity has been shown to alter phytoremediation performance in *L. minor* (Walsh et al., 2021).

Relevant body of work show that three site-level constraints recur across the applied literature and bear directly on the present case (Jewell & Bell, 2023). First, evidence presented by Popa et al. (2017) and Coughlan et al. (2023), surmise that duckweeds tolerate only low

water velocities, on the order of 0.1 m s^{-1} without shelter, so still or slow-moving water is required. Second, substrate hydraulic conductivity governs percolation losses, favouring low-permeability soils or lined ponds (Allam et al., 2016). And water availability is decisive: in dry regions, evaporation and seepage can exceed replenishment, causing pond drawdown, loss of the standing crop and failure of the system (Rani et al., 2025; Duan et al., 2026). As reflected in the perspective of scholars such as Duan et al. (2026), water availability receives comparatively limited attention in assessments of duckweed

potential, although the question of whether water or nutrient supply becomes limiting first can be resolved only by calculation at a defined scale.

2.3 Nutritional composition and performance as an animal feed

Interest in duckweed as a protein source is long-standing. Early screening by studies conducted by Boyd (1968) and Rusoff et al. (1980) amongst others, established the family as a credible source of protein and amino acids and subsequent work positioned it as a high-protein feed resource for domestic animals and fish (Cheng & Stomp, 2009). Systematic compositional analysis across all five genera has since characterised protein, fat, starch, amino acid and fatty acid profiles in detail, with the genus *Wolffia* proving particularly protein-rich (Appenroth et al., 2018; Obando et al., 2026). Contemporary reviews advanced by Xu et al. (2023), Sosa et al. (2024) and Song et al. (2025), as well as a wider body of research, place crude protein for the family broadly between 16 and 42 per cent of dry matter depending on species, clone and cultivation regime, alongside appreciable mineral and vitamin content.

Evidence from feeding studies is more equivocal than compositional data alone would indicate. Duckweed has been evaluated in cattle diets (Huque et al., 1996; Omotoso et al., 2023), in broiler diets (Mwale & Francisca, 2013; Salian et al., 2026), and more recently across ruminant systems generally (Kalra et al., 2024; Chaji & Pormhammad, 2025), with results that are broadly encouraging at moderate inclusion but that deteriorate under full substitution. As articulated by Lambert et al. (2025), amino acid profiles from manure-grown biomass have been judged adequate for broilers while potentially limiting in histidine and methionine for pigs and cattle. Most consequentially, Demann et al. (2023), and related contributions posit that crude-protein digestibility vary widely between batches of the same material. Duckweed is therefore not a uniform commodity ingredient, and ration formulation on published averages rather than on measured composition of the material actually produced is unsound.

2.4 Cultivation on manure-derived and digestate media

The circular case for duckweed rests on cultivating it in nutrient-bearing waste streams rather than in clean water with synthetic fertiliser. The phytoremediation literature is extensive and establishes efficient uptake of nitrogen, phosphorus and a range of other constituents (Körner et al., 2003; Ekperusi et al., 2019; Zhou et al., 2023). More directly relevant, several groups have now cultivated *Lemna* on anaerobically digested effluents. Growth on anaerobically digested dairy processing wastewater has been demonstrated with simultaneous biomass generation and effluent remediation (O'Mahoney et al., 2022), and dairy soiled water has been optimised as a growth medium (Redmond et al., 2025).

The pilot-scale evidence is where the operating limits become visible. Case in point, a full-season outdoor trial undertaken by Lambert et al. (2025), at a pig-manure processing facility in Belgium recorded approximately eight tonnes of dry biomass and 2.8 tonnes of protein per hectare per year, with mean removal rates of $1.2 \text{ g N m}^{-2} \text{ d}^{-1}$ and $0.13 \text{ g P m}^{-2} \text{ d}^{-1}$ on the better-performing systems, while a parallel system fed on constructed-wetland effluent suffered die-off and produced low-protein biomass. Critically, growth on the successful systems ceased after roughly 100 to 120 days as pH and electrical conductivity rose, indicating ammonia toxicity and progressive salt accumulation. As evidenced by Lambert et al. (2022), the same research group had previously documented salt accumulation as a limiting mechanism in continuous manure-fed systems, and corresponding works including Li et al. (2025), on biogas slurry has shown that performance depends strongly on dilution ratio. Nitrogen speciation also matters independently of concentration, since the ratio of nitrate to ammonium

influences both growth rate and protein content (Petersen et al., 2021). Digestate is thus a viable medium, but only within a dilution and monitoring regime established empirically for the specific effluent.

2.5 Bioenergy pathways and integration with anaerobic digestion

Duckweed accumulates starch under nutrient limitation while carrying little lignin, a combination that favours conversion to fuels and has attracted sustained attention (Cheng & Stomp, 2009; Cui & Cheng, 2015; Chen et al., 2022). Duckweed biomass has also been assessed by studies such as (Gaur et al., 2017), a co-substrate for anaerobic digestion. However, in line with the configuration examined in the aforementioned study, the energy pathway runs in the opposite direction: manure is digested, and the digestate rather than the duckweed carries the value. Household biodigesters are established technology across sub-Saharan Africa, but their dissemination remains modest, constrained chiefly by installation cost, maintenance capability and access to technical support rather than by technical infeasibility (Tolessa, 2024). Probabilistic techno-economic assessment nonetheless indicates quantifiable net benefit to smallholders under a range of assumptions (Seglah et al., 2022; Tolessa, 2023). The implication for system design is that the digester, not the pond, is the component most likely to fail in service.

2.6 Feed and food safety

The capacity of duckweed to accumulate solutes from the water column underlies both its utility as a remediation organism and its hazard profile when the cultivation medium carries contaminants (Zhou et al., 2023; Ishizawa et al., 2025; Thingujam et al., 2026). Reviews of novel protein sources carried out by Fourounjian et al. (2020) and Yahaya et al. (2022), identify heavy metals, pathogens, mycotoxins and pesticide residues as the principal hazard classes, and note that many hazards arise from the production method rather than from the organism itself. Furthermore, Mwale and Francisca (2013) as well as Mgbeahuruik et al. (2023) in their direct assessment of microbiological risk from wastewater-grown biomass, in a poultry context, report that anaerobic digestion reduces pathogen load substantially but does not eliminate every hazard class. It was also noted that calcium oxalate content in some genera constrains use in non-ruminant diets. Safety in a digestate-fed system must therefore be demonstrated by measurement of the source water, the digestate and the finished dried product, rather than inferred from the presence of a digestion step.

2.7 Circular-economy framing and integrated system concepts

The systems literature provides the organising logic for combining these elements. Circular-economy scholarship has moved from conceptual review toward implementation tools intended to operationalise resource loops in practice (Kalmykova et al., 2018; Reike, 2024; Osei-Akoto et al., 2026), and water-centred framings position water as the medium through which nutrient and energy cycles are linked. Duckweed occupies an unusual position in this framing because a single pond simultaneously treats an effluent, recovers nutrients and produces a saleable biomass (Obando et al., 2026). Evidence on the net environmental balance of such ponds is mixed, and greenhouse-gas fluxes from duckweed treatment systems have been shown to depend on operating conditions rather than being uniformly favourable (Mohedano et al., 2019; Sun et al., 2020). Environmental benefit therefore requires system-specific assessment before it can be claimed.

Four integrated configurations recur in the applied literature and are adopted here as the candidate set. Duckweed-tilapia aquaponics couples water polishing with fish production. Duckweed-integrated swine wastewater treatment applies the plant to a high-strength effluent with feed as a secondary output. Duckweed in poultry waste management returns biomass to poultry rations. Duckweed in bioenergy, biofertiliser and feed production routes livestock manure through anaerobic digestion and uses the digestate as the cultivation medium. Each is individually documented; what the literature does not provide is a basis for choosing between them at a specific site.

2.8 Synthesis and the gap addressed

Three conclusions follow from this review. First, the biological and compositional case for duckweed is well established, but performance is clone-specific and cannot be transferred from published values to an unidentified population. Second, cultivation on digestate is demonstrated at pilot scale, yet the failure modes, ammonia toxicity and salt accumulation, are well characterised and impose a monitoring burden that any deployment must accept. Third, and most relevant here, the literature characterises configurations individually but offers no transparent procedure for selecting among them under the constraints of a particular site. Published feasibility work tends to report the performance of a configuration already chosen on grounds that are seldom made explicit. The question that arises at a given location is accordingly comparative, and is determined by the local water supply, the existing livestock enterprise, the available labour and the accessible market. The present study addresses that question.

3. Materials and methods

3.1 Study design

The study adopted a qualitative feasibility-assessment design combining structured evidence synthesis, site characterisation and multi-criteria decision analysis. No experimental cultivation, digestion or feeding trial was undertaken; the output is a reasoned system selection and implementation framework, not a measured performance dataset. This design constraint is stated at the outset because it governs the interpretation of every quantitative figure reported below.

3.2 Study site

The proposed pilot location is at Ngobit, Lamuria Division, Laikipia County, Kenya, approximately 200 km north of Nairobi at roughly 0.0586° S, 36.7608° E. The setting is semi-arid highland, with pronounced dry periods and a smallholder cattle enterprise comprising approximately fifty head across a small farmer group, alongside access to a seasonal watercourse. Site parameters relevant to system selection were water availability and seasonality, land geomorphology and slope, solar irradiance, on-farm nutrient availability in the form of cattle manure, and the cost and availability of household labour. Site characteristics and herd figures were obtained during a scoping visit and from project documentation supplied by the local implementing organisation (Help Self Help Centre, personal communication, 2022).

3.3 Evidence base

The evidence synthesis drew on SCOPUS and institutional library holdings, supplemented by ScienceDirect, PubMed, Google Scholar, conference proceedings and reports from international

organisations. One hundred and ten academic and institutional documents were retained, spanning duckweed taxonomy and physiology, cultivation on nutrient-rich media, nutritional composition, feeding performance, anaerobic digestion and circular-economy system design. The synthesis was narrative rather than systematic; it was intended to establish the parameter ranges and failure modes relevant to system selection, not to estimate a pooled effect.

3.4 Definition of candidate systems

Four configurations were specified so that each represented a coherent and independently documented pathway rather than an arbitrary variant. DA couples duckweed cultivation with tilapia aquaculture, using the plant for water polishing and as a supplementary fish feed. DSW applies duckweed to swine wastewater treatment with feed production as a secondary output. DPF integrates duckweed into poultry waste management, returning the biomass as a supplement within poultry rations. DBBF routes cattle manure through anaerobic digestion, uses the resulting digestate as the cultivation medium, and returns dried duckweed to the cattle ration while the biogas serves household energy demand.

3.5 Conversion of the SWOT analysis into a weighted decision matrix

A conventional SWOT analysis was first constructed for each configuration. Because narrative SWOT output cannot by itself justify a ranking, the qualitative findings were subsequently converted into a weighted additive decision matrix. This follows established practice for combining SWOT with multi-criteria decision analysis, in which the qualitative factor set is retained but the comparison between alternatives is made explicit and reproducible (Kurttila et al., 2000; Gottfried et al., 2018; Grošelj et al., 2024). As demonstrated by Ferrer-Martí et al. (2018), comparable multi-criteria approaches have been applied to household digester programmes in low-resource settings.

The criterion set was derived from the conditions that the reviewed evidence indicates a duckweed-integrated system must satisfy concurrently. Feed-production relevance follows from the compositional and feeding evidence examined in Section 2.3, and circular resource integration from the systems evidence in Section 2.7. Water and site suitability follows from the environmental constraints established in Section 2.2, and resource-recovery potential from the digestate and bioenergy evidence in Sections 2.4 and 2.5. The remaining three criteria were derived from the site characteristics set out in Section 3.2: livestock-system compatibility from the presence of an established cattle enterprise and the absence of any other livestock species, operational simplicity from the farmer group's lack of prior experience with anaerobic digestion or managed aquaculture, and scalability and market potential from the limited local market for a novel feed ingredient.

Weights were assigned to reflect the relative importance of each criterion to the pilot's stated purpose, with livestock-system compatibility weighted most heavily because the intervention is intended to serve an existing cattle enterprise rather than to establish a new one. Each configuration was rated against each criterion on a five-point scale, where 1 denotes very poor and 5 very strong. The weighted compatibility score for configuration j was calculated as:

$$S_j = \sum_i w_i r_{ij} \quad (1)$$

where S_j is the total score for configuration j , w_i is the weight assigned to criterion i (with $\sum w_i = 1.00$), and r_{ij} is the rating of configuration j against criterion i . The matrix is a structured representation of the

qualitative evidence and should be read as a decision-support instrument; it does not constitute measured performance data.

3.6 Robustness testing

Three tests were applied to establish whether the conclusion depends on the weight vector chosen. First, scores were recomputed under equal weighting of all seven criteria. Second, each criterion was removed in turn and the remaining weights rescaled to unity. Third, the rating matrix was examined for dominance, since an alternative that equals or exceeds all others on every criterion is first-ranked under any non-negative weight vector and its selection is therefore weight-invariant. The sensitivity of the result to the ratings themselves was assessed by comparing the margin between the leading alternatives with the largest score change obtainable by revising a single rating cell.

4. Results

4.1 Site observations

A naturally occurring duckweed population was present at and near the proposed location, co-habiting with the free-floating fern *Azolla*. The population was identified to genus (*Lemna*) on morphological grounds but was not resolved to species. This omission is material to the assessment that follows: morphological characters within Lemnaceae are sparse and frequently insufficient for species-level discrimination, and molecular tools are required for reliable identification of clones intended for commercial use (Bog et al., 2020; Braglia et al., 2021; Morello et al., 2026). Since growth rate and protein concentration differ appreciably between species and between clones of the same species, the productivity of the resident population cannot be inferred from published values for any named species.

4.2 Consolidated SWOT findings

Table 2 presents the consolidated SWOT synthesis across the four configurations. Two patterns are apparent prior to the introduction of the scoring. First, all four configurations share pathogen transfer as a threat, which indicates that feed safety is a system-level requirement rather than a discriminating criterion. Second, the weaknesses of DA, DSW and DPF are dominated by enterprise mismatch, whereas those of DBBF are dominated by operational unfamiliarity and seasonal water risk. These constitute a qualitatively different category of constraint, and one more readily addressed through operator training and design specification.

Table 2. Consolidated SWOT synthesis for the four candidate configurations.

System	Principal strengths	Principal weaknesses	Principal opportunities	Principal threats
DA	Phytoremediation of pond water; polyculture income from fish; established duckweed–tilapia precedent	Weak fit with a cattle-based livelihood; dissolved-oxygen management; higher net water demand	Separate cultivation and grow-out ponds; recirculation of treated water	Pathogen transfer; flood damage in the wet season; drying cost of surplus biomass
DSW	Nutrient-dense substrate; direct substitution of purchased protein; treated effluent for irrigation	Long hydraulic retention requirement; competition from algae; no swine enterprise at the site	Reuse of polished effluent; downstream biofuel integration	Pathogen contamination of pasture and watercourses

System	Principal strengths	Principal weaknesses	Principal opportunities	Principal threats
DPF	Protein and mineral supplement for poultry; low-cost additive at modest inclusion	Low tolerated inclusion rate; pathogen concerns; mismatch with the target enterprise	Integration with anaerobic digestion; standardised litter handling	Microbiological contamination of the feed chain
DBBF	Biogas for household energy; digestate as a nutrient stream; direct compatibility with cattle manure	Mineralisation lag between digestion and uptake; limited farmer experience with digester operation	Reduced purchased-feed expenditure; manure valorisation; route to a saleable feed ingredient	Dry-season water shortage; uncertainty over local duckweed identity

Note. Elements were synthesised from the evidence base described in Section 3.3 and from the site characteristics described in Section 3.2.

4.3 Comparative scoring

Table 1 reports the weighted decision matrix and Figure 1 shows how each configuration's total is composed. DBBF obtained the highest compatibility score at 4.60 of 5.00, followed by DSW at 3.05, DA at 2.70 and DPF at 2.65. The margin between DBBF and the next-ranked configuration is large and is driven predominantly by a single criterion: DBBF is the only configuration whose primary substrate is the waste stream the target enterprise already produces. Its advantage on circular resource integration and resource recovery reinforces, but does not create, that lead.

Table 1. Weighted decision criteria, ratings and compatibility scores for the four candidate configurations.

Criterion	Weight	DA	DSW	DPF	DBBF
Livestock-system compatibility	0.25	1	1	1	5
Circular resource integration	0.20	4	4	3	5
Feed-production relevance	0.15	3	4	4	5
Water and site suitability	0.10	2	3	3	3
Operational simplicity	0.10	2	2	3	3
Resource-recovery potential	0.10	4	5	3	5
Scalability and market potential	0.10	4	4	3	5
Weighted compatibility score (max. 5.00)	1.00	2.70	3.05	2.65	4.60

Note. DA = duckweed–tilapia aquaponics; DSW = duckweed-integrated swine wastewater treatment; DPF = duckweed in poultry waste management and feed production; DBBF = duckweed in bioenergy, biofertiliser and animal feed production. Ratings are on a five-point scale where 1 denotes very poor and 5 very strong. Scores are computed using Equation 1 and represent a structured synthesis of the qualitative evidence; they are not experimental measurements.

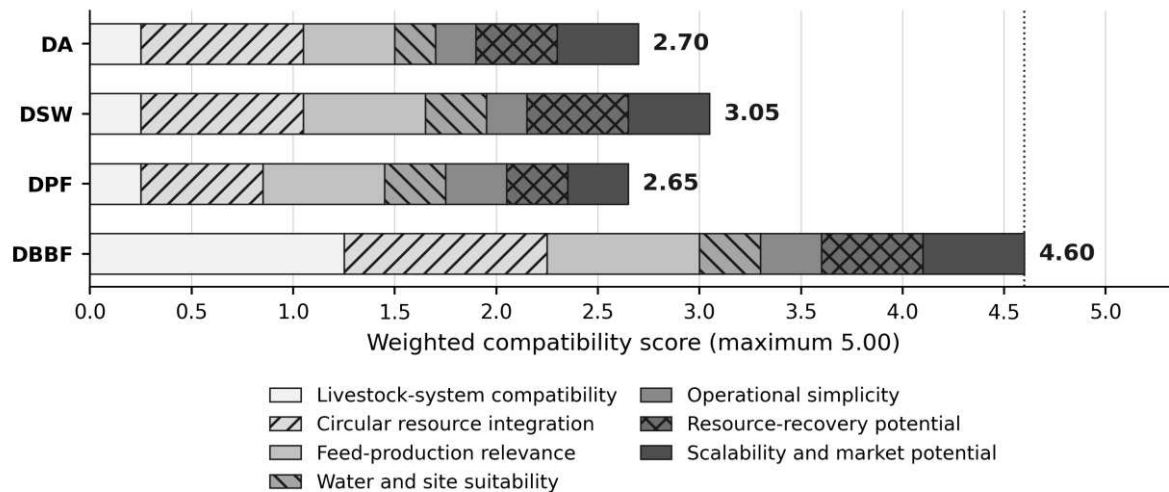


Figure 1. Composition of the weighted compatibility score for each candidate configuration. Segment lengths show each criterion's weighted contribution; totals are printed at the end of each bar. The dotted reference line marks the highest score obtained.

Note. Scores derive from the decision matrix in Table 1 and are structured decision-support indicators rather than experimental performance data.

4.4 Robustness of the ranking

Because the weights encode a judgement, the ranking was tested against alternative weighting schemes. Table 4 reports scores under equal weighting of all seven criteria and under removal of each criterion in turn with the remaining weights rescaled to unity. DBBF ranks first in every case. The magnitude of its lead varies, narrowing most when livestock-system compatibility is removed, but the order is unchanged throughout.

A stronger result follows from inspection of the rating matrix itself. DBBF equals or exceeds every alternative on every one of the seven criteria, and strictly exceeds DA on all seven, DSW on five and DPF on five. It therefore weakly dominates the alternative set. A dominant alternative is first-ranked under any non-negative weight vector, so the outcome of this analysis is independent of the weights entirely: no admissible reweighting, whether derived from a different analyst, a stakeholder panel or a formal elicitation procedure, can displace DBBF from first place. This is confirmed by the limiting case in which the whole weight is placed on a single criterion, where DBBF is first outright on four criteria and joint-first on the remaining three.

The residual question is therefore the accuracy of the ratings rather than the weights. Here the baseline margin is informative. DBBF leads DSW by 1.55 points, whereas the largest change achievable by revising any single rating cell is 1.00 point, obtained by moving a rating the full width of the scale on the most heavily weighted criterion. Reversal would require at least two cells to be misjudged by the maximum possible amount and in opposing directions. The ranking is not sensitive to ordinary disagreement over individual ratings.

Two qualifications should be read alongside this. First, dominance is a property of the rating matrix as constructed, and the ratings were assigned by the authors from the evidence base rather than elicited from an independent panel; dominance establishes that the conclusion does not depend on the weighting, not that the ratings are beyond dispute. Second, the three lower-ranked configurations are separated by margins of 0.40 points or less, which is well within the range that reasonable disagreement

could produce. No meaningful distinction should be drawn between them. The defensible claim is that DBBF ranks first and that the other three rank materially below it.

Table 4. Robustness of the ranking under alternative weighting schemes.

Weighting scheme	DA	DSW	DPF	DBBF	First-ranked
Baseline weights	2.70	3.05	2.65	4.60	DBBF
Equal weights	2.86	3.29	2.86	4.43	DBBF
C1 removed, rescaled	3.27	3.73	3.20	4.47	DBBF
C2 removed, rescaled	2.38	2.81	2.56	4.50	DBBF
C3 removed, rescaled	2.65	2.88	2.41	4.53	DBBF
C4 removed, rescaled	2.78	3.06	2.61	4.78	DBBF
C5 removed, rescaled	2.78	3.17	2.61	4.78	DBBF
C6 removed, rescaled	2.56	2.83	2.61	4.56	DBBF
C7 removed, rescaled	2.56	2.94	2.61	4.56	DBBF

Note. C1 to C7 denote the criteria listed in Table 1, in the order given there. Scores under each scheme are computed using Equation 1 with the stated weight vector normalised to unity. Because DBBF weakly dominates all alternatives across the criterion set, its first-ranked position holds under any non-negative weighting and is not confined to the schemes tabulated here.

5. Proposed implementation framework for DBBF

5.1 System architecture

Figure 2 presents the proposed resource loop. Cattle manure is collected and charged to an anaerobic digester sized to the herd; biogas serves household cooking demand, and the digestate is diluted and dosed into a shallow cultivation pond. Harvested duckweed is solar-dried, milled and incorporated into a protein-enriched ration returned to the same herd. Residual digestate not consumed by the pond is applied to cropland.

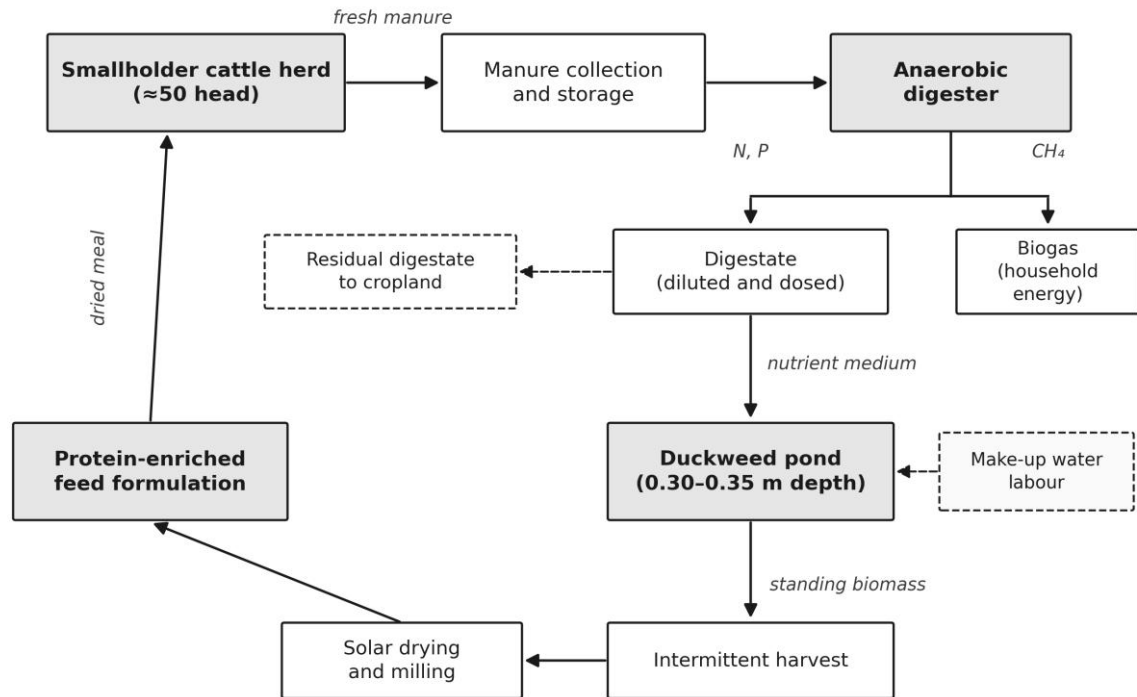


Figure 2. Proposed duckweed–bioenergy–biofertiliser–feed (DBBF) resource loop. Solid arrows denote principal material and energy flows; dashed arrows denote external inputs and residual outputs.

Note. The configuration is a semi-closed loop. Make-up water, household labour and basal forage remain external inputs, and nitrogen losses occur at several points in the chain.

The configuration is a semi-closed loop rather than a closed one, and the framing matters for how its benefits should be claimed. Make-up water, household labour and basal forage remain external inputs, and nitrogen is lost at several points in the chain. The system should therefore be understood as reducing purchased protein input and displacing woodfuel, not as achieving nutrient self-sufficiency.

5.2 Pond design and nutrient dosing

A shallow pond of approximately 0.30 to 0.35 m depth is proposed, consistent with the requirement that the standing biomass remain within reach of the nutrient-bearing water column. Digestate dosing is the principal operational control and the principal operational risk. The pilot-scale evidence indicates that undiluted or insufficiently diluted manure-derived media inhibit growth through free-ammonia toxicity, and that salts accumulate progressively in continuous systems until growth ceases (Lambert et al., 2025; Li et al., 2025). A dilution series established experimentally at the site, together with routine monitoring of pH, total ammoniacal nitrogen and electrical conductivity, therefore constitutes a precondition for sustained operation.

5.3 Harvesting regime

Intermittent removal of a fraction of the standing crop is proposed, retaining sufficient surface coverage to suppress algal competition and maintain the exponential growth phase. Harvest frequency and intensity interact with nutrient loading and should be optimised empirically rather than fixed in advance,

since the optimum depends on the growth rate of the resident genotype under local irradiance and temperature (Pasos-Panqueva et al., 2024).

5.4 Drying and ration formulation

Fresh duckweed is approximately ninety per cent water, so dehydration governs both the cost and the microbiological quality of the final ingredient. Open solar drying is the appropriate low-cost technology for this setting, but drying time, final moisture content, protein retention and microbial load must be measured rather than assumed. Dried and milled biomass is intended for incorporation into ration formulations alongside locally available energy sources such as maize germ and wheat pollard. Given the reported variability in duckweed protein digestibility between batches as outlined by Demann et al. (2023), inclusion rates should be set from measured composition of the site's own product rather than from published averages.

6. Discussion

6.1 Contextual fit as the decisive criterion

The principal finding is that configuration selection for smallholder deployment is governed less by the intrinsic merits of each pathway than by its alignment with the resource base and livelihood structure already present. DA, DSW and DPF are all technically sound and each is supported by a substantial literature, but each requires the household to add an enterprise (fish, swine or poultry) that it does not currently operate. DBBF asks the household to process a waste stream it already generates and to return a product to animals it already keeps. Where capital is scarce and the failure of an unfamiliar enterprise carries severe consequences for the household, this distinction is decisive.

6.2 Circularity rather than protein concentration

The case for DBBF should not rest principally on protein substitution. Considered in isolation, substitution is a limited claim, and one for which duckweed holds no clear advantage over purchased concentrate once drying and labour costs are accounted for. The stronger claim is that a single organic waste stream yields three outputs, namely household energy, a nutrient medium and a protein-rich biomass, and that the economics of the system should be assessed across all three. This reframing also changes what should be measured: the appropriate functional unit is not biomass yield but cost per kilogram of usable protein delivered to the animal, with the biogas and fertiliser value credited alongside.

6.3 Genotype identity as a prerequisite

Definitive identification of the resident population is the first task in any deployment sequence, not a subsequent refinement. Species and clones within Lemnaceae differ substantially in growth rate and composition, morphological identification is unreliable, and plastid barcoding provides the necessary resolution (Bog et al., 2019). A commercial specification for the resulting feed ingredient must rest on an identified and performance-tested genotype; without it, neither yield projections nor nutritional claims can be supported.

6.4 Water and nitrogen balance at herd scale

A feasibility assessment that does not quantify the resource demand of the system it proposes affords little basis for evaluation. This section therefore develops a first-order balance for the proposed configuration from published parameters, so that the scale of the intervention can be judged rather than assumed. Inputs and outputs are set out in Table 5.

Two independent constraints bound the system. The first is nitrogen. A herd of fifty animals producing approximately 3 kg of fresh manure per head per day yields 150 kg d^{-1} , which at a nitrogen content of 0.4 to 0.6 per cent of fresh weight supplies 0.60 to 0.90 kg N d^{-1} to the digester and thence to the pond. At the areal uptake rate of $1.2 \text{ g N m}^{-2} \text{ d}^{-1}$ recorded in outdoor pilot operation (Lambert et al., 2025), that nitrogen flux saturates a pond of 500 to 750 m^2 . Above this area the pond is nutrient-limited rather than light- or temperature-limited, and further expansion yields no additional biomass without an external nitrogen input.

The second constraint is water. Open-water evaporation at this elevation and aridity is taken as 4 to 6 mm d^{-1} , as reflected across the work of scholars such as Mutiga et al. (2010) and Ratshiedana et al. (2025), range consistent with satellite-derived actual evapotranspiration for cultivated land in the Upper Ewaso Ng'iro North basin; a closed duckweed mat reduces evaporative loss by approximately one third relative to open water (Soltani et al., 2020; Duan et al., 2026), giving 2.7 to 4.0 mm d^{-1} across the pond surface. Applied to the nitrogen-limited area, gross demand is $1.7 \text{ to } 2.5 \text{ m}^3 \text{ d}^{-1}$. Against a basin mean rainfall of 700 mm yr^{-1} , equivalent to 1.9 mm d^{-1} , net make-up requirement falls to roughly 0.6 to $1.6 \text{ m}^3 \text{ d}^{-1}$ on an annual average, but rainfall in this system is tri-modal and largely absent in the dry season, so the gross figure is the one that governs dry-season operation.

Expressed as a water footprint, the pond consumes 1,220 to 1,830 litres of blue water per kilogram of dry biomass, or 3,480 to 5,210 litres per kilogram of crude protein, during periods without rainfall. Comparison with the water footprint of imported soybean meal is frequently invoked in support of duckweed, but the comparison is only meaningful if made on a like-for-like basis: the footprint of rain-fed soy is overwhelmingly green water, whereas every litre consumed by the pond is blue water that must be abstracted and delivered (Chouchane et al., 2020; Mekonnen & Hoekstra, 2020). A favourable total-footprint comparison can therefore coexist with an unfavourable blue-water comparison, and claims of water advantage should accordingly be expressed on a blue-water basis.

The most consequential result, however, concerns scale rather than either constraint individually. The nitrogen-limited pond yields 1.1 to 1.6 kg of dry biomass per day, equivalent to 0.38 to 0.58 kg of crude protein, or 8 to 12 g per head per day across the herd. Set against a lactating cow's crude-protein requirement of the order of 2 kg d^{-1} , the system as specified supplies well under one per cent of herd protein demand. Supplying even ten per cent would require approximately 1.3 ha of pond surface and two to three times the nitrogen the herd itself produces, which would mean importing nutrients and abandoning the closed-loop premise on which the configuration's advantage rests.

This finding does not invalidate the selection of DBBF, although it constrains the claims that may reasonably be advanced for the configuration. At herd scale and on the farm's own manure, duckweed is a marginal protein supplement rather than a substitute for purchased concentrate. Its defensible value proposition is the joint product: household biogas, a managed nutrient stream, a reduction in uncontrolled manure loss, and a modest protein increment, assessed together. It also relocates the

binding constraint. The preceding literature identifies water as the limiting factor in semi-arid duckweed systems, and water is indeed demanding in footprint terms, but at this herd size the pond is small in absolute volume and nitrogen saturates before water does. Proposals to scale the system must therefore address nitrogen supply as the primary constraint.

Table 5. First-order water and nitrogen balance for the proposed DBBF configuration at Ngobit.

Parameter	Value or range	Basis
Herd size	50 head	Site records
Fresh manure production	150 kg d ⁻¹	Site records (3 kg head ⁻¹ d ⁻¹)
Nitrogen content of fresh manure	0.4–0.6 %	Assumed; requires site measurement
Nitrogen flux available to pond	0.60–0.90 kg N d ⁻¹	Calculated
Areal nitrogen uptake rate	1.2 g N m ⁻² d ⁻¹	Lambert et al. (2025), pilot scale
Nitrogen-limited pond area	500–750 m ²	Calculated
Dry-matter productivity	2.19 g m ⁻² d ⁻¹	Lambert et al. (2025), 8 t ha ⁻¹ yr ⁻¹
Crude-protein productivity	0.77 g m ⁻² d ⁻¹	Lambert et al. (2025), 2.8 t ha ⁻¹ yr ⁻¹
Dry biomass output	1.1–1.6 kg d ⁻¹	Calculated
Crude-protein output	0.38–0.58 kg d ⁻¹	Calculated
Protein supplied per head	8–12 g head ⁻¹ d ⁻¹	Calculated
Open-water evaporation	4–6 mm d ⁻¹	Assumed; cf. Mutiga et al. (2010)
Evaporation beneath a closed mat	2.7–4.0 mm d ⁻¹	Oron et al. (1985), one-third reduction
Mean rainfall	1.9 mm d ⁻¹ (700 mm yr ⁻¹)	Basin mean
Gross pond water demand	1.7–2.5 m ³ d ⁻¹	Calculated
Blue water per kg protein, dry season	3,500–5,200 L	Calculated
Blue water per kg protein, annual mean	1,000–2,700 L	Calculated

Note. Calculated values are first-order estimates derived from published parameters and site records; they have not been measured at the site. Blue water denotes abstracted water that must be physically delivered to the pond, as distinct from green water supplied directly by rainfall.

6.5 Feed safety

The use of digestate as a cultivation medium creates a biosafety boundary that must be demonstrated rather than assumed. Duckweed accumulates metals and other contaminants from the water column, and novel protein sources carry a recognised hazard profile encompassing heavy metals, pathogens, mycotoxins and pesticide residues (van der Spiegel et al., 2013). Anaerobic digestion reduces pathogen load but does not eliminate every hazard class. Microbiological and potentially toxic element characterisation of the source water, the digestate and the dried product should therefore be built into the validation protocol from the outset, as set out in Table 3.

6.6 Energy context and digester operation

Household biodigester programmes across sub-Saharan Africa have a long history but persistently modest dissemination, with adoption constrained by installation cost, maintenance capability and technical support rather than by technical feasibility (Tolessa, 2024). Techno-economic assessment nevertheless indicates quantifiable economic benefit to smallholders from anaerobic digestion under a range of assumptions (Tolessa, 2023). The implication for this framework is that the digester, not the

pond, is the component most likely to fail in service, and that provision for maintenance and operator training should be resourced accordingly.

6.7 Staged validation

Figure 3 below, sets out a four-phase pathway with explicit decision gates. The structure is deliberately sequential: biological characterisation precedes productivity measurement, which precedes processing and safety work, which precedes integrated demonstration. Each gate poses a question whose negative answer returns the programme to the preceding phase rather than permitting progression on optimism. Table 3 specifies the indicators against which each gate should be judged.

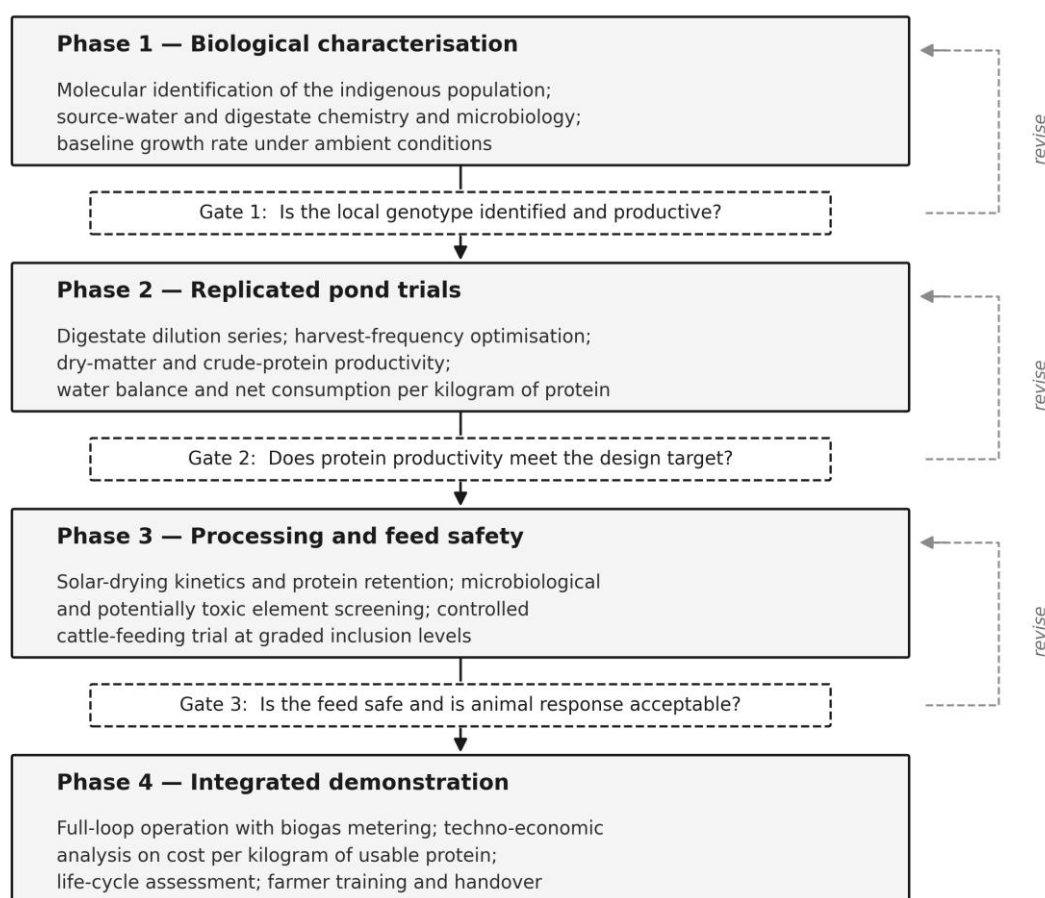


Figure 3. Staged research-to-commercialisation pathway with decision gates. A negative answer at any gate returns the programme to the preceding phase rather than permitting progression.

Note. The pathway operationalises the validation requirements identified in Section 6 and specified in Table 3; it is a proposed schedule, not a validated commercialisation plan.

Table 3. Indicators proposed for empirical validation of the DBBF pilot.

Domain	Indicator	Unit	Purpose
Duckweed biology	Fresh biomass productivity	kg m ⁻² d ⁻¹	Growth performance under ambient conditions
Duckweed biology	Dry biomass productivity	kg m ⁻² d ⁻¹	Usable biomass yield after dehydration
Nutrition	Crude protein concentration	% dry matter	Feed value of the harvested biomass

Domain	Indicator	Unit	Purpose
Nutrition	Protein productivity	kg protein m ⁻² d ⁻¹	Integrates yield and quality in one metric
Water chemistry	pH	dimensionless	Culture stability and free-ammonia risk
Water chemistry	Total ammoniacal nitrogen	mg L ⁻¹	Nitrogen availability and toxicity threshold
Water chemistry	Orthophosphate	mg L ⁻¹	Phosphorus availability
Water chemistry	Electrical conductivity	mS cm ⁻¹	Salt accumulation in a recirculating system
Digestion	Specific biogas yield	m ³ kg ⁻¹ VS	Energy performance of the digester
Feed	Inclusion rate	% of ration dry matter	Optimisation of substitution level
Livestock	Average daily gain	kg d ⁻¹	Animal response to the formulated ration
Livestock	Feed conversion ratio	kg feed kg ⁻¹ gain	Production efficiency
Economics	Cost per kilogram usable protein	KES kg ⁻¹ protein	Comparison against purchased protein sources
Safety	Faecal indicator and pathogen count	CFU g ⁻¹	Microbiological safety of the dried product
Safety	Cadmium, lead, arsenic, mercury	mg kg ⁻¹ dry matter	Potentially toxic element screening

Note. VS = volatile solids; CFU = colony-forming units; KES = Kenyan shilling. These indicators are proposed for future experimental work and were not measured in the present study.

6.8 Limitations

This study is a feasibility assessment, not an experimental trial, and its limitations follow directly from that. Biomass productivity, protein yield, digestate suitability, feed performance, economic return and environmental benefit are all unmeasured at this site. The weighted decision matrix is a structured representation of qualitative evidence; its ratings were assigned by the authors from the reviewed evidence rather than elicited from an independent stakeholder panel. Dominance analysis establishes that the ranking is invariant to the weighting applied, but not that the individual ratings are beyond dispute. The resident duckweed population was not identified to species. The water and nitrogen balance in Section 6.4 is a first-order calculation built on published parameters and on an assumed manure nitrogen content, and is sensitive to both; it indicates the order of magnitude of the system's output, not its realised performance. No techno-economic analysis or life-cycle assessment was performed, and the digester capacity, pond area and herd figures used here are design premises rather than validated parameters. The evidence synthesis was narrative and its search was not pre-registered. These constraints bound the conclusions to the claim actually made: that DBBF is the configuration best matched to this site's constraints, and that a defined programme of measurement is required before deployment.

7. Conclusions

Duckweed-integrated production offers a plausible route to relieving the feed-protein constraint faced by smallholder cattle producers in semi-arid Kenya, but the configuration chosen matters more than the decision to use duckweed at all. Of four candidate systems evaluated against the constraints of a proposed pilot site at Ngobit, the duckweed–bioenergy–biofertiliser–feed configuration scored highest

at 4.60 of 5.00, and retained first place under alternative weighting schemes. Its advantage rests on using a waste stream the target enterprise already produces and returning a product to animals it already keeps, while recovering energy and nutrients from the same flow.

A first-order balance nevertheless bounds what the configuration can deliver. The herd's own manure saturates a pond of 500 to 750 m² and yields 8 to 12 g of crude protein per head per day, well under one per cent of a lactating cow's requirement, so the system should be advanced as a joint energy, nutrient and feed intervention rather than as a route to protein self-sufficiency. The contribution of this work is the decision procedure, the implementation framework and that quantified bound, rather than any measured performance claim. The unresolved questions are specific and tractable: the identity and productivity of the resident genotype, the dilution regime that sustains growth without ammonia or salt inhibition, the water consumed per kilogram of usable protein, the cost and protein retention of solar drying, the microbiological and elemental safety of the product, and the response of the herd to graded inclusion. The staged pathway proposed here is intended to answer those questions in the order in which their answers constrain the next decision.

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Ethics approval. No human or animal experimental intervention was undertaken. The study comprised literature synthesis, non-invasive site observation and conceptual system analysis.

Consent to participate. Not applicable.

Consent for publication. Not applicable.

Data availability. All data supporting the findings are contained within the article. The decision matrix inputs are reported in full in Table 1, permitting independent recalculation. Site information was obtained under personal communication and is not publicly archived.

Author contributions. Conceptualisation: C.O.I. Methodology: C.O.I. and O.O.A. Formal analysis: C.O.I. Investigation: C.O.I. Writing, original draft: C.O.I. Writing, review and editing: C.O.I. and O.O.A. Both authors read and approved the final manuscript.

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