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Make it circular: an AKAIE model to evaluate the uptake of insect meal in aquaculture

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Abstract

Novel feed ingredients have emerged in response to the growing sustainability and circularity challenges facing aquaculture. Among these, insect meal derived from black soldier fly (*Hermetia illucens*) has attracted increasing attention for its potential to support circular production models. However, the adoption of such innovations remains limited, and existing studies often overlook how adoption evolves beyond the initial uptake.

In this context, the present study applies the AKAIE framework—Awareness, Knowledge, Adoption, Implementation, and Effectiveness—to examine the adoption process of *Hermetia illucens* meal among 28 Italian trout farmers. The analysis reveals dynamics often neglected in adoption studies by identifying four farmer profiles: Non-adopters, Experimenters, Partial Adopters, and Advanced Adopters. Results indicate that farmers perceive insect meal as an incremental innovation requiring minimal adjustments to existing practices, although high feed costs and limited consumer acceptance persist as major barriers. Environmental benefits are the most widely recognized, while economic and social advantages appear less evident.

By integrating the post-adoption dimension, this research aims to advance the understanding of innovation diffusion in aquaculture. The AKAIE framework could represent a practical tool for policymakers seeking to monitor the diffusion of circular feed innovations and the factors influencing their implementation under the European sustainability agenda.

Keywords: Circular economy, Innovation, Aquaculture, Insect meal, *Hermetia illucens*, Trout farming

Introduction

The pillars of the European Green Deal, including the Farm to Fork (F2F) Strategy, the Biodiversity Strategy, and the Circular Economy Action Plan, call for major regulatory efforts to make agri-food systems more resilient, sustainable, and circular in line with the 2030 Agenda (COM, 2019; Puskarski and Sniadach, 2022). This policy direction is reinforced by the European Commission's communication "*Strategic orientations for a more sustainable and competitive European aquaculture for the period 2021–2030*" (COM, 2021a) and by the European Maritime, Fisheries and Aquaculture Fund (EMFAF) 2021–2027, which dedicates Priority 2 to promoting sustainable aquaculture.

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At the core of these policy frameworks lies the transfer of knowledge and innovation, seen as key drivers of the blue transition. In this regard, aquaculture research has introduced a plethora of innovative practices (IPs) and technologies (ITs) (Joffre et al. 2017; Asche and Smith, 2018; Kumar et al. 2019; Lebel et al. 2021) spanning several domains, including breeding and genetics (Sciuto et al. 2022), biosecurity and disease management (Pepi and Focardi, 2021; Bondad-Reantaso et al. 2023), sustainable management (Pietrelli, 2022; Costigan et al. 2022; Scroggins et al. 2022; Arantzamendi et al. 2023; Zilia et al. 2023), and nutrition and feeding (Mulazzani et al. 2021; Busti et al. 2024).

New feed ingredients are increasingly attracting the scientific community's interest, as reported in the reviews of Yue and Shen (2022) and Sogari et al. (2023). Specifically, in the last decade, different authors (e.g., Henry et al. 2015; Varelas et al. 2019; Maulu et al. 2022; Biteau et al. 2024) reviewed the significant importance of the introduction of insect meal (IM) into farmed fish diets, evaluating their potential role in enhancing circularity and sustainability of the aquaculture sector. Research on IM in aquaculture reveals both well-established findings and still unresolved or controversial areas. Among the well-established findings, robust evidence confirms the positive effects of IM on fish-related parameters and multiple dimensions of sustainability. Some recent reviews (e.g., Tran et al. 2022, 2025; Hua et al. 2021; Raghuvaran et al. 2024) reported encouraging results related to the effects on animal nutrition, health, and performance. Insects are inherently part of the wild fish diet, and their amino acid profile composition is comparable to fishmeal (Gasco et al. 2020; Busti et al. 2024). Case studies investigating the inclusion of IM in aquafeeds further support these results, reporting positive outcomes on fish health (Bruni et al. 2020; Alfiko et al. 2022), growth performance, and filet quality (Caimi et al. 2020; Chemello et al. 2020).

The review also highlights benefits extending beyond the animal level, emphasizing how insect rearing for food and feed can contribute to the United Nations Sustainable Development Goals (SDGs) (Vala et al. 2024). Insect farming shows strong potential for advancing SDG 1 (No Poverty) and SDG 2 (Zero Hunger) by creating new food production opportunities and a low-resource industry accessible to low-income communities (Madau et al. 2020). Given the minimal input requirements and high reproductive capacity, insects can be bred efficiently at scale without extensive facilities, making large-scale production both feasible and sustainable (Tschirner and Kloas, 2017; Smetana, 2021; Hameed et al. 2022). Consequently, insect farming may contribute to poverty alleviation by reducing hunger, generating local employment, and enhancing food security in rural areas (Barragan-Fonseca et al. 2022). Although further research is needed to fully assess its environmental footprint (Smetana et al. 2021), insect farming can also enhance circularity (Cadinu et al. 2020; Cammack et al. 2021; Masi et al. 2024a) by transforming food industry by-products into sustainable protein sources for animal feed (Jensen et al. 2021). It may also advance SDG 6 (Clean Water and Sanitation) (Schroeder et al. 2019) and SDG 13 (Climate Action) (Dicke, 2018) by promoting resource-efficient food systems with low environmental impact (Ojha et al. 2020). With limited land and water requirements, insect production contributes to preserving natural resources. Moreover, as an alternative to fishmeal and soy-based feeds (Madau et al. 2020), insect-based feeds can support SDG 14 (Life Below Water) and SDG 15 (Life on Land), helping to preserve marine biodiversity and reduce land conversion pressures (Naylor et al. 2009; Ismat and

Hussain, 2025). Additionally, the IM sector can foster SDG 8 (Decent Work and Economic Growth) and SDG 5 (Gender Equality) by creating new employment opportunities and reducing social inequalities, especially in regions with limited access to land (Laar et al. 2017; Dangles and Casas, 2019). Overall, insect farming emerges as an inclusive and innovative business (Chia et al. 2019), capable of promoting more sustainable consumption and production patterns, thereby contributing to SDG 12 (Responsible Consumption and Production) (Dicke, 2018).

The literature collectively highlights the potential of insects as a valuable raw material that benefits fish, society, and the environment. However, several controversial aspects remain. Among them, the social acceptability of IM as aquafeed is one of the most debated issue, involving both supply and demand sides (Rumpold, 2021; Sogari et al. 2023; Glencross et al. 2025). On the demand perspective, empirical studies on European consumers generally show positive (Giotis and Drichoutis et al. 2021) or neutral attitudes toward indirect entomophagy, as feed origin appears less relevant than production methods or the product's origin (Ankamah-Yeboah et al. 2018). Factors most influencing acceptability include knowledge and familiarity with the practice (Roccatello et al. 2024), food neophobia (Bazoche and Poret, 2021), and product-related attributes such as appearance, nutritional quality, and hygiene standards (Llagostera et al. 2019). Moreover, several studies (e.g., Arru et al. 2022; Ribeiro et al. 2022; Dolfi et al. 2025) emphasize consumers' high price sensitivity, suggesting that a favorable attitude toward insect-based feeds does not necessarily translate into a willingness to pay for fish fed with them (Popoff et al. 2017). On the production side, high initial investment costs continue to represent a significant barrier (Arru et al. 2019; Rumbos et al. 2021), mainly reflecting the immaturity of the IM sector in Europe (Casartelli et al. 2020; Busti et al. 2024). Although research in this field has expanded rapidly, the use of IM in aquafeeds was only authorized in the EU in 2017 and further extended in 2021 (COM, 2017; COM, 2021b). Consequently, limited knowledge about the profitability of insect farming (Niyonsaba et al. 2021), together with regulatory and technological constraints and the still small number of European companies producing IM, continues to hinder large-scale expansion (Vandeweyer et al. 2021; Van Huis et al. 2021).

Set against this complex background, traditional theories of innovation adoption, such as the Theory of Planned Behavior and the Technology Acceptance Model, have been widely applied to analyze the farmers' willingness to introduce new feed ingredients in fish diet (Brugere et al. 2021; Ouko et al. 2022). However, these approaches generally treat the adoption stage as the endpoint of the process. The present study argues that interpreting "adoption" as a final decision offers only a partial understanding of innovation dynamics. Indeed, in the post-adoption phase, farmers may continue to innovate, partially embrace, or even abandon the IP. As noted by Rogers (1983, p. 184), "*the decision to adopt or reject is often not the terminal stage in the innovation-decision process.*" Therefore, the present study seeks to address this gap through the lens of the of Awareness, Knowledge, Adoption, Implementation, and Effectiveness (AKAIE) theoretical sequence (Vecchio et al. 2023). Specifically, it aims to examine the introduction of Black Soldier Fly Meal (BSFM) as a raw material for aquafeeds in Italian trout farming across the 5-phase sequence.

Material and methods

Given the notable heterogeneity of the aquaculture sector and the implications of using different IMs, this study focuses on the introduction of BSFM in Italian trout farming. Trout production was selected as a case study since it represents the leading farmed fin-fish segment in Italy, accounting for around 35,000 tons annually, approximately 26% of total national aquaculture output, and over 50% of freshwater production (Eurostat, 2023). In this sector, feed costs constitute the most significant component of operating expenses in trout farms, representing around the 50% of total production costs in 2022 (STECF, 2024), making feed innovation a critical lever for competitiveness and sustainability. From here, the study therefore investigates the introduction of BSFM, which has been extensively tested in aquaculture, particularly in rainbow trout (*Oncorhynchus mykiss*) (Mulazzani et al. 2021). Different Italian case studies have demonstrated promising results, showing that partial replacement of fishmeal with BSFM can sustain growth performance and improve feed conversion efficiency (Bruni et al. 2020; Caimi et al. 2021; Rimoldi et al. 2021). Indeed, the species *Hermetia illucens* is considered one of the most promising sources of insect protein due to its favorable environmental profile, low breeding requirements, and high adaptability to cost-effective substrates (Mancini et al. 2018; Cappellozza et al. 2019; Gasco et al. 2020; Rossi et al. 2023).

Material

A questionnaire was administered via a Computer-Assisted Web Interviewing (CAWI) tool to a sample of trout farmers in Italy. The questionnaire included a part related to the aquaculture farm's internal and external contextual factors, and then specific questions investigating each phase of the AKAIE sequence, from awareness to the post-adoption phase, including perceived or actual benefits obtained from the introduction of BSFM.

All responses to the poll were voluntary, and informed consent was required before participation. The survey was administered between September 1st and November 15th, 2023, and approximately 60 trout farmers were invited to participate through producers' associations and existing networks within the Italian aquaculture sector. A convenience sampling approach was adopted. At the end the sample consisted of 34 farmers, of whom 28 provided complete and valid questionnaires for analysis.

AKAIE model

The proposed model provides a structured approach to identify factors influencing the introduction of BSFM into the diet of Italian-farmed trout. The model offers the opportunity to assess the farm's position in the IP adoption process through a 5-phase sequence (Fig. 1).

In the initial phase, the farmer becomes aware of the existence of the IP (A—awareness). As interest increases, the farmer would be willing to acquire more information (K—knowledge). At this point, the farmer can introduce the new practice, in this case BSFM, for the first time (A—adoption). Later, based on the individual's perception of the practice, the farmer may commit to a higher level of adoption than just the initial purchase (I—implementation). In the last stage (E—effectiveness), the farmer evaluates the benefits obtained from the IP, which depend heavily on the degree and timing of use.

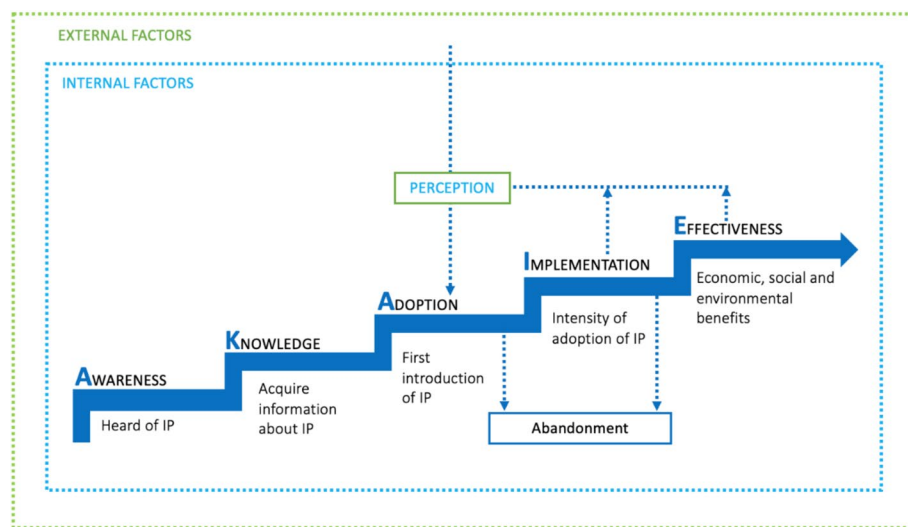


Fig.1 The AKAIE model. Figure adapted from Vecchio et al. (2023)

Given its ability to encompass the post-adoption phases, the AKAIE sequence is considered a general model that can be applied to study the adoption process of an IP or IT across different operational fields of aquaculture and for different species (Vecchio et al. 2023).

Survey design

The survey was divided into two parts. In the first section, the internal and external contextual variables of the farms (such as gender, age, level of education, economic size, farm growth, farm investments, etc.) were studied (Table 8—Appendix). In the second, the aspects related to farmers' perceptions, knowledge, and level of adoption of BSFM were investigated following the AKAIE sequence. For each stage, specific survey questions were developed to obtain a comprehensive picture of trout farmers' positions in the adoption process. Figure 2 shows an overview of the most relevant questions identified for the AKAIE sequence (Table 9—Appendix), which enabled first identifying eligible farmers (through the "awareness" filter question) and then the different levels of IM use: non-adopters, experimenters, partial adopters, and advanced adopters.

The identification of variables and survey items was grounded in established theoretical and empirical frameworks. Specifically:

- o The definition of the AKAIE stages applied to the aquaculture sector was derived from Vecchio et al. (2023), who have reviewed and implemented the previously tested AKAP model (Evenson, 1997). Then, the questionnaire was created, and questions were adapted to the aquaculture context from validated empirical analyses developed for the agricultural sector and structured around the AKAP/AKAIE sequence (Masi et al. 2022a; Masi et al. 2025).
- o The design of perception-related variables drew on existing frameworks in the agri-food domain, particularly the FACOPA model (Vecchio et al. 2022a), and was further

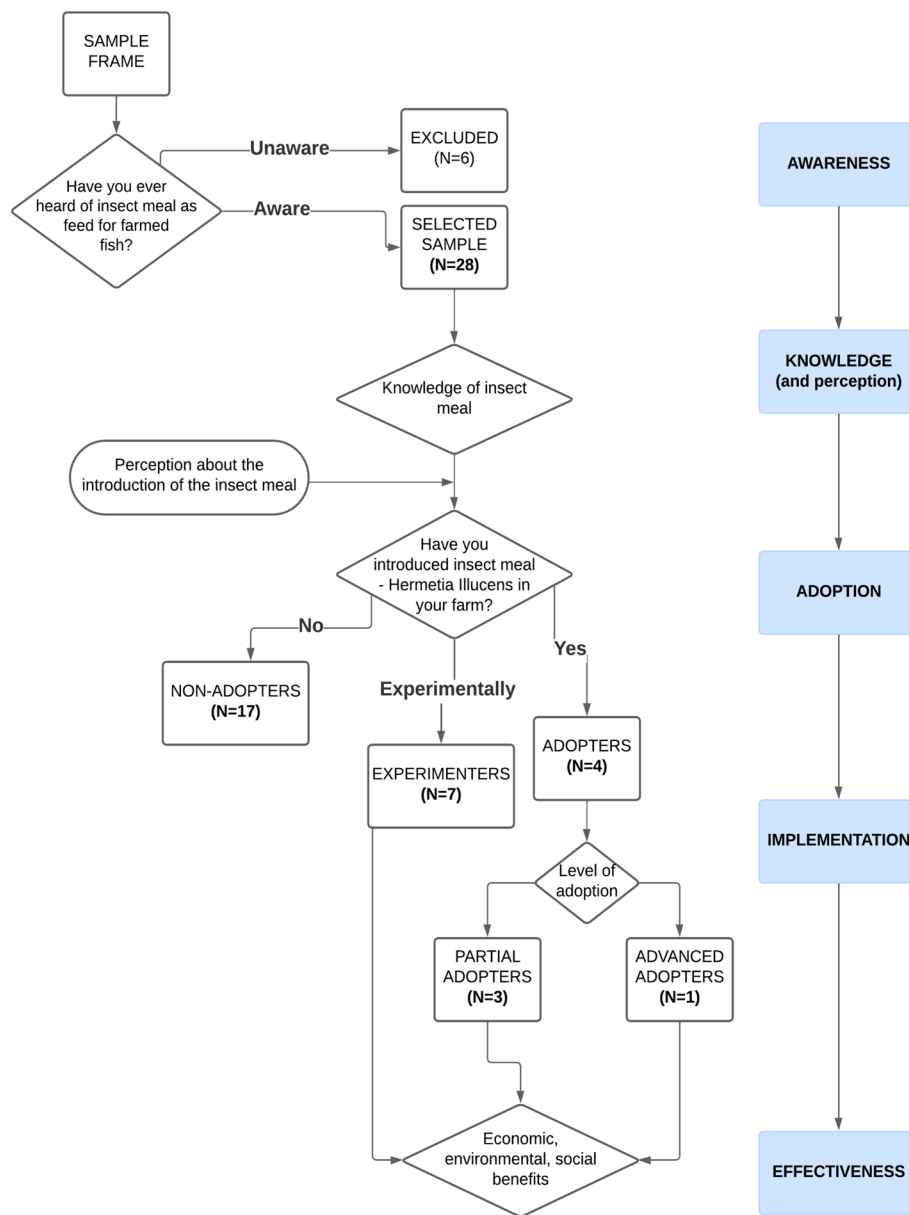


Fig. 2 Study framework for IM adoption

refined through a review of studies addressing the main barriers to IM adoption in aquafeeds.

This process enabled the identification of the most recurrent categories of perceived barriers influencing aquaculture feed innovation, namely: economic (e.g., high initial costs), institutional (e.g., lack of regulation, certification, or incentives), organizational (e.g., compatibility issues in farm management), and social (e.g., limited territorial diffusion and low consumer acceptance).

Since *Awareness* is identified with the farmer’s understanding of the existence of IP (Coleman et al. 1955; Masi et al. 2024b), it has been defined through the question:

“Have you ever heard of insect meal for feeding farmed fish?”. Participants who acknowledged their awareness of IM as aquafeed were deemed eligible to proceed with the questionnaire.

Knowledge is the understanding of facts, truths, and information obtained through direct experience and learning (Spender, 1996). Accordingly, the questions in this phase relate to knowledge of specific IM sources and the intensity of the information acquired from external sources. Within the AKAIE sequence, the type of knowledge considered is inherently subjective, consistent with previous definitions in the literature (e.g., Menozzi et al. 2023) and reflects respondents’ self-perceived understanding of the proposed innovation.

Before analyzing the adoption of IM, particular attention needs to be paid to studying farmers’ *perception*, which can be defined as a subjective mental process shaped by the socio-structural profile of the farm and the environment (internal and external factors) in which the innovation takes place (Markus and Kitayama, 2010; Reimer et al. 2012; Hoff and Stiglitz, 2016). Farmers’ perceptions were measured using different variables (Table 9—Appendix) and assessed on a Likert scale from 1 (strongly disagree) to 5 (strongly agree), highlighting the main barriers to IM introduction. In the final representation of results, values 1 and 2 were analyzed as “I do not agree,” 3 as “I have no definite opinion,” while 4 and 5 as “I agree.”

Adoption refers to the farmer’s decision to adopt a new idea, behavior, or practice (Damanpour and Gopalakrishnan, 2001). In this study, adoption represents the stage at which BSFM is introduced on the farm. Questions identifying this phase concerned whether the IP was introduced, the impact on production cost, and the price level.

Implementation refers to the farmer’s decision to increase the inclusion level of BSFM-based feeds in fish diets, extending their use to a larger share of production or, in some cases, adopting them across the entire farming cycle (Vecchio et al. 2023). The assessment of the degree of IP utilization, in terms of time of use and level of IP introduction on the farm, allows distinguishing a low level from an advanced state of adoption.

Effectiveness is the evaluation of the economic, environmental, and social benefits derived from introducing the new practice (Vecchio et al. 2023). It is assumed that farmers can evaluate the different advantages and disadvantages of IP adoption at various stages: If they experiment (“Experimenters”), at an initial level of adoption (“Partial adopters”), or at a more advanced stage (“Advanced Adopters”). Questions to assess this phase regard the benefits of introducing the proposed IP, including market acceptability.

Results

Description of farmers

Most trout farmers in the sample ($n=28$) were male (85.7%). The average age of respondents was 47, ranging from 27 to 76. The surveyed farmers who had completed high school education accounted for 42.9% of the sample. 46.4% of the companies reported an annual turnover of more than € 1,000,000. The target market of their products was mainly national (46.4%).

Furthermore, 46.4% of the companies reported economic growth over the last five years. Regarding investments in IPs and ITs, 39.3% of trout farmers stated that they

had invested in both in the previous five years, while 35.7% did not make any kind of investment. The EMFAF public funds covered a share of the assets, while internal resources funded the other. Lastly, around 35% of trout farmers belonged to a trade or producers' association.

Farmers were asked whether they had adopted or experimented with BSFM in trout diets. In this way, it was possible to distinguish *Adopters* (14.29%), *Experimenters* (25%), and *Non-adopters* (60.71%). Table 1 characterizes farmers' profiles based on internal and external factors.

AKAIE results

Awareness and knowledge

As shown in Fig. 3, all 28 farmers were aware of the existence of IM as aquafeed, while more than half (60.71%) did not know a specific IM and were not able to provide an example of it (Question B, Table 9—Appendix). Most farmers became aware through their participation in fairs/conferences/events (75%) and kept up to date on nutrition innovations for 1 to 4 h per month (67.86%). Table 2 reports the questions asked to investigate the “Awareness” and “Knowledge” phases for the identified groups of farmers.

Table 1 Questions to characterize the trout farmers

Variable (A)	Response categories
Gender	Male Female
Age	Respondent's age
Level of education	Until middle school or equivalent High school Bachelor's degree Master's degree and post-degree
Economic size (€)	Over 1,000,000 500,000 to 1,000,000 100,000 to 500,000 Less than 50,000
Target market	Regional National Other destination
Farm growth in the last 5 years	Growing economically Stable Economically downsized
Farm investments in the last 5 years	Innovative practices and technological innovations Innovative practice only Technological innovation only No investments
Institutional support—european maritime fisheries and aquaculture fund	Open-ended question
Group membership	Yes No
Share of feed costs in the annual budget	Open-ended question

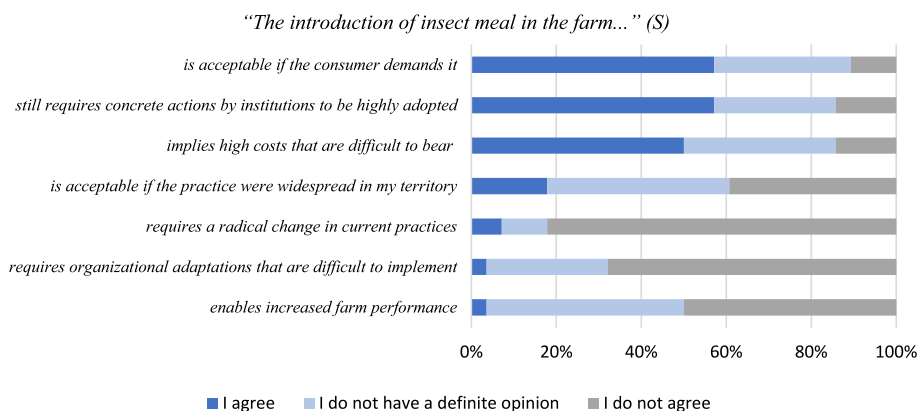


Fig. 3 Barriers to the introduction of BSFM in trout farming

Perception

The farmer’s perception is influenced by the context in which the innovation is transferred, which helps shape an attitude toward innovation, either positively or negatively, leading to adoption of the IP (Masi et al. 2022a). Looking at the overall sample (n=28) (Fig. 3), most farmers believed that the inclusion of insects in fish diets does not require radical changes to current routines (e.g., feeding practices, system cleaning) (82.1%) or major organizational adjustments (67.9%). However, greater uncertainty emerged regarding the actual performance of the practice and its diffusion across the territory. Furthermore, farmers indicated low consumer acceptance (57%), lack of institutional support, and high entry costs (50%) as the main barriers to the inclusion of IM in aquafeeds.

Table 3 reports farmers’ perceptions of IM adoption across the different groups, confirming the relevance of the barriers previously discussed.

Adoption

The results of the overall sample (n=28) show that a large proportion of trout farmers (78.57%) would be willing to integrate BSFM into their fish diet (Question F, Table 9—Appendix). Moreover, 14% of farms adopted this practice, while 25% experimented with the proposed IP (Question G, Table 9—Appendix). Respondents who introduced IM (experimenters and adopters) into trout diets reported a level of inclusion below 15% in the formulation. This finding confirms the literature (e.g., Liland et al. 2021), which indicates that inclusion levels above 20–25% may negatively affect production performance. In the overall sample, most farmers (82.14%) (Question H, Table 9—Appendix) considered the price of BSFM-based feed to be higher than that of current diets. However, this perception decreased among adopters (75%) and experimenters (71%) (Table 4). Furthermore, 71% of the overall sample believed that the BSFM has a more significant impact on production costs than the common diets (Question I, Table 9—Appendix), confirming the opinion of experimenters (71%). In comparison, adopters reported lower accordance (50%) (Table 4).

Among the positive aspects (Question J, Table 9—Appendix), the farmers highlighted improvements in growth performance and digestibility, as well as reduced environmental impact, following the adoption of BSFM. On the other hand, negative

Table 2 Questions related to the AKAIE sequence

Phase sequence	Question	Response categories
Awareness	Have you ever heard of insect meal for feeding farmed fish?(B)	Yes
		No
Knowledge	Do you know any specific insect meal?(C)	Yes
	How did you learn about insect meal?(D) (multiple answer)	no
		Other entrepreneurs
		Specialized journals
Producer groups		
Adoption	How much time do you spend informing and updating yourself on innovations in fish feed?(E)	Private consultants
		Trade associations
		Participation in trade fairs or conferences
		0 h/month
Adoption	Are you willing to introduce insect meal, in particular from black soldier fly larvae (<i>Hermetia illucens</i>) in your farm?(F)	Between 1 and 4 h/month
		Between 4 and 8 h/month
	Have you introduced* insect (<i>Hermetia illucens</i>) meal in your farm?(G)	Over 8 h/month
		Yes
	Based on your knowledge, what is the price level of introducing insect meal into fish feed?(H)	No
		Yes
		Only experimentally
	Based on your knowledge, how much does/ would the introduction of insect meal in fish feed affect the cost of production?(I)	No
Higher than the current feed price		
Same price as the feed currently used		
If you have introduced these meals, tell us briefly about the positive aspects of your experience (J)	Lower than the current feed price	
	Higher than the current feed price	
If you have introduced these meals, tell us briefly about the negative aspects of your experience (K)	Same price as the feed currently used	
	Lower than the current feed price	
Implementation	To which extent did you introduce insect meal (<i>Hermetia illucens</i>) in your production? (L)	Open-ended question
		Open-ended question
	How long have you introduced insect (<i>Hermetia illucens</i>) meal into your business?(M)	Only on certain groups of fish
		On all production
		Never
		Less than 1 year
		From 1 to 3 years
		From 4 to 6 years
		More than 6 years

Table 2 (continued)

Phase sequence	Question	Response categories
Effectiveness	What benefits do you think you gain or have gained from introducing insect meal in the fish diet? (N) (multiple answer)	Economic benefits
		Environmental benefits
		Social benefits
		None of the above
	What are the benefits in using insect (<i>Hermetia illucens</i>) meal in your view?(O)	Exclusively for the company
		Exclusively for the company's external environment
Perception	In your opinion, with the introduction of insect (<i>Hermetia illucens</i>) meal into fish diet, are the costs to be incurred outweighed by the expected benefits?(P)	Yes
		No
	In your opinion, would the consumer be willing to pay more for a fish raised on insect meal than for a more conventional diet?(Q)	Yes
		No
	In your opinion, how much more would the consumer be willing to pay for a fish product raised with insect meal?(R)	Up to 10% more
		Between 11 to 25%
		Between 26 to 50%
	Statement	Would not be willing to pay more
Perception	Response	Response
	The introduction of insect meal (<i>Hermetia illucens</i>) on the farm...(S)	–
	...enables increased farm performance	Likert scale from 1 to 5
	...requires organizational adaptations that are difficult to implement	Likert scale from 1 to 5
	...requires a radical change in current practices	Likert scale from 1 to 5
	...still requires concrete actions by institutions to be highly adopted	Likert scale from 1 to 5
	...implies high costs that are difficult to bear without a policy incentive	Likert scale from 1 to 5
	...is acceptable if the practice is widespread in my territory	Likert scale from 1 to 5
...is acceptable if the consumer demands it	Likert scale from 1 to 5	

aspects (Question K, Table 9—Appendix) mainly indicated regard to the exceptionally high price of IM feed, and, to a lesser extent, a particularly “*unpleasant odor*” and the “*need to clean the farming systems more frequently.*” During the analysis, two experimenters abandoned the BSFM for two reasons: the “*benefits do not compensate for the costs*” and that “*the consumer is unwilling to pay more.*”

Implementation

Looking at different levels of adoption, following Rogers (1983), two distinct groups could be identified (Table 5): *Partial adopters* (75%), who showed a lower and reduced level of BSFM use, and *Advanced adopters* (25%), who showed a more substantial and prolonged use.

Table 3 Profiling the farmer type

Variables (A)	Non-adopters (n = 17)	Experimenters (n = 7)	Adopters (n = 4)	Total sample
Gender	Male (88%)	Male (86%)	Male (100%)	Male (85.7%) Female (14.3%)
Farmer's age (mean years)	46 years	52 years	48 years	47 years
Level of education	High school (41.2%)	High school (42.9%)	Master's degree and post-degree (50%); High school (50%)	Until middle school or equivalent (7.1%); High school (42.9%); Bachelor's degree (14.3%); Master's degree and post-degree (35.7%);
Time spent on information	Between 1 and 4 h/month (59%)	Between 1 and 4 h/month (86%)	Between 1 and 4 h/month (50%); Over 8 h/month (50%)	0 h/month (14%); Between 1 and 4 h/month (68%); Between 4 and 8 h/month (7%); Over 8 h/month (11%)
Economic size (€)	Over 1,000,000 (41%); 100,000 to 500,000 (35%)	Over 500,000 (85%)	Less than 500,000 (75%)	Over 1,000,000 (46.4%); 500,000 to 1,000,000 (7.1%); 100,000 to 500,000 (32.1%); Less than 50,000 (10.7%)
Farm growth in the last 5 years	Growing economically (41%); Stable (41%)	Growing economically (71%)	Stable (50%)	Growing economically (46.4%); Stable (35.7%); Economically down-sized (17.9%)
Farm investments in the last 5 years	Neither innovative practice nor technological innovations (47%) Technological innovation only (18%)	Innovative practices and technological innovations (71%)	Innovative practices and technological innovations (50%); Innovative practice only (50%)	Innovative practices and technological innovations (39.3%); Innovative practice only (10.7%); Technological innovation only (14.3%); No investments (35.7%)
Target market	National (53%)	National (50%)	Regional (50%)	National (46.4%); Regional (32.1%); Other destination (21.5%)
Geographical area	North-east (47%)	North-east (43%) North-west (43%)	North-east (75%)	North-east (50%) North-west (25%) Central (14%) South and Islands (11%)
Institutional support—EMFAF	Yes (76%)	Yes (71%)	Yes (50%)	Yes (71%)
Group membership	Yes (29%)	Yes (71%)	Yes (25%)	Yes (35%)
Share of feed costs in the annual budget	Over 30% (76%)	Over 40% (43%)	Over 40% (75%)	Over 40% (70%)

Section A of the questionnaire is reported in Appendix

Table 4 Awareness and Knowledge variables of the identified groups of farmers

Variable	Response categories	Non-adopters (n = 17)	Experimenters (n = 7)	Adopters (n = 4)
Awareness of the existence of IM (B)	Yes	100%	100%	100%
	No	–	–	–
Knowledge of specific insect meal (C)	Yes	35%	43%	50%
	No	65%	57%	50%
Information sources* (D)	Other entrepreneurs	47%	14%	–
	Specialized journals	41%	14%	–
	Producer groups	12%	43%	25%
	Private consultants	18%	14%	–
	Trade associations	35%	29%	25%
	Participation in trade fairs or conferences	76%	71%	100%
Time spent on information (E)	0 h/month	18%	14%	–
	From 1 to 4 h/month	65%	86%	50%
	Between 4 and 8 h/month	12%	–	–
	Over 8 h/month	6%	–	50%

Sections C, D, and E of the questionnaire are reported in Appendix

* Multiple answer

Partial and advanced adopters can be represented by examining the internal and external factors in Table 6. Variables of the socio-demographic profile indicate internal factors. In contrast, external factors are characterized by the agroecological and institutional context, including information sources that influence the perception and the decision to adopt.

Effectiveness

Most farmers believed that the use of IM mainly benefits the environment. However, socio-economic benefits were also reported as BSFM use increased. Table 7 shows the detailed views of the experimenter and adopter groups.

Discussion

This study contributes to understanding the adoption of BSFM in Italian trout farming by examining the entire process through the AKAIE framework and the role of internal and external factors shaping their decisions. Although the small subgroup sizes limit generalizability, our findings provide descriptive insights that both align with and diverge from the IT literature, reflecting the distinctive nature of IP.

The analysis highlights that adoption dynamics are highly case-specific (Verbeke et al. 2015; Sebatta et al. 2018; Arru et al. 2019; Rumbos et al. 2021) and considerations may vary according to the type of innovation, the domain of study (e.g., nutrition), and the contextual conditions influencing farmers' behavior (Welter, 2011; Brugere, 2021; Mulazzani et al. 2021). Despite the small sample size, the study provides exploratory insights that highlight the main contextual conditions related to BSFM uptake, with a particular attention to post-adoption phases:

Table 5 Perception variables of the identified group of farmers

Statements "The introduction of insect meal in the farm..." (S)	Type Farm	Rating scale		
		I do not agree	I do not have a definite opinion	I agree
Enables increased farm performance	Adopters	25%	75%	–
	Experimenters	71.43%	28.57%	–
	Non-adopters	47.06%	47.06%	5.88%
Requires organizational adaptations that are difficult to implement	Adopters	100%	–	–
	Experimenters	57.14%	28.57%	14.29%
	Non-adopters	64.71%	35.29%	–
Requires a radical change in current practices	Adopters	100%	–	–
	Experimenters	57.14%	14.29%	28.57%
	Non-adopters	88.24%	11.76%	–
Still requires concrete actions by institutions to be highly adopted	Adopters	–	25%	75%
	Experimenters	28.57%	42.86%	28.57%
	Non-adopters	11.76%	23.53%	64.71%
Implies high costs that are difficult to bear	Adopters	25%	25%	50%
	Experimenters	14.29%	28.57%	57.14%
	Non-adopters	11.76%	41.18%	47.06%
Is acceptable if the practice were widespread in my territory	Adopters	25%	50%	25%
	Experimenters	71.43%	28.57%	–
	Non-adopters	29.41%	47.06%	23.53%
Is acceptable if the consumer demands it	Adopters	–	–	100%
	Experimenters	14.29%	28.57%	57.14%
	Non-adopters	11.76%	23.53%	64.71%

Section S of the questionnaire is reported in Appendix

Table 6 Adoption variables of the identified groups (Adopters and Experimenters)

Variable		Experimenters (n = 7)	Adopters (n = 4)
Price level (H)	No difference	29%	25%
	More than now	71%	75%
	Less than now	–	–
Impact on cost of production (I)	No difference	29%	25%
	More than now	71%	50%
	Less than now	–	25%

Sections I and J of the questionnaire are reported in Appendix

Table 7 Level of adoption

Groups identified	Introduction of BSFM in the trout diet (L)	Time of use in the farm (M)
Partial adopters	Only on certain groups of fish	Less than 1 year
Advanced adopter	On all production	More than 1 year

Sections L and M of the questionnaire are reported in Appendix

- 1) Internal factors
- 2) Regarding farmers' profiles, the adopters appeared generally more educated than experimenters and non-adopters, confirming previous evidence that higher educa-

tion is often associated with innovation uptake (Wetengere, 2011). No substantial age differences emerged between groups, which may be explained by the overall young age of the respondents. However, consistent with previous findings (e.g., Obiero et al. 2019), our results confirmed that advanced adopters of aquaculture innovations are generally younger than partial adopters. The case of a partial adopter nearing retirement (Farm 3) remains only partly interpretable, as his advanced age indicates that succession dynamics should be further investigated when assessing age-related effects (Bartoli and De Rosa, 2013).

- 3) Regarding the farm profile, it is noteworthy that the adopter category includes both large and small-to-medium-sized enterprises (SMEs). Black soldier fly meal could therefore represent an innovative solution capable of strengthening a production system composed mainly of SMEs (Vecchio et al. 2021, 2022b; Masi et al. 2025), for which the identification of accessible and easily implementable innovations remains crucial. The tendency of SMEs to adopt this innovation is also supported by Mulazzani et al. (2021), who observed that farms using very intensive and low-cost feeding systems can adopt IM only when they achieve highly competitive feed conversion ratios (FCR). Reflecting this potential risk, both experimenters who discontinued the IP were large companies with annual turnovers exceeding €1,000,000.
- 4) External factors
- 5) Regarding the agroecological context, the environmental parameters can significantly influence the decision to adopt an innovation (Robertson et al. 2012; Costa-Pierce et al. 2021; Cascante et al. 2022). Indeed, according to the results, the most advanced adopter came from Central Italy, while partial adopters from the North-east. Linked to this is the target market, which similarly may influence one behavior over another, as Rumbos et al. (2021) confirmed.
- 6) Furthermore, the institutional context plays an important role. Results indicate that adopting companies invested in both IPs and ITs, highlighting costs that are difficult to sustain without policy incentives. However, EMFAF support (Measure 2.48—Aid to aquaculture of a structural nature) seems less evident among advanced adopters, possibly reflecting a gradual shift toward greater reliance on private resources. Previous studies (e.g., Bostock et al. 2016; Blomquist and Waldo, 2022) have examined the role of public policies in supporting aquaculture investment activities. In light of this literature, some reasonable doubts may arise as to whether European aquaculture policy's function more as investment multipliers rather than as instruments capable of ensuring long-term economic sustainability.
- 7) As highlighted in the literature, innovation adoption also depends on relational assets that enable stable knowledge exchange (Doloreux et al. 2009). Our results showed that group membership could positively influence the first introduction of BSFM, represented in our sample by Experimenters, as also reported by Joffre et al. (2020). In later stages, however, it does not appear decisive for early or advanced adopters, consistent with Obiero et al. (2019). Information sources also play a crucial role in facilitating adoption (Joffre et al.; 2019). Trade fairs were the most frequently mentioned, likely serving as meeting points for stakeholders and as opportunities to gather information and advance adoption. Advanced adopters also relied on producer groups and trade associations. Overall, our findings suggest that IP adoption

may foster more balanced relational structures through ambidexterity (Cofré-Bravo et al. 2019).

Farmers also pointed out the actual and potential benefits of adopting BSFM. Positive environmental externalities were the most frequently mentioned, while only adopters partly recognized economic and social benefits. A considerable share of trout farmers, however, did not expect to gain advantages from the introduction of this innovation. According to respondents, potential economic benefits could derive mainly from consumers' willingness to pay and, to a lesser extent, from institutional support.

Regarding potential bottlenecks to BSFM adoption, several considerations could be drawn. From an organizational perspective, compatibility issues may arise (Lioutas and Charatsari, 2020; Rowan, 2023). However, trout farmers did not report significant changes in farm routines as barriers to adoption, as reflected in their high willingness to test BSFM (78.6%) and the relatively large share of experimenters (39%). Overall, IM can therefore be considered an incremental or semi-incremental innovation (Lamberti et al. 2011; Adamseged et al. 2022), essentially representing the refinement or extension of an existing technique.

From an investment and market perspective, all farmer categories identified high costs and low consumer acceptability as the most critical barriers to BSFM adoption, confirming findings by Rumbos et al. (2021) and Mulazzani et al. (2021). Feed expenses represent a major budget item for more than 30% of respondents; therefore, the higher price of IM compared to fishmeal constitutes a significant constraint to uptake (Kleih et al. 2013; Henry et al. 2015; Arru et al. 2019). Nonetheless, updated regulations and market analyses could improve scalability and cost efficiency (Fletcher et al. 2021; Rabobank, 2021; Van Huis et al. 2021; FAO, 2022), supporting the transition toward a circular agri-food system (Barragán-Fonseca et al. 2022). Consumer acceptance of IM-fed fish and circular consumption more broadly remains a "black box" (Rumbos et al. 2021; Yeter et al. 2025). Evidence suggests that awareness of the sustainability benefits of insect-based ingredients can increase acceptance of indirect entomophagy (Bazoche and Poret, 2021; Altman et al. 2022; Arru et al. 2022; Sogari et al. 2023) and, in some cases, willingness to pay (Llagostera et al. 2019). However, consumer trust in aquaculture products remains limited (Masi et al. 2022b), and knowledge of current and emerging practices, such as the use of IM in aquafeeds, is still low (Popoff et al. 2017).

Conclusions

Given the ambitious SDGs, the challenges outlined by European Strategies, and the European Maritime, Fisheries and Aquaculture Fund Programme for Italy, models capable of systematically analyzing the innovation process are increasingly needed. In this regard, the application of the AKAIE model constitutes the main contribution of this study, offering a comprehensive framework for assessing innovation diffusion in

aquaculture that covers not only phases up to adoption but also the post-adoption one. Monitoring the progression of IPs and ITs along these stages can help policymakers understand how innovations spread, which barriers emerge, and what factors influence implementation. Nonetheless, our results confirm that adopting and implementing IPs is a complex, multistage process shaped by several interacting variables.

The study presents some limitations. Although the surveyed farms accounted for about 20% of Italian trout producers in 2022 (STECF, 2024), the results are exploratory and cannot be generalized. A more detailed characterization of farms, considering production systems, growth performance, processing activities, and marketing strategies, would have provided a deeper understanding of the results. Moreover, perceptions of sectoral prospects can significantly affect innovation behavior. These aspects require further investigation and will be explored in future research.

Finally, the use of a CAWI survey may have inadvertently excluded farms with limited digital engagement. However, there is no clear evidence that less innovative farms were systematically under-represented.

Despite these limitations, the study demonstrates the usefulness of the AKAIE framework as a tool to capture the multistage dynamics of innovation adoption and implementation in aquaculture. This case study helps fill a gap in the literature by excavating the “ex-post” mechanisms of innovation uptake in circular economy transitions. The high presence of planners and experimenters in the sample suggests that BSFM, being incremental, may be favorably received by Italian trout farmers. Beyond the high entry costs, the results highlight a practice potentially compatible with less structured enterprises. Introducing protein alternatives into feed can be viewed as a low-risk investment, since, unlike technological investments, it does not require capitalization and offers immediate feedback on its benefits. Appropriate marketing strategies could help offset initial costs and enhance social acceptability, for instance, through niche-market positioning for small firms or private-label approaches for larger ones.

Future research should aim to provide a more comprehensive understanding of stakeholder perceptions of future outlook, operating contexts, and market structures, alongside forthcoming regulatory and policy interventions. Such insights will be essential to support local innovation transfer and promote effective, circular, and sustainable management in aquaculture.

Appendix 1: Sections of the questionnaire

See Tables (8 and 9)

Table 8 Partial and advanced adopters' profiles

	Variable	Partial adopters			Advanced adopter
		Farm 1	Farm 2	Farm 3	farm 4
Internal factors	Gender	Male	Male	Male	Male
	Age	44 years	44 years	76 years	28 years
	Level of education	Master's degree and post-degree	High school	High school	Master's degree and post-degree
	Time spent on information	Over 8 h/month	1–4 h/month	1–4 h/month	Over 8 h/month
	Economic size	Over € 1,000,000	€ 100,000 to € 500,000	Less than € 50,000	€ 100,000 to € 500,000
	Company growth in the last 5 years	No	No	Yes	Yes
	Investments in the last 5 years	Innovative practices and technological innovations	Innovative practice only	Innovative practice only	Innovative practices and technological innovations
External factors	Target market	Extra-EU	Regional	Regional	National
	Geographical area	North-East	North-East	North-East	Center
	Institutional support—EMFAF	Yes	Yes	No	No
	Information sources*	Participation in trade fairs or conferences	Participation in trade fairs or conferences	Participation in trade fairs or conferences	Participation in trade fairs or conferences, producers' groups, trade associations
	Group membership	No	No	No	No

* Multiple answer

Table 9 Effectiveness of identified groups

Variable	Type of farmer		
	Experimenters who decided to abandon the practice (n = 2)	Experimenters (n = 7)	Adopters (n = 4)
Benefits(N)*	Environmental (100%)	Environmental (86%) No benefit (14%)	Environmental (75%); Economic (50%); Social (25%); No benefit (25%)
Type of benefits (O)	Both for the farm and the external environment (50%)	Both for the farm and the external environment (71%);	Both for the farm and the external environment (75%);
	Exclusively for the external environment (e.g., territory, environment, society, etc.) (50%)	Exclusively for the external environment (e.g., territory, environment, society, etc.) (29%)	Exclusively for the external environment (e.g., territory, environment, society, etc.) (25%)
Offsetting costs against expected benefits (P)	No (100%)	Yes (71%); No (29%)	Yes (75%); No (25%)
Consumer's willingness to pay (Q)	No (100%)	Yes (14%); No (86%)	Yes (75%); No (25%)
In your opinion, how much more would the consumer be willing to pay for a fish product raised with insect meal? (R)	Would not be willing to pay more (100%)	Up to 10% more (14.29%) Would not be willing to pay more (85%)	Up to 10% more (50%) Between 11 to 25% (25%) Would not be willing to pay more (25%)

Sections N, O, P, Q, and R of the questionnaire are reported in Appendix

* Multiple answer

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Author contributions

Y.V. Conceptualization; data curation; formal analysis; investigation; methodology; validation, visualization; software; writing—original draft preparation; writing—review and editing. E.S.M. Data curation; methodology; software; writing—review and editing. M.M. Conceptualization; data curation; formal analysis; investigation; software; methodology; validation, visualization; writing—original draft preparation; writing—review and editing. F.A. Validation, supervision. M.D.R. Conceptualization; data curation; formal analysis; investigation; methodology; validation, visualization; writing—original draft preparation; writing—review and editing.

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Data availability

The data was collected anonymously via a Computer-Assisted Web Interviewing tool. The data generated and analyzed during this study are available from the corresponding author on reasonable request.

Declarations

Ethical approval

Prior to participation, all participants were informed of the purpose of the study, the voluntary nature of their participation, and their right to withdraw at any time without penalty. Explicit informed consent was obtained from participants before the surveys were administered.

Competing interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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