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RESEARCH PAPER

Transitioning towards sustainable aquaculture: adoption, production, and productivity outcomes of climate-smart feed ingredients among smallholder fish farmers in rural Kenya

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Abstract

The quest for economically viable and ecologically responsible aquafeed ingredients has emerged as one of the most pressing priorities in smallholder aquaculture development across sub-Saharan Africa. The present study investigates the field-scale adoption, production dynamics, and productivity implications of four climate-smart feed ingredients; mosquito fern (*Azolla pinnata*), black soldier fly larvae (BSFL; *Hermetia illucens*), duckweed (*Lemna minor*), and earthworm (*Eisenia fetida*) within Kenya's Aquaculture Business Development Programme (ABDP) framework. Data were collected from 297 smallholder farmers across 14 ABDP-implementing counties spanning the Western, Nyanza, Eastern, and Central regions of Kenya, using a structured interview protocol and a descriptive cross-sectional design. The respondent profile was dominated by middle-aged farmers (36–60 years; 78%) and males (73%). *A. pinnata* emerged as the predominant feed ingredient in terms of both adoption breadth and production volume, with an aggregate output of 292,535 kg valued at USD 343,816. The most consequential productivity gains, however, were attributable to BSFL, whose combined application with farm-made feed elevated fish output per production cycle by 50.00 ± 6.10% which was statistically significant improvement relative to all other treatment combinations ($P < 0.05$). Collectively, these findings substantiate the agronomic and economic case for integrating climate-smart ingredients into smallholder aquaculture systems in Kenya, while underscoring persistent barriers that continue to constrain the diffusion of duckweed and earthworm-based feeding practices.

Introduction

Global aquaculture production has expanded markedly over the past three decades, yet the sector's continued growth is increasingly imperilled by structural vulnerabilities in its feed supply chains. In Kenya, where declining inland and coastal capture fisheries have elevated aquaculture to a strategic instrument for food security, rural income generation, and nutritional improvement (FAO, 2024), these vulnerabilities are acutely felt. The shrinking productivity of Lake Victoria and other national water bodies — driven by overexploitation, habitat degradation, and the compounding effects of climate change has accelerated the Government of Kenya's commitment to farmed fish production, operationalised in part through the Aquaculture Business Development Programme (ABDP), a joint initiative co-funded by the International Fund for Agricultural Development (IFAD) (ABDP, 2021).

Notwithstanding the expansion of aquaculture in Kenya, feed costs remain the single largest operational expenditure for smallholder fish farmers. Commercial pelleted feeds, formulated principally with marine fishmeal, fish oil, and soybean meal, are subject to pronounced market volatility and long-term supply insecurity (Bansemer et al., 2023). Beyond their economic burden, these ingredients carry significant environmental externalities: escalating demand for wild-caught fishmeal exerts pressure on already depleted marine resources, while large-scale soybean cultivation has been implicated in tropical deforestation and the consequent destabilisation of regional carbon sinks (Nagappan et al., 2021; Maulu et al., 2021). These converging pressures have catalysed a paradigm shift in aquafeed science toward ingredients that are simultaneously nutritious, economically accessible, and environmentally benign.

An extensive body of evidence now documents the nutritional adequacy of a range of alternative feed resources, including leguminous plant proteins (Ghosh & Ray, 2019; Maundu et al., 2024), photosynthetic microalgae (Shah et al., 2018; Cai et al., 2021; Nagappan et al., 2021), and insect-derived meal (Wachira et al., 2021; Mikołajczak et al., 2022; Kals et al., 2024). Among these, climate-smart ingredients — defined by their low lifecycle carbon footprints, compatibility with circular economy principles, and capacity to maintain or enhance fish growth performance have garnered particular attention as transformative solutions for resource-limited production systems (Munguti et al., 2024). Cultured macrophytes such as *Azolla* spp. and duckweed (*Lemna* spp.) can be propagated on-farm using aquaculture effluent, essentially valorising a waste stream as a nutritive input (Slembrouck et al., 2018; Opiyo et al., 2024), while BSFL and earthworm biomass can be generated through the bioconversion of organic farm wastes, simultaneously addressing waste management imperatives and generating protein-dense feed materials (Vernooij et al., 2019; Musyoka et al., 2020a; Diener et al., 2011).

Despite these well-documented advantages, the on-farm adoption of climate-smart feed ingredients by smallholder aquaculturalists in Kenya has remained limited and geographically uneven. Knowledge deficits, limited access to demonstration facilities, inadequate institutional support, and insufficient alignment between technology design and smallholder realities continue to suppress uptake (Brugere et al., 2021). To address this technology-adoption gap, the ABDP implemented a comprehensive programme of structured capacity-building interventions, encompassing technical training workshops and on-site extension support targeting smallholder farmers and their field extension officers across its implementing counties.

The present study was designed to systematically assess the outcomes of this intervention by documenting the production volumes, adoption patterns, and productivity impacts of four priority climate-smart ingredients: *A. pinnata*, BSFL (*H. illucens*), duckweed (*L. minor*), and earthworm (*E. fetida*). By situating these outcomes within the broader discourse on sustainable aquafeed innovation in sub-Saharan Africa, this paper seeks to generate evidence that can inform future programming, extension strategies, and policy development in Kenya and comparable contexts.

Materials and Methods

Study area and participant selection

The study was conducted across 14 counties designated as ABDP implementation sites: Migori, Kisii, Kisumu, Siaya, Busia, Kakamega, Meru, Tharaka Nithi, Embu, Kirinyaga, Nyeri, Kiambu, Machakos, and Kajiado (Figure 1). Site selection for the ABDP was predicated on a multi-criteria assessment of aquaculture suitability, encompassing perennial water availability, soil characteristics favourable to earthen pond construction, adequate land resources for production expansion, and the presence of an active smallholder farming community engaged in fish culture (IFAD, 2017). All farmers enrolled in the programme received a standardised package of aquaculture inputs; including commercial pelleted feeds alongside technical extension support aimed at improving husbandry practices and production efficiency.

Study participants were drawn exclusively from farmers who had commenced independent production of at least one climate-smart feed ingredient at the time of the survey. A total of 297 individuals, distributed across the 14 counties, voluntarily consented to participate. This purposive sampling approach ensured that respondents possessed direct experiential knowledge of the climate-smart feeds under investigation, rendering their production records and production-outcome data suitable for rigorous analysis.

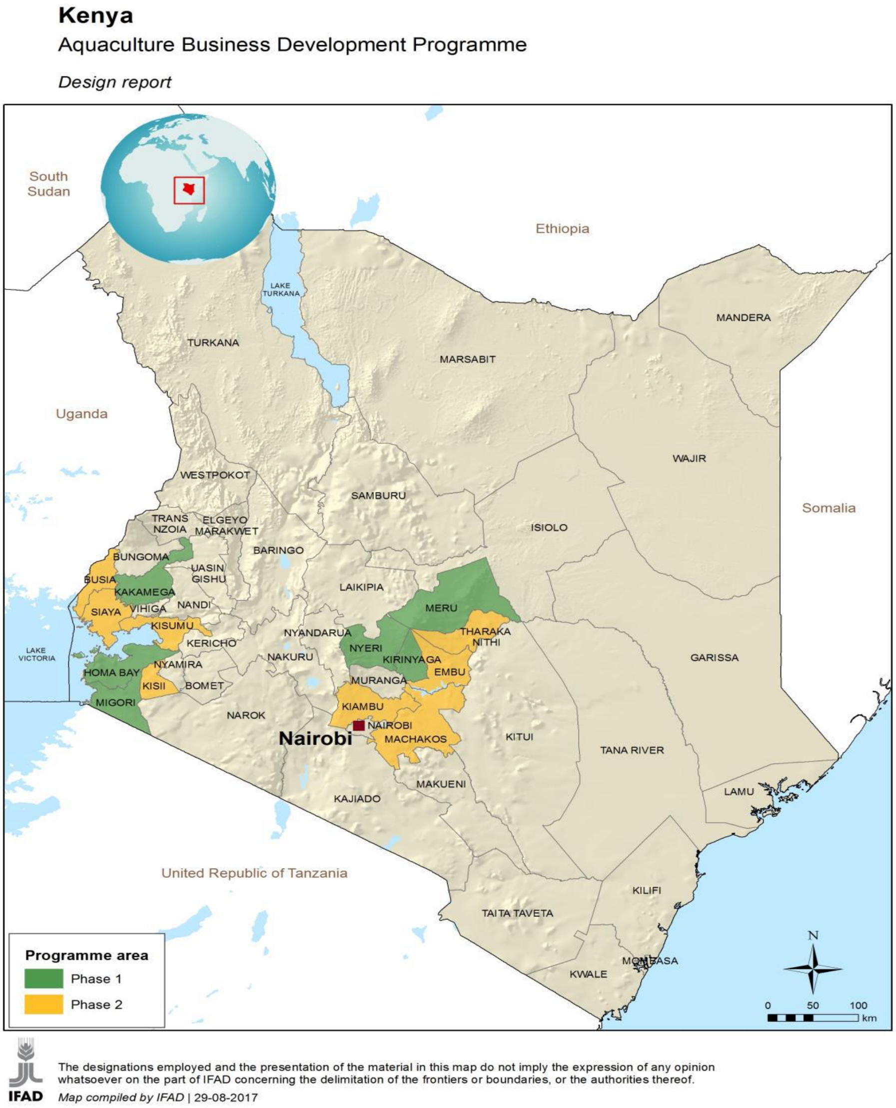

Figure 1. Spatial distribution of the 14 ABDP-implementing counties constituting the study area (Source: IFAD, 2017).

Data collection

Field data were gathered in February 2025 using a fully structured interview protocol administered to each of the 297 participating farmers. The instrument captured information on the types and combinations of climate-smart feeds being produced, quantities harvested over defined production periods, and longitudinal fish production records spanning 2023–2024. Interview responses were transcribed in real time into standardised digital spreadsheets. Farmer record books maintained as part of the ABDP's monitoring and evaluation framework served as an independent secondary data source to cross-validate interview-derived production figures and to supplement records where direct recall was incomplete. Quantitative field observations during scheduled extension visits provided additional contextual validation. Supplementary secondary data were drawn from peer-reviewed literature to contextualise findings within the broader agronomic and environmental performance characteristics of the four target ingredients.

Statistical analysis

All primary data were coded and processed using SPSS Statistics (Version 23, IBM Corp.). Frequencies and descriptive means were calculated to characterise the socio-demographic profile of respondents and to summarise feed production outputs by county and ingredient type. The effect of climate-smart feed type on fish production per cycle was evaluated using one-way analysis of variance (ANOVA). Where ANOVA yielded a statistically significant result, pairwise mean comparisons were conducted using Tukey's Honestly Significant Difference (HSD) post-hoc procedure to identify which treatment groups differed significantly from one another. The threshold for statistical significance was set at $P \leq 0.05$ throughout. All production data are reported as means ± standard error (SE).

Results

Socio-demographic profile of respondents

Across the 14 counties surveyed, the cohort of farmers actively producing and utilising climate-smart feed ingredients was characterised by a distinct age and gender profile. Middle-aged individuals (36–60 years) constituted the overwhelming majority of adopters (78%), whilst younger farmers (18–35 years) represented 14% of the sample and elderly respondents (>60 years) accounted for the remaining 8% (Figure 2a). Gender analysis revealed more male in the fish farming business with male farmers comprising 73% of the cohort against 27% female participation (Figure 2b).

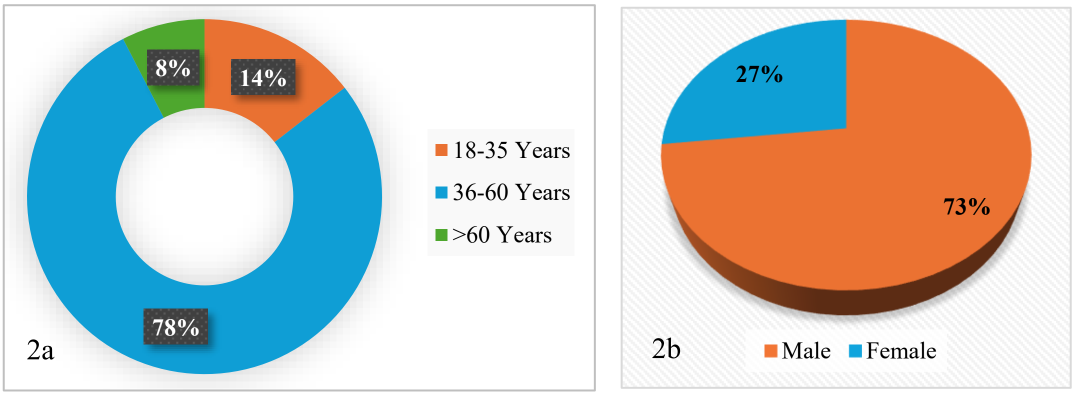

Figure 2 (a, b). Age and gender distribution of smallholder fish farmers adopting climate-smart feeds across 14 ABDP-implementing counties in Kenya.

The disaggregation of adoption rates by age group and feed type, detailed in Table 1, reveals a consistent dominance of *A. pinnata* across all demographic segments. This ingredient was most intensively adopted by farmers in the 36-60-year bracket (61.4%), far exceeding all other categories. Within the same age cohort, BSFL was the second most reported sole-ingredient adoptee (4.1%), while the combined use of *A. pinnata* and duckweed was recorded among 3.8% of middle-aged farmers. Combinations involving BSFL with farm-made feeds were documented across all age groups, albeit at modest frequencies. Notably, duckweed as a standalone ingredient was entirely absent among the youngest (18–35 years) and oldest (> 60 years) age groups, and earthworm adoption remained marginal throughout.

Table 1. Age-stratified distribution of climate-smart feed type adoption among 297 smallholder fish farmers across 14 ABDP-implementing counties, Kenya.

Age (Years)	Climate-smart feed type	n	Frequency (%)
18–35	Azolla	27	9.3
	Azolla + BSFL	4	1.4
	Azolla + Duckweed	2	0.7
	BSFL + Farm-made feed	1	0.3
	Duckweed	0	0.0
	BSFL	7	2.4
	Earthworm	1	0.3
36–60	Azolla	178	61.4
	Azolla + BSFL	7	2.4
	Azolla + Duckweed	11	3.8
	BSFL + Farm-made feed	6	2.1
	Duckweed	10	3.4
	BSFL	12	4.1
	Earthworm	2	0.7
>60	Azolla	17	5.9
	Azolla + BSFL	2	0.7
	Azolla + Duckweed	0	0.0
	BSFL + Farm-made feed	1	0.3
	Duckweed	0	0.0
	BSFL	1	0.3
	Earthworm	1	0.3

Production volumes and geographic distribution of climate-smart feeds

A. pinnata dominated the production landscape, with an aggregate output of 292,535 kg (valued at USD 343,816) recorded across the study area — more than double the volume of the second most-produced ingredient (Figure 3). BSFL production reached 107,550 kg (USD 146,689), representing a substantive but notably lower level of output. Duckweed and earthworm production were markedly more limited, yielding 23,649 kg (USD 26,900) and 6,304 kg (USD 7,216), respectively.

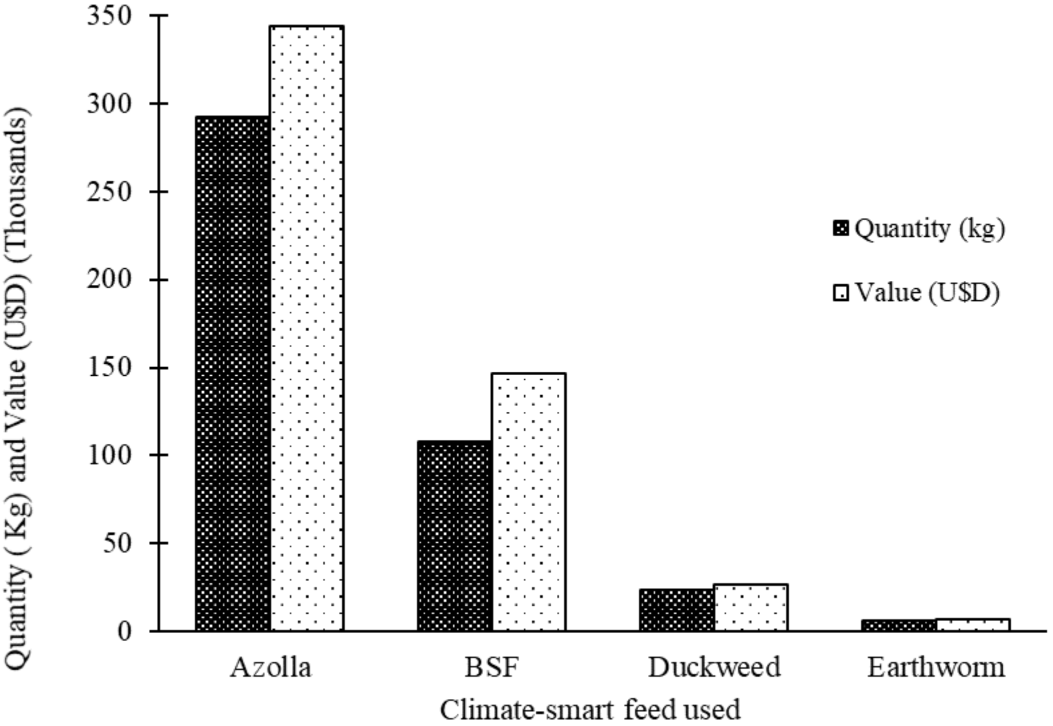

Figure 3. Aggregate production volume (kg) and estimated monetary value (USD) of four climate-smart feed ingredients produced by smallholder fish farmers across 14 ABDP-implementing counties, Kenya.

Challenges of dried fish marketing

A. pinnata and BSFL were the only two ingredients recorded in all 14 counties, affirming their suitability for diverse agro-ecological conditions. Machakos County led production of *A. pinnata* with 102,197 kg, while Kakamega County recorded the highest BSFL output at 63,260 kg (Figure 4). The geographic reach of duckweed and earthworm was considerably more circumscribed, with production activities documented in only 6 of the 14 counties. Kakamega remained the primary producer of duckweed (10,972 kg), followed by Meru County (10,200 kg).

Impact of climate-smart feed supplementation on fish production

The integration of climate-smart feeds into smallholder fish production regimes yielded statistically significant improvements in fish biomass per production cycle across all treatment combinations ($P < 0.05$; Table 2, Figure 5). The magnitude of this effect varied substantially by feed type. The most pronounced gains were observed among farmers supplementing commercial feed with BSFL combined with farm-made feed, who recorded a mean production increase of 50.00 ± 6.10% — a value that was significantly higher than all other groups ($P < 0.05$). At the other end of the spectrum, earthworm supplementation produced the least improvement, with a mean increase of only 26.57 ± 5.50% significantly below the majority of other treatments ($P < 0.05$). The remaining feed types including sole *A. pinnata*, duckweed, BSFL, and various two-way combinations generated intermediate production gains broadly ranging from 32% to 38%.

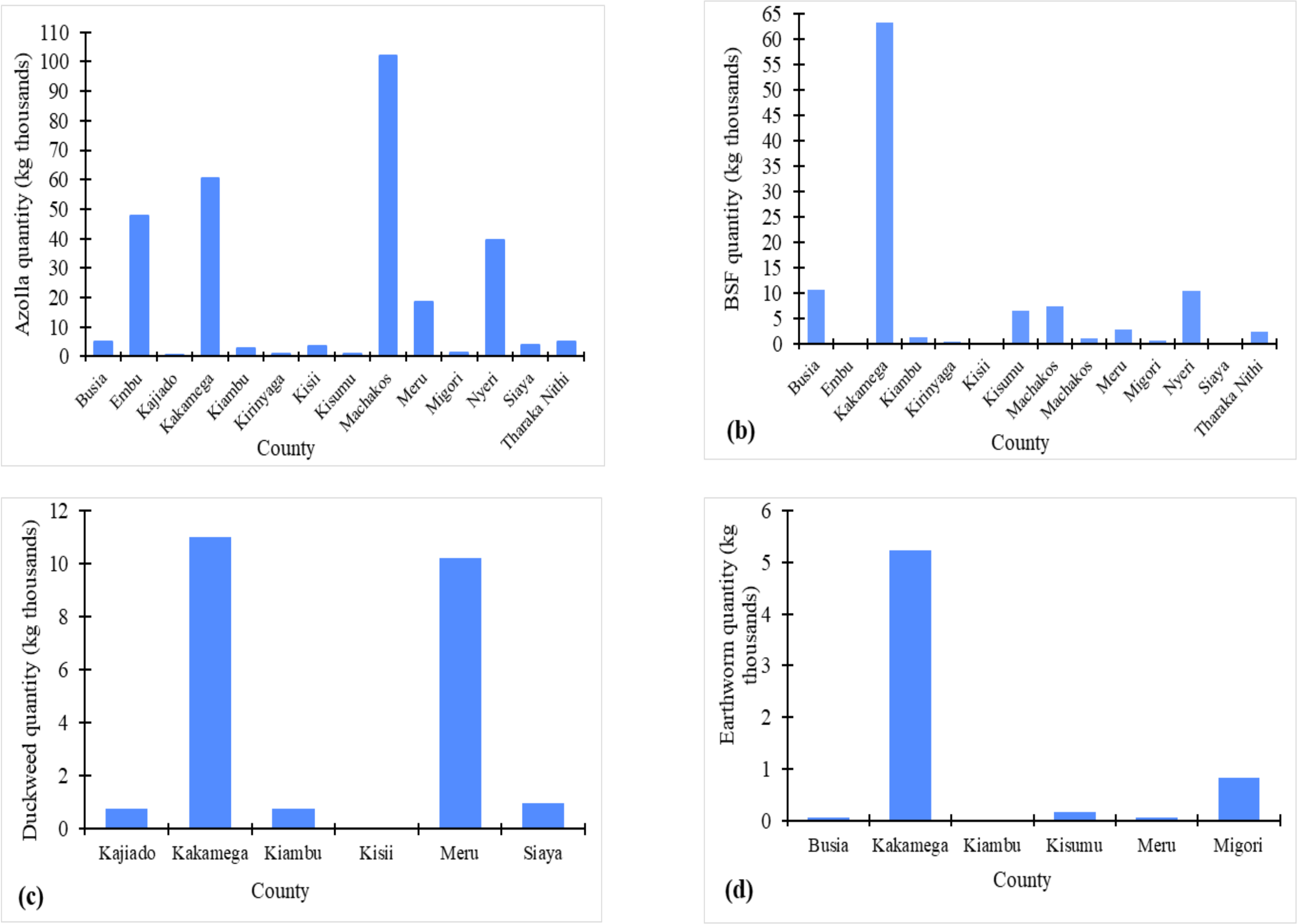

Figure 4. County-level production volumes (kg) of (a) A. pinnata, (b) BSFL, (c) duckweed, and (d) earthworm, across ABDP-implementing counties in Kenya, 2021–2024.

Table 2. Change in fish production per cycle (Mean ± SE, kg) associated with the adoption of climate-smart feed supplements in lieu of or in combination with commercial feed, across 14 ABDP-implementing counties, Kenya.

Alternative feed type	**Fish production per cycle (WCSF) (kg)**	**Fish production per cycle (CSF) (kg)**	**Production increase (%)**
Azolla (*Azolla pinnata*)	172.90 ± 4.47^{a}	229.71 ± 6.43^{a}	32.65 ± 2.60^{a}
Azolla + BSFL	286.44 ± 4.31^{b}	386.72 ± 2.10^{b}	34.51 ± 4.55^{a}
Azolla + Duckweed	140.08 ± 8.86^{a}	189.42 ± 12.41^{c}	36.04 ± 1.67^{a}
BSFL + Farm-made feed	217.50 ± 5.49^{c}	332.50 ± 6.60^{b}	50.00 ± 6.10^{b}
Duckweed (Lemna minor)	122.50 ± 4.49^{a}	161.86 ± 3.51^{c}	32.79 ± 5.38^{a}
BSFL (*Hermetia illucens*)	221.40 ± 4.87^{c}	296.93 ± 5.97^{a}	37.97 ± 5.09^{a}
Earthworm (*Eisenia fetida*)	151.67 ± 9.32^{a}	191.67 ± 7.13^{c}	26.57 ± 5.50^{c}

*WCSF = production cycle without climate-smart feeds; CSF = production cycle with climate-smart feeds. Within each column, values sharing a common superscript do not differ significantly ($P \geq 0.05$; Tukey's HSD post-hoc test)

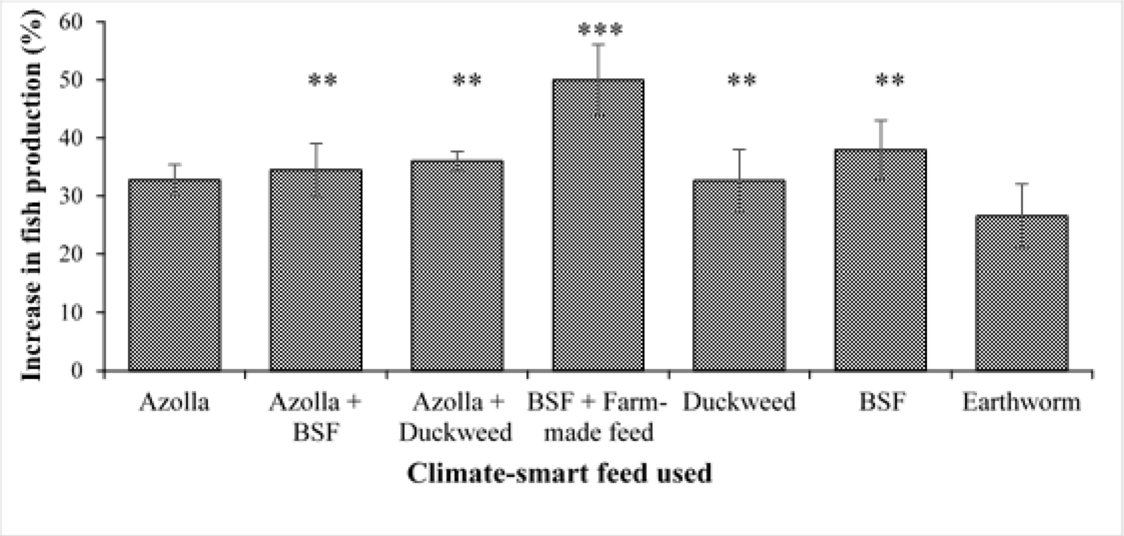

Figure 5. Mean percentage increase (± SE) in fish production per cycle attributable to each climate-smart feed type, as a supplement to the commercial feed baseline provided under the ABDP, Kenya.

Table 3. Comparative carbon footprints of the four climate-smart feed ingredients evaluated in this study, alongside conventional fishmeal and soybean meal as reference benchmarks.

Ingredient	Carbon footprint (kg CO_2eq kg^{-1})	Basis	Relative to fishmeal	Reference
Azolla pinnata	Net CO_2 sink (sequesters 1.38 g CO_2 g^{-1} DW)	Per kg dry biomass	Carbon-negative; net CO_2 fixation	Hassaan & Hashem (2021); Baviskar et al. (2023)
Black soldier fly larvae (*Hermetia illucens*)	~5.09–0.83 kg CO_2eq kg^{-1}	Per kg dried larvae meal (LCA, waste substrate)	71–87% lower than fishmeal	Pishgar-Komleh et al. (2022); Smetana et al. (PMC, 2022)
Duckweed (*Lemna minor*)	3.54–6.54 kg CO_2eq kg^{-1} protein; net CO_2 fixation during growth	Per kg protein yield (slurry-grown)	Comparable to faba bean protein (3.61); lower than conventional aquafeed	Stadtlander et al. (2025, Sci. Rep.)
Earthworm (*Eisenia fetida*)	130–189 g CO_2eq kg^{-1} substrate DM (vermicomposting); lower N_2O vs conventional composting	Per kg substrate dry matter processed	~78–90% lower CH_4 than composting; N_2O reduction vs. control	Cao et al. (2021, PMC); Ren et al. (2018)
Fishmeal (reference — conventional)	~2.9–10.3 kg CO_2eq kg^{-1}	Per kg meal (LCA, wild-capture origin)	Baseline comparator	FAO (2024); Bansemer et al. (2023); Salter & Lopez-Viso (2021)
Soybean meal (reference — conventional)	~1.99 kg CO_2eq kg^{-1} (European market); up to 8–10 kg CO_2eq kg^{-1} with land-use change (South American origin)	Per kg meal	Baseline comparator: land-use change greatly amplifies footprint	Nagappan et al. (2021); Donau Soja/FiBL (2025)

DW = dry weight; LCA = life cycle assessment; CO_2eq = carbon dioxide equivalent. Carbon footprint values are derived from published life cycle assessments and experimental studies. Ranges reflect variation across production systems, substrates, and geographic contexts. Negative values for *A. pinnata* and *L. minor* indicate net CO_2 sequestration during biomass production. Values for fishmeal and soybean meal include contributions from wild-capture depletion and land-use change, respectively.

Discussion

The present investigation documents, for the first time from a multi-county extension programme perspective, the real-world adoption trajectories and productivity outcomes of four climate-smart aquafeed ingredients in rural Kenya. The findings bear directly on the twin imperatives of feed cost reduction and ecological sustainability that now define the frontier of smallholder aquaculture development in sub-Saharan Africa.

The macro-level drivers shaping this context are well established. The global market for marine fishmeal, the predominant protein source in commercial pelleted feeds, is characterised by supply inelasticity and upward price pressure, with wild capture volumes stagnating despite sustained aquaculture demand (Shati et al., 2022; FAO, 2024). Concurrently, the environmental consequences of large-scale soybean cultivation encompassing deforestation, biodiversity loss, and net greenhouse gas emissions have drawn intensifying regulatory and public scrutiny (Salter & Lopez-Viso, 2021). Against this backdrop, climate-smart feed ingredients, which are producible at the farm level with minimal capital outlay and offer verifiable lifecycle benefits, represent a structurally superior trajectory for smallholder aquaculture systems in emerging economies (Kals et al., 2024; Soma et al., 2024; Maulu et al., 2021).

The carbon footprint data summarised in Table 3 provide a compelling quantitative case for the climate superiority of the ingredients evaluated in this study relative to the conventional feed inputs they are designed to displace. Fishmeal, sourced from wild-capture marine fisheries, carries a carbon footprint estimated at 2.9–10.3 kg CO_2eq kg^{-1} a figure driven by fuel consumption in capture fishing, fishmeal processing, and associated transport (FAO, 2024; Bansemer et al., 2023). Soybean meal, the principal plant protein source in commercial aquafeed, is even more variable: European market grades incur approximately 1.99 kg CO_2eq kg^{-1}, but South American soybeans grown on land converted from tropical forest can exceed 8–10 kg CO_2eq kg^{-1} once land-use change emissions are allocated (Nagappan et al., 2021; Donau Soja/FiBL, 2025). Against this baseline, all four climate-smart ingredients investigated in the present study demonstrate substantially reduced — or, in the case of the two aquatic macrophytes, net negative — greenhouse gas emission profiles.

A. pinnata and *L. minor* (duckweed) are photosynthetically active carbon sinks during cultivation. Research has quantified a carbon sequestration rate of up to 1.38 g CO_2 per gram dry biomass for *A. pinnata* propagated on organic effluents (Baviskar et al., 2023; Hassaan & Hashem, 2021), while duckweed protein produced on diluted animal slurry has been assigned a lifecycle footprint of 3.54–6.54 kg CO_2eq kg^{-1} protein broadly equivalent to faba bean protein and substantially below that of conventional aquafeed protein concentrates (Stadtlander et al., 2025). Importantly, neither macrophyte involves soil tillage or land-use change, eliminating the two largest emission hotspots associated with terrestrial crop production. Their cultivation on aquaculture effluent further offsets the environmental cost of nutrient waste disposal, yielding a net circular economy dividend.

BSFL reared on organic waste substrates carries a lifecycle carbon footprint of approximately 0.83–5.09 kg CO_2eq kg^{-1} dried larvae meal, depending on production scale, energy source, and substrate type (Pishgar-Komleh et al., 2022; Smetana et al., 2022). This represents a 71–87% reduction relative to conventional fishmeal and compares favourably with soybean meal across most LCA scenarios. The key driver of this advantage is the bioconversion of pre-existing waste streams: BSFL diverts organic carbon from landfill or open composting where it would otherwise generate methane and nitrous oxide into protein-rich biomass and organic fertilizer from insect waste. Vermicomposting of organic substrates using *E. fetida* likewise produces markedly lower methane emissions than conventional composting (130–189 g CO_2eq kg^{-1} substrate dry matter versus 100–239 g CO_2eq kg^{-1} for standard composting) and substantially suppresses N_2O fluxes compared to unmanaged organic decomposition (Cao et al., 2021; Ren et al., 2018). The production of vermicompost as a co-product simultaneously reduces the demand for synthetic fertilisers on associated crop enterprises, generating an indirect emission credit that is rarely captured in narrowly scoped LCAs. Collectively, the carbon footprint profiles documented in Table 3 reinforce the designation of all four evaluated ingredients as genuinely climate-smart and provide a scientifically grounded foundation for their prioritisation within Kenya's aquaculture climate adaptation strategies.

The socio-demographic pattern of adoption documented here predominantly male farmers aged 36–60 years is congruent with the wider empirical literature on technology diffusion in Kenyan aquaculture (Obiero et al., 2019). Middle-aged farmers typically combine greater financial stability, established social networks, and accumulated farming experience with sufficient openness to innovation — attributes that collectively reduce the perceived and actual risk of adopting novel production practices. The systematic underrepresentation of women and younger farmers in the adopter profile, however, signals a structural inequity that warrants deliberate redress. Gender-responsive extension approaches and youth-targeted incentive schemes would need to be embedded within future programme cycles to ensure more equitable access to the productivity gains that climate-smart feeds demonstrably afford.

A. pinnata achieved the widest spatial coverage and the highest production volumes of any ingredient evaluated, an outcome explicable through its convergence of agronomic, economic, and social advantages. Its rapid surface colonisation of water bodies, tolerance of a broad range of environmental conditions, low input requirements, and demonstrated palatability to Nile tilapia at conventional inclusion rates render it particularly well-suited to smallholder contexts (Korsa et al., 2024; Das et al., 2018). The ease of technology transfer — farmers who master basic cultivation can rapidly mentor peers, as confirmed by extension observation — further amplifies its diffusion potential (Das et al., 2018). Nutritionally, *A. pinnata* provides a crude protein content of approximately 29%, inclusive of a complement of essential micro- and macroelements, enabling it to function as a meaningful partial fishmeal replacer within practical diet formulations (Mandal et al., 2010; Opiyo et al., 2024). The 32% improvement in fish production per cycle observed in this study is consistent with earlier controlled feeding trials and validates *A. pinnata* as a cost-effective supplement for smallholder ponds. Its value extends further into climate change mitigation: as a free-floating aquatic fern with an active nitrogen-fixing cyanobacterial symbiont, *A. pinnata* sequesters atmospheric CO_2 whilst simultaneously enriching the water column with fixed nitrogen, a dual ecological function rarely achievable with conventional feed inputs (Baviskar et al., 2023; Yohana et al., 2023).

Black soldier fly larvae emerged as the most impactful ingredient in terms of fish production per cycle, achieving a 50% yield increase when applied in concert with farm-made feeds, a finding that reflects the well-characterised nutritional superiority of BSFL meal. With crude protein concentrations commonly ranging between 40% and 55% on a dry matter basis, together with a favourable amino acid balance and lipid profile, BSFL is particularly effective at stimulating rapid somatic growth in omnivorous warm-water species such as Nile tilapia (*Oreochromis niloticus*) (Wachira et al., 2021; Limbu et al., 2022; Opiyo et al., 2023). Controlled dietary trials have demonstrated that BSFL meal can substitute fishmeal at inclusion levels of 50–75% without impairing feed conversion or final weight gain, in some cases producing superior economic returns through reduced feed costs (Wachira et al., 2021). The adoption dynamics of BSFL observed in this study also reflect a notable shift in farmer perceptions: where insect-based feeds were previously regarded with scepticism, concerted stakeholder engagement and demonstration activities under the ABDP have generated measurable attitudinal change (Ouko et al., 2022). From a circular economy standpoint, BSFL bioconversion of organic market and farm waste generates both protein-rich biomass and frass, a slow-release organic fertiliser while reducing greenhouse gas emissions by an estimated 5.09 kg CO_2eq per kg of final product relative to conventional waste disposal pathways (Pishgar-Komleh et al., 2022; Abro et al., 2020).

The more geographically restricted adoption of duckweed merits careful contextualisation. Although duckweed (principally *L. minor*) possesses one of the highest protein contents of any macrophyte, reaching 36.94% on a dry matter basis under optimal nutrient conditions (Naseem et al., 2021; Chakrabarti et al., 2018) its cultivation demands a degree of agronomic precision that may not be readily accessible to resource-constrained farmers. Maintaining productive duckweed cultures requires regular monitoring of water nutrient status and periodic fertiliser application, and generating quantities sufficient to constitute a meaningful dietary fraction necessitates cultivation ponds or tanks of commensurate area (Leng et al., 1995; Opiyo et al., 2023). These logistical constraints, compounded by relative unfamiliarity among farmers who were not previously exposed to aquatic plant culture, are likely to account for its confinement to six counties. Nonetheless, the 32.79% improvement in fish production observed where duckweed was adopted demonstrates its substantive nutritional contribution and justifies continued investment in simplified, modular cultivation systems adaptable to smallholder settings. Its additional capacity to improve the omega-3 long-chain polyunsaturated fatty acid (LC-PUFA) profile of farmed fish flesh and thereby enhance the nutritional value of the final product for consumers — represents a compelling quality benefit beyond basic growth performance (Opiyo et al., 2022; Sosa et al., 2024; Opiyo et al., 2024).

Earthworm (*E. fetida*) vermiculture occupied the lowest rung of adoption across virtually all dimensions assessed in this study. The barriers appear to be both technical and perceptual. Vermiculture, the controlled rearing of earthworms on organic substrates for biomass production is not an established agricultural practice in most Kenyan smallholder communities, and the processing steps required to convert live worms into a stable, dry feed ingredient remain poorly standardised at the farm level (Musyoka et al., 2019).The physicochemical properties of earthworm-rearing substrates, which must be maintained within narrow bounds of temperature, moisture, and pH to support optimal worm growth and nutritional quality, impose a management burden that exceeds the capacity of many farmers without dedicated infrastructure (Musyoka et al., 2019; Musyoka et al., 2020b). The presence of earthworm-derived anti-nutritional factors, whose biological significance in fish diets remains to be fully characterised, further tempers enthusiasm for wider inclusion. Despite this, earthworms retain substantial potential: reported fishmeal replacement values of 30–40% in *O. niloticus* diets, combined with the production of vermicompost as a high-quality organic soil amendment for integration into on-farm crop production, position earthworm farming as an attractive multipurpose circular enterprise where technical capacity can be adequately supported (Musyoka et al., 2020a; Chakrabarty et al., 2009).

Conclusions

This study offers substantive empirical evidence that climate-smart aquafeed ingredients particularly *A. pinnata* and BSFL are gaining meaningful traction among smallholder fish farmers in ABDP-implementing counties of rural Kenya, following structured capacity-building interventions. The integration of these ingredients into production systems yielded statistically significant improvements in fish biomass per cycle, with BSFL-supplemented regimes achieving the most striking gains (50.00 ± 6.10%). These outcomes affirm both the agronomic viability and the ecological rationale for substituting or supplementing conventional commercial feeds with locally producible, low-footprint alternatives.

The persistence of adoption barriers for duckweed and earthworm, however, underscores that biological potential alone is insufficient to drive technology uptake at scale. Contextual factors including production complexity, knowledge accessibility, infrastructure requirements, and socio-cultural attitudes exert equally determinative influence on adoption trajectories. Future programme design should therefore incorporate simplified, farmer-validated cultivation protocols, peer-to-peer learning mechanisms, and targeted support for women and youth to ensure that the benefits of climate-smart feeds are distributed equitably across the smallholder landscape.

At the systemic level, the expansion of climate-smart feed adoption in Kenya's aquaculture sector will require not only continued investment in farmer training and demonstration infrastructure, but also coherent policy frameworks that incentivise circular economy approaches to feed production, reduce the regulatory friction associated with novel feed ingredients, and align national aquaculture development agendas with both food security and climate adaptation imperatives. The present findings provide a multi-county empirical foundation upon which such frameworks can be constructed.

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Ethical Approval

This investigation constituted a survey-based study administered to consenting adult farmers within the framework of a government-supported agricultural development programme. No experimental interventions on human subjects or animals were performed. All participants provided informed verbal consent prior to interview, were assured of the confidentiality of their responses, and retained the right to withdraw from the study at any time without consequence. Formal institutional ethical approval was not required under applicable national guidelines for this category of participatory social survey.

Informed Consent

Informed verbal consent was obtained from each of the 297 participating farmers prior to data collection. Participation was voluntary throughout, and no identifying personal information was recorded or retained beyond that necessary for programme monitoring.

Conflicts of Interest

The authors declare that no competing financial interests or personal relationships exist that could have exerted any influence on the work reported in this paper.

Data Availability Statement

The datasets supporting the findings reported in this study are available upon reasonable request from the corresponding author. Unrestricted public dissemination of the raw data is precluded by the privacy commitments made to participating farmers and by conditions associated with the ABDP programme evaluation framework.

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Author Contributions

M.A.O.: Conceptualization, methodology, formal analysis, data curation, writing — original draft, review and editing. M.W., D.N., N.J., D.K., F.J.A., H.O., M.A., I.W., G.N., R.L., S.M.: Investigation, resources, project administration. R.A.: Supervision, funding acquisition, review and editing. All authors have read and approved the final version of this manuscript.

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