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By Hadfield, B., Clunie, B.J., Pope, T.W. and Roberts, J.M.

DOI link to the version of record on the publisher's site

Hadfield, B., Clunie, B. J., Pope, T. W., and Roberts, J. M. (2026) 'Industry perceptions of biological control in food manufacturing environments: A qualitative analysis of barriers and opportunities', *Annals of Applied Biology*, 189(2), article number e70155.

Received: 2 February 2026 | Revised: 27 July 2026 | Accepted: 18 August 2026

DOI: 10.1111/aab.70155

ORIGINAL ARTICLE

Annals of Applied Biology
An international journal of the aab

WILEY

Industry perceptions of biological control in food manufacturing environments: A qualitative analysis of barriers and opportunities

Bethany Hadfield | Ben J. Clunie | Tom W. Pope | Joe M. Roberts

Applied Entomology Group, Centre for Crop and Environmental Science, Harper Adams University, Newport, UK

Correspondence
Joe M. Roberts, Applied Entomology Group, Centre for Crop and Environmental Science, Harper Adams University, Newport, Shropshire, TF10 8NB, UK.
Email: jroberts@harper-adams.ac.uk

Abstract

Progressive withdrawal of synthetic chemical insecticides and evidence of resistance in important pest species have led to increased interest in biological control within food manufacturing environments. However, the acceptability of these approaches to industry remains largely unknown. We conducted an exploratory qualitative study comprising semi-structured interviews with 17 food manufacturing professionals associated with 15 focal facility contexts in northwest England and north Wales (UK). Sentiment analysis was used descriptively to characterise attitudinal valence, while reflexive thematic analysis examined conditional acceptability, perceived barriers and potential routes to implementation. Sentiment analysis classified 40.7% of participant utterances as positive, 40.3% as neutral and 19.0% as negative. Participant accounts showed that willingness to consider any of the approaches was usually conditional on locations, controls or approvals. Five principal barriers were identified: (1) food safety and quality concerns, (2) retailer requirements, (3) health and safety considerations, (4) resistance to novel approaches and (5) negative connotations associated with biological terminology. Participants identified controlled trials, formal risk assessment, stakeholder education and evidence of efficacy and cost-effectiveness as potential facilitators. These findings do not estimate the prevalence of these views across the wider food manufacturing sector. Rather, they provide exploratory evidence that some experienced UK professionals would consider biological control when supported by appropriate authorisation, operational evidence, contamination controls and engagement with retailers and relevant assurance stakeholders.

KEYWORDS

biological control, food safety, integrated pest management, stakeholder attitudes, stored-product insects

1 | INTRODUCTION

Pest management in food manufacturing presents a practical tension because the environments most in need of effective insect control may also be the least amenable to intervention. Stored-product insects such as the Mediterranean flour moth (*Ephestia kuehniella* Zeller (Lepidoptera: Pyralidae)), Indian meal moth (*Plodia interpunctella* Hübner (Lepidoptera: Pyralidae)), and biscuit beetle (*Stegobium paniceum* (L.) (Coleoptera: Ptinidae)) can cause economic losses through contamination and product rejection (Hagstrum & Phillips, 2017). German cockroaches (*Blattella germanica* L. (Blattodea: Ectobiidae)) compound these challenges as they can carry pathogenic bacteria and may precipitate costly corrective action when detected (Tang et al., 2019). Warmth, humidity, harbourage and continuous product flow can support pest activity while food-safety requirements constrain the interventions available. Methyl bromide was phased out for most controlled uses under the Montreal Protocol, and replacement fumigants may require exposure periods that disrupt production (Hagstrum & Phillips, 2017). The withdrawal or restriction of several insecticide classes such as organochlorines and organophosphates has further narrowed chemical options (Arthur, 2012). Pyrethroids remain among the residual insecticides evaluated for stored-product insects (Scheff et al., 2026), and gel baits containing active ingredients such as indoxacarb or clothianidin are used against German cockroaches (Davari et al., 2018; Konkala & Narra, 2024). However, insecticide resistance is well documented in German cockroaches (Fardisi et al., 2019), and behavioural resistance such as glucose aversion may further erode the efficacy of some bait formulations (Wada-Katsumata & Schal, 2024).

Against this background, biological control has attracted attention as a complementary pest management option. Entomopathogenic fungi, such as *Metarhizium anisopliae* (Metschnikoff) Sorokin (Hypocreales: Clavicipitaceae) and *Beauveria bassiana* (Bals.-Criv.) Vuill. (Hypocreales: Cordycipitaceae), infect through the insect cuticle (Mannino et al., 2019) and laboratory studies report activity against German cockroaches and stored-product moth larvae (Ashbrook et al., 2022; Bahmani et al., 2020; Zhang et al., 2018). *Bacillus thuringiensis* Berliner (Bacillales: Bacillaceae) produces insecticidal crystal proteins that act after ingestion by susceptible larvae (Zhang et al., 2017), and strains active against *E. kuehniella* and *P. interpunctella* have been reported (Abdelmalek et al., 2016). Products containing *B. thuringiensis* are authorised for some insect control uses in the United Kingdom, although authorisation is product- and use-specific (Health and Safety Executive, 2025). Parasitoids such as *Lariophagus distinguendus* Förster (Hymenoptera: Pteromalidae), an ectoparasitoid of coleopteran larvae and pupae, have been used against *S. paniceum* in museum collections (Querner et al., 2019), while *Trichogramma* species are widely studied against lepidopteran pests (Basana Gowda et al., 2021; Parra et al., 2022; Razinger et al., 2016; Zang et al., 2021). Evidence from agricultural or heritage settings does not, however, establish acceptability or operational suitability in food manufacturing.

Despite a growing evidence base for biological control efficacy against pests, a critical knowledge gap impedes translation to food manufacturing because little is known about whether industry would accept such approaches over conventional synthetic chemical pesticide applications. Food manufacturing operates within a complex web of regulatory requirements, retailer specifications and audit standards that collectively shape pest management decisions. In the United Kingdom, this is strongly influenced by the BRCGS Global Standard Food Safety. Section 4.14 of Issue 9 addresses preventive pest management, competent provision, documented inspection and treatment, action when infestation is identified, and protection of products, raw materials and packaging from contamination. Inspection arrangements are risk-based, and control measures must comply with applicable legislation (BRCGS, 2022). The associated Best Practice Guideline on Pest Management describes an integrated framework for prevention, detection, monitoring and eradication, including collaboration between trained site personnel and competent pest management organisations while retaining responsibility with the manufacturing site (BRCGS, 2025). A novel biological approach would therefore need to be incorporated into the site's documented pest management programme, authorised for the intended use and supported by evidence of efficacy and acceptable microbiological, physical and chemical contamination risk.

Technical, quality assurance, hygiene and operations personnel navigate competing demands (e.g., effective pest control, food safety compliance, production continuity and cost management) in ways that laboratory efficacy data cannot reliably predict. Comparable work has examined why food manufacturers adopt or resist other novel interventions, identifying validation requirements, operational constraints, cost and customer acceptance as recurrent barriers (Chen et al., 2024), but we are not aware of published research examining food industry perceptions of biological control, leaving a fundamental question unanswered: even if biological control agents work under controlled conditions, will the industry permit their use? This study addresses that gap through qualitative investigation of food manufacturing professionals' attitudes towards biological control. We employed semi-structured interviews to explore three central questions: (1) which biological control methods, if any, might industry professionals consider acceptable; (2) what barriers would impede adoption; and (3) what conditions or processes might facilitate implementation.

2 | MATERIALS AND METHODS

2.1 | Ethical approval and informed consent

This study received ethical approval from the Harper Adams University Research Ethics Committee (application no.: 0428-202407-PGMSC). Participants received information about the study and provided informed consent to take part and to audio record. Names, organisations and location details arose in some source recordings and transcripts and were therefore treated as identifiable research data. Participants were assigned identifiers P1 to P17, and direct identifiers and precise facility details were removed from quotations and summaries reported.

2.2 | Study design and rationale

A qualitative approach using semi-structured interviews was selected for this exploratory research for three reasons. First, interviews permitted real-time explanation of biological control concepts to participants unfamiliar with these methods, ensuring informed responses rather than reactions to misunderstood premises. Second, the semi-structured format allowed systematic coverage of predetermined topics while enabling pursuit of unanticipated themes as they emerged, which was valuable when investigating an unexplored domain where relevant concerns cannot be fully anticipated. Third, interviews facilitated exploration of reasoning underlying stated positions, moving beyond binary acceptance/rejection to understand the conditions, caveats and concerns shaping attitudes (Adeoye-Olatunde & Olenik, 2021). The first author works professionally in pest management and had prior professional contact with some members of the recruitment network. Two participants were approached by a colleague on the first author's behalf, and one was reached through a personal contact. This position facilitated access and shared technical understanding but may also have shaped how participants framed their responses. The potential influence of this position is considered in the interpretation and limitations.

2.3 | Participant recruitment and characteristics

Participants were recruited through convenience sampling between March and June 2025. Potential participants were approached directly in person, by email or through LinkedIn, principally using the first author's professional networks. Two participants were approached by a colleague on behalf of the research team and one was identified through a personal contact. Twenty-three individuals were approached. Seventeen participated, five declined or did not respond, and one agreed to participate but did not attend the scheduled interview to give a response rate of 74%.

Eligibility criteria were not prospectively documented. In practice, participants were required to work in food manufacturing and to have knowledge of, or involvement in, their facility's pest management arrangements. The sample comprised 17 participants associated with 15 focal facility contexts in northwest England and north Wales (Table 1). P1 and P7 described the same facility, as did P4 and P14, although the members of each pair held different roles or remits. P2 and P13, and P12 and P16, respectively, worked for the same parent companies but at different facilities; P2, P7, and P8 held multi-site roles. Participants were predominantly male ($n = 11$, 65%) and reported food-industry experience ranged from 8 years to more than 30 years. Roles comprised Technical ($n = 6$), Quality Assurance ($n = 5$), Hygiene Management ($n = 4$), and Operations ($n = 2$). Participants referred principally to BRCGS, while SALSA and FSSC 22000 were also represented, and retailer-specific standards were frequently discussed.

The final sample size was determined partly by access to this specialised professional population and the exploratory scope of the study. Its adequacy was subsequently considered using the principle of information power, under which sample sufficiency depends on the specificity of the research aim, relevance and experience of participants, quality of the interview dialogue and depth of analysis rather than on a numerical threshold alone (Malterud et al., 2016). The study addressed a focused question, participants had direct knowledge of or involvement in food-manufacturing pest management, and the interviews generated detailed accounts. The first author's assessment was that later interviews did not generate substantively new themes but no prospective saturation threshold or stopping rule was specified. The sample therefore supports exploratory thematic interpretation rather than representative estimation of attitudes across the food manufacturing sector.

2.4 | Interview procedure and materials

Interviews were conducted individually, either face-to-face at participants' workplaces or through Microsoft Teams according to participant preference. The interview guide covered: (1) participant background and existing pest management practices; (2) knowledge and previous experience of biological control; (3) responses to entomopathogenic fungi, *B. thuringiensis* and parasitoid wasps; and (4) perceived barriers and facilitators. The guide was pilot tested with three food manufacturing professionals who were not among the 17 study participants and whose roles did not involve pest management decisions. Pilot data were not included in the analysis. The pilot indicated that participants required explicit clarification that the biological controls were being considered as responses to active infestations rather than as routine prophylactic introductions.

A common set of core concepts was covered, but the wording and examples varied within the semi-structured format. Entomopathogenic fungi were generally described as formulated sprays applied in a manner analogous to a conventional insecticide treatment, with locust control used as an example and infection through the insect cuticle explained. *Bacillus thuringiensis* was described as a bacterium whose action prevents susceptible larvae from completing development and does not provide immediate knockdown of adults. Parasitoids were explained using beetle or moth pests, with the target stage described as an egg or immature stage depending on the example. The same reference photographs, which indicated organism size, were shown to all participants.

Depending on the participant and the developing discussion, examples and prompts referred to warehouses, racking, production areas, plant rooms or segregated spaces. Some participants themselves proposed restrictions such as production shutdown, product removal or subsequent cleaning; when food-safety concerns arose, the interviewer sometimes probed possible use in non-open-product areas. Location-specific caveats therefore arose through a combination of

TABLE 1 Reported facility and operational contexts represented in the interviews.

Context	Participant(s); function	Product context	Production context	Pest context	Shelf life/storage
C1	P1/P7; Hygiene	Cereal products	Open; ambient	SPI in raw materials and finished goods	≥12 months; on- and off-site storage
C2	P2; Technical	Bread	Open; ambient	SPI in raw materials	<7 days; stored off-site
C3	P3; Quality	Food additives	Closed; ambient	Seasonal ants and wasps	≥12 months; stored off-site
C4	P4/P14; Technical/Quality	Pasta	Open; ambient	SPI in raw materials and finished goods	≥12 months; stored on-site
C5	P5; Quality	Bread	Open; ambient	SPI in raw materials	<7 days; stored off-site
C6	P6; Hygiene	Bread	Open; ambient	SPI in raw materials	<7 days; stored off-site
C7	P8; Technical	Ready meals	Open; chilled	SPI in raw materials	Variable
C8	P9; Technical	Beverages	Closed; ambient	Seasonal flying insects and ants	≥12 months; stored off-site
C9	P10; Operations	Ice cream	Open; chilled	Low activity; potential ingress	≥12 months; stored on-site
C10	P11; Technical	Cheese	Open; chilled	Low activity; potential ingress	≥12 months; stored on-site
C11	P12; Quality	Confectionery	Open; ambient	Seasonal flying insects and ants	≥12 months; stored on-site
C12	P13; Operations	Bread	Open; ambient	SPI in raw materials	<7 days; stored off-site
C13	P15; Hygiene	Confectionery	Open; ambient	Seasonal flying insects and ants	≥12 months; stored on-site
C14	P16; Technical	Confectionery	Open; ambient	SPI in raw materials	≥12 months; stored on-site
C15	P17; Quality	Confectionery	Open; ambient	SPI in raw materials	≥12 months; stored on-site

Note: Contexts are based on the participant matrix and describe the focal facility or operational setting discussed; P2, P7 and P8 held multi-site roles. P1/P7 and P4/P14 worked at the same facilities. P2/P13 and P12/P16 worked for the same parent companies at different facilities. Categories are reported characteristics rather than independently inspected site attributes. Product and operational descriptors were intentionally aggregated to protect participant and organisational confidentiality. More detailed combinations of product type, process, storage arrangements and facility characteristics could permit deductive identification within this geographically bounded specialist sample. Product moisture content, and whether the ready meal context involved meat-containing products, were not recorded consistently across interviews and have not been inferred retrospectively. The shelf life and storage column reports the approximate finished-product life and the principal storage arrangement described by the participant; these are reported rather than measured or independently verified specifications.
Abbreviation: SPI = stored-product insect.

participant responses and adaptive probing. Interviews lasted 36 to 81 min (mean: 49 min) and were audio-recorded with consent and transcribed using Minutes AI software, with all transcripts subsequently reviewed against recordings and corrected for accuracy by the first author. Quotations were lightly edited only to remove fillers, repetition or evident transcription errors; ellipses and square brackets indicate omissions or clarifications where required.

2.5 | Data analysis

Two complementary analytical approaches were used. Sentiment analysis was a secondary, descriptive method used to characterise attitudinal valence and participant-level variation; it was not used for hypothesis testing or population-level inference. Utterance-level mean polarity scores for participant utterances were calculated using the sentimentr package (version 2.9.0) in R version 4.5.2 (R Core Team, 2025; Rinker, 2021), with interviewer speech excluded. The algorithm accounts for valence shifters including negation, amplification, de-amplification and adversative conjunctions. For graphical description, scores were operationally classified as positive (>0.05), neutral (> −0.05 to ≤0.05), or negative (≤−0.05). These cut-offs were used to summarise the corpus consistently and were not interpreted as validated diagnostic thresholds. Thematic analysis conducted using NVivo 15 software (Lumivero, Denver, CO) provided the primary interpretive framework. A six-phase reflexive thematic analysis approach as described by Braun and Clarke (2006) and operationalised by Byrne (2022) was followed: (1) familiarisation through repeated transcript reading; (2) systematic initial coding of meaning units; (3) collation of codes into candidate themes; (4) review of themes against coded extracts and the full dataset; (5) definition and naming of final themes; and (6) integration of themes into a coherent analytical narrative. The first author conducted primary coding, with themes reviewed and refined through discussion with the senior author. Analysis was inductive, allowing themes to emerge from participant accounts while remaining attentive to the research questions.

Conditional consideration was summarised for each participant–method pairing (17 participants × three methods; 51 pairings). A pairing was coded C (conditional consideration) when the participant explicitly indicated that the method could be considered in at least one area of a food-manufacturing facility or under a specified condition. R (rejection) was assigned only when the participant explicitly rejected the method throughout the facility, including alternative locations or safeguards explored during the interview. U (unclear) was assigned when the response was ambiguous, internally conflicting, based on a material misunderstanding of the method, or did not

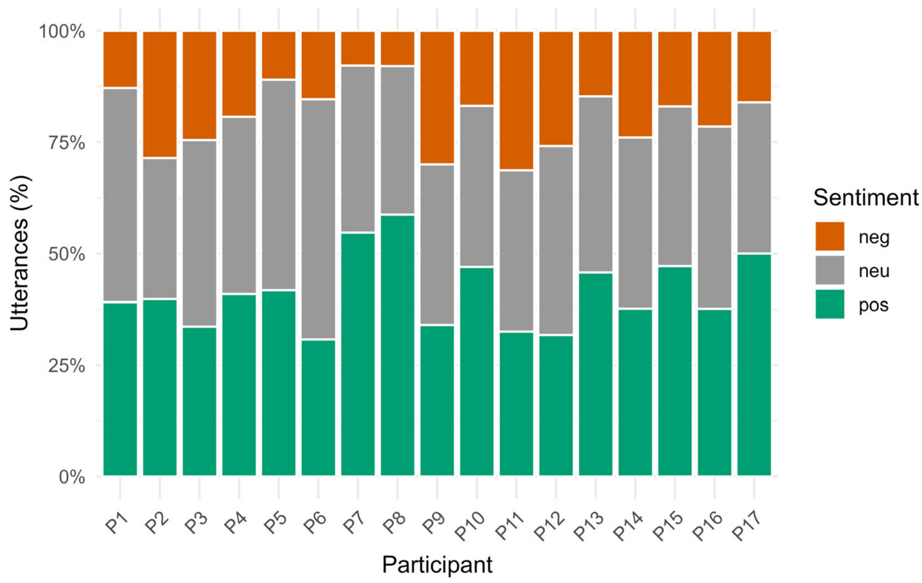

FIGURE 1 Sentiment distribution across interview participants (P1–P17). Stacked bars show the proportion of participant utterances classified as positive (polarity >0.05; green), neutral (>−0.05 to ≤0.05; grey) or negative (≤−0.05; orange). Of 1615 utterances, 40.7% were classified as positive, 40.3% as neutral and 19.0% as negative (mean polarity = 0.058).

directly answer the question. Classifications were based on participant speech rather than interviewer summaries or paraphrases; examples referring only to agriculture or unrelated non-food premises were not treated as evidence of in-facility consideration. A C classification indicates willingness to consider further assessment and does not imply approval, adoption or use.

3 | RESULTS

3.1 | Sentiment towards biological control

Sentiment analysis encompassed 1615 participant utterances across 17 interviews (range: 50–179; mean = 95). Of these, 40.7% were classified as positive, 40.3% as neutral and 19.0% as negative, with an overall mean polarity of 0.058 (SD = 0.202). Individual profiles varied: positive utterances ranged from 30.8% for P6 to 58.7% for P8, while negative utterances ranged from 7.8% for P7 to 31.3% for P11 (Figure 1). These values are descriptive summaries of the interview corpus rather than estimates of attitude prevalence or evidence of statistically significant differences among participants. Their principal value is in complementing the thematic analysis by showing that the mixture of receptive, neutral and concerned accounts identified qualitatively was also reflected in the polarity distribution.

3.2 | Conditional acceptability of biological control methods

Participants' accounts were frequently conditional and were therefore summarised using the three-state rule rather than a binary acceptance-rejection distinction. Conditional consideration was identified for entomopathogenic fungi in 16 participant accounts, for *B. thuringiensis* in 13 and for parasitoids in 12. Corresponding rejection counts were one, one and four, while zero, three and one accounts, respectively, were classified as unclear (Table S1). Entomopathogenic fungi were often contemplated in at least one setting, usually because a fungal spray could be compared with familiar insecticide treatments. P5, for example, said 'As long as it's controlled, I wouldn't have too many concerns around that', while P4 considered a fungal approach potentially feasible away from exposed product. Discussion of *B. thuringiensis* generated concern about introducing a bacterium into a food environment. P2 described it as a harder sell' because the site sought to keep bacterial levels low, and P4 noted that *Bacillus* was among the organisms monitored in that production context. Parasitoids prompted the strongest foreign-body concern. P9 explained, 'So for me … it's where they die … even though the product's enclosed, what you don't want is to find bodies, even on packaging'. P16 similarly worried that introducing wasps could create an additional foreign-body risk.

Conditional consideration did not follow a simple hierarchy by professional function. All six Technical, all five Quality and all four Hygiene participants considered the fungal approach under at least one condition; among the two Operations participants, P13 considered it whereas P10 rejected it. For *B. thuringiensis*, conditional consideration was recorded for four of six Technical participants, four of five Quality participants, all four Hygiene participants and P13 in Operations. The remaining pairings comprised one rejection and three unclear responses, including P10's response, which was classified as unclear because it treated the bacterial treatment as an introduced insect. Parasitoids produced greater differentiation: all five Quality participants considered their use under specified restrictions, as did three of four Hygiene participants and three of six Technical participants. P6's response was unclear because it distinguished food-contact from non-contact areas without explicitly accepting use in the latter. The two Operations participants differed, with P13 considering use only in a segregated non-food area and P10 rejecting it throughout the facility. These within-sample contrasts are descriptive and may reflect the interaction of professional responsibilities, product exposure and facility configuration rather than role alone.

Production context was especially visible in the bread-sector accounts. All four participants imposed or anticipated location-specific restrictions on parasitoid use. P2 rejected an in-facility trial; P5 confined possible consideration to closed dispatch with packaged stock; P6 preferred areas away from food contact but did not state a definite position; and P13 contemplated warehousing or other non-food areas. These participants represented Technical, Quality, Hygiene and Operations functions, reinforcing that professional role and facility context should be considered together. The three chilled contexts diverged. P8 (ready meals) and P11 (cheese) considered both microbial approaches subject to zoning, worker-safety controls, product removal or cleaning, but differed on parasitoids, which P8 rejected in product and storage areas while P11 considered them where location and severity justified it. P10 (ice cream) rejected both the fungal and parasitoid approaches throughout the facility and was the only participant to reject entomopathogenic fungi. The conditions attached to consideration also differed in character by professional function. All four Hygiene participants framed acceptability spatially, identifying non-food, warehouse, basement, external or otherwise non-production areas as the settings in which evaluation could occur (P1, P6, P7, P15), and two described a staged trial preceding wider use (P1, P7). Quality participants more often attached documentary or customer-facing conditions, including testing and documentation (P3), allergen and retailer checks (P12), and customer and contamination controls (P17). Technical participants more often expressed conditions in terms of formal risk assessment and severity thresholds, including risk review (P2), product segregation with parasitoids as a crisis option (P4), zoning and worker-safety controls (P8), and enclosed goods as an assessed last resort (P9). The two Operations accounts diverged, with P13 restricting use to areas without food exposure and P10 rejecting two of the three modalities; neither emphasised downtime or throughput. Rejections and unresolved positions were also unevenly distributed. All four rejections of parasitoid use were recorded for Technical (P2, P8, P16) and Operations (P10) participants; no Quality or Hygiene participant rejected parasitoids. Two of the three unclear responses concerning *B. thuringiensis* were recorded for Technical participants (P2, P16), and no Hygiene participant recorded a rejection of any modality. These distributions are descriptive, rest on group sizes of two to six participants, and are reported as narrative contrasts rather than as evidence that professional function determines position.

Two facilities were represented by more than one participant, permitting within-facility comparison. At C1, both Hygiene participants (P1, P7) recorded conditional consideration for all three modalities. At C4, the Technical participant (P4) recorded conditional consideration for all three, whereas the Quality participant (P14) rejected *B. thuringiensis* while considering the other two; this was the only rejection of *B. thuringiensis* recorded in the sample. Positions also varied by function within single product sectors. Across the four bread contexts, the parasitoid classification differed for each of the four functions represented, spanning rejection (P2, Technical), conditional consideration (P5, Quality; P13, Operations), and an unclear response (P6, Hygiene). Across the four confectionery contexts, the Quality and Hygiene participants (P12, P15, P17) each recorded conditional consideration of parasitoids, while the Technical participant (P16) rejected them. Both closed-production contexts (C3, food additives; C8, beverages) recorded conditional consideration for all three modalities.

TABLE 2 Barrier themes and frequencies identified in the thematic analysis.

Theme	*n*	Description
Food safety and quality	17	Concerns about product contamination, spoilage, allergenicity, or effects on food grade status
Retailer requirements	13	Need for approval from retail customers; prescriptive specifications limiting pest management options
Health and safety	9	Potential effects on workers; concerns about biological agents as pathogen vectors
Resistance to change	8	Reluctance to adopt novel approaches without extensive precedent; first-mover disadvantage
Negative terminology	4	Adverse associations triggered by terms "wasp," "bacillus," and "fungi"

3.3 | Barriers to adoption

Five interconnected barrier themes were identified in the thematic analysis (Table 2). Food safety and quality concerns appeared in all 17 interviews. Participants asked whether fungal material entering food production environments would affect product safety or food-grade status, and P11 asked whether an agent could spread, become airborne, spoil product or be pathogenic. Retailer requirements were coded in 13 interviews. P5 stated 'We are led by the customer in regards to their policies and practices and their expectations' and P8 described some retailers as 'quite prescriptive on what you can and what you can't do'. Participants also saw retailer endorsement as a potential accelerator. P15 suggested that endorsement by a major retailer could normalise the approach and make others more willing to try it. These accounts describe participants' perceptions of commercial governance rather than direct evidence from retailers. Health and safety concerns, coded in nine interviews, included possible worker exposure and the possibility that introduced insects could act as bacterial vectors. P11 recalled a *Listeria* case reportedly linked to fruit flies and used it to explain concern about introduced insects carrying bacteria. Resistance to change was coded in eight interviews: P17 observed that 'Nobody wants to really be the first one to try something out,' and P12 similarly described fear of being first. Finally, four participants discussed adverse associations with biological terminology. P1 warned, 'Don't call them wasps, because as soon as you mention the word wasp, what have you got in your head?' and P7 noted that the word *Bacillus* could evoke pathogenic connotations.

TABLE 3 Facilitator themes and frequencies identified in the thematic analysis.

Theme	*n*	Description
Controlled trials	15	Demonstration of efficacy in operational food manufacturing environments; phased implementation
Risk assessment	13	Formal frameworks for evaluating biological control risks against benefits and alternatives
Stakeholder education	9	Targeted communication to retailers, auditors and site personnel
Proof of efficacy	8	Evidence of pest suppression comparable to or exceeding chemical methods
Cost-effectiveness	5	Demonstrated savings compared to current treatments; reduced product losses

3.4 | Pathways to adoption

Five facilitator themes were identified in the thematic analysis (Table 3). Controlled trials were coded in 15 interviews. P2 wanted to see 'how it works with somebody else … proven results from it and not just … test scenarios … in a working business.' Participants also proposed phased evaluation in secluded or non-food areas and comparison with a preceding period. Formal risk assessment was coded in 13 interviews and was framed as an enabling comparison of the risks of the proposed treatment, the pest problem and available alternatives. P4 summarised the decision as weighing 'what's going to cause you the least problems.' Stakeholder education was coded in nine interviews. P11 emphasised that education would be needed not only for production sites but also for retailers, auditing bodies and other food-industry stakeholders, while P12 favoured concise 'Videos or PowerPoints … as punchy as possible.' Proof of efficacy was coded in eight interviews, including questions about speed of action and performance relative to current methods. Cost-effectiveness was coded in five. One participant reported that their business spent almost £300,000 annually on heat treatments for moth control, illustrating why credible evidence of savings might affect consideration of an alternative.

4 | DISCUSSION

This exploratory study examines attitudes towards biological pest control among food manufacturing professionals. Within this sample of 17 experienced UK participants, responses were more frequently characterised by conditional consideration than categorical rejection. This should not be interpreted as evidence that the wider food manufacturing sector is broadly receptive. Rather, the findings indicate that some professionals can identify circumstances in which biological control might be evaluated, provided that concerns surrounding legality, efficacy, contamination, worker safety and customer approval are addressed. The barriers described here resemble those reported for other food-safety-related technologies in manufacturing settings, where validation requirements, operational constraints, budgetary priorities and customer acceptance were the principal impediments to adoption (Chen et al., 2024). The concerns specific to living agents appear to sit on top of that more general pattern rather than replacing it.

Participants expressed different concerns about the three biological control modalities. Entomopathogenic fungi frequently elicited conditional consideration, potentially because a formulated spray applied by trained personnel resembled existing insecticide treatments. Products containing *B. thuringiensis* have established insect control uses, although legal authorisation is product- and use-specific (Health and Safety Executive, 2025; Raymond & Federici, 2017). The method nevertheless generated additional concern because *Bacillus* was associated with microbiological contamination by participants. This is consistent with evidence that pathogenic microorganisms occupy a prominent position in food-sector risk perception (Lupo et al., 2016). These concerns are not solely perceptual. The close genomic relationship between *B. thuringiensis* and *Bacillus cereus* has complicated routine discrimination in food testing, and commercial *B. thuringiensis* strains have been implicated in foodborne outbreaks (Fichant et al., 2022). Commercial preparations have also been reported to carry enterotoxin genes and to elevate *B. cereus* group counts within treated production systems, although concentrations in edible tissue remained below thresholds of concern in that study (Ten et al., 2026). Participants who described monitoring *Bacillus* and wishing to keep bacterial counts low were therefore identifying a substantive analytical and food-safety issue rather than reacting only to an unfamiliar organism.

The parasitoid scenario generated the strongest concern because the control organism could itself be perceived as a physical contaminant. Product and process characteristics appeared relevant alongside professional role. The restrictive responses of bread-sector participants are consistent with open handling during cooling and the vulnerability of exposed product to foreign-body contamination. Where dispatch follows shortly after production, the interval over which a biological agent could suppress a population is also short, although dispatch schedules and product life were reported by participants rather than verified in this study. Dry, ambient products with long storage periods, including cereals, pasta and powdered confectionery, may provide a longer interval over which suppression of stored-product insects could occur. However, these products can also be intrinsically susceptible to stored-product insect infestation, and open handling of powders or dry ingredients may increase concern about biological material entering the product. Three chilled contexts were represented: ready meal production and two dairy processing settings, cheese and ice cream. These raised a different set of considerations, because deliberate introduction of microbial or invertebrate agents would need to be reconciled with segregation, environmental hygiene and microbiological monitoring requirements already directed at controlling microbial growth in perishable products. The most restrictive account in the sample arose in one of these contexts. P10, an Operations respondent in open chilled ice cream production, rejected both entomopathogenic fungi and parasitoids throughout the facility and gave an unclear response on *B. thuringiensis*; this was the only rejection of the fungal approach recorded in the sample. The combination of an operational remit, open handling of a chilled perishable product and an established microbiological monitoring regime is consistent with the concerns expressed, although a single participant cannot establish that this configuration is systematically less permissive. The number of participants within each production category was too small to determine whether these characteristics systematically predict acceptance.

Conditional interest in parasitoids should not be interpreted as support for unrestricted release within production areas. Based on participants' concerns, the most plausible setting for initial evaluation would be a spatially segregated dry-goods storage or warehouse area in which no exposed food was present and movement towards production areas could be controlled. Intact packaging could reduce the probability of product contamination, although complete sealing may also prevent parasitoids from reaching hosts within infested products. Candidate applications would therefore need to define where accessible host stages occurred, how parasitoid movement would be contained and monitored, and how dead insects would be removed. Commercial supply and on-site rearing of *L. distinguendus* are established in stored-product protection (Niedermayer, Pollmann, & Steidle, 2016), so the limiting factor is unlikely to be availability of the agent. Releases within open-production or areas vulnerable to microbiological contamination would be difficult to reconcile with the concerns expressed by this sample. Even within separated storage areas, the possibility of parasitoid bodies appearing on packaging remained an important perceived barrier. These concerns closely reflect the structure of BRCGS pest management requirements. Issue 9 expects sites to prevent pest activity and treatments from presenting contamination risks, maintain detailed records, use competent providers and determine inspection and response measures through documented risk assessment (BRCGS, 2022). The Best Practice Guideline similarly emphasises prevention, site-specific programme design, monitoring and demonstrable control of infestations (BRCGS, 2025). The standards do not necessarily prohibit biological agents, but the absence of established precedents, suitably authorised products and validated operating procedures may increase the evidential burden associated with their adoption. BRCGS does not itself require retailer permission for every treatment; nevertheless, participants described retailer codes and commercial relationships as an additional layer of governance. Their portrayal of retailers as gatekeepers is consistent with contractual supply-chain structures described elsewhere in the UK food sector (Towill, 2005), rather than being a direct requirement of the BRCGS pest management clauses. It also echoes findings from UK food and drink manufacturers, among whom customer requirement was a primary driver of certification decisions (Evans & Taylor, 2021), and from buyer-side research in which food safety requirements were set largely in response to buyers' own customers rather than to regulation alone (Adebiyi & Bourquin, 2025). Engagement with retailers, certification bodies where relevant, standard-setting organisations and specialist pest management providers would therefore likely be needed before biological approaches could move beyond isolated trials. How such approaches are described may matter to that engagement. Evidence from agricultural settings indicates that biologicals are frequently not regarded as safer alternatives even where regulatory assessment supports their use (Mulugeta et al., 2024), and that peer discussion can shape willingness to trial an unfamiliar biological input more than information provision alone (Foolen-Torgerson et al., 2025). Both are consistent with participants' emphasis on stakeholder education and their reluctance to be the first adopter.

Participants' emphasis on operational trials presents both an opportunity and a practical difficulty. Laboratory efficacy alone was generally considered insufficient because it does not reproduce facility-specific product flows, hygiene controls, harbourage, temperature regimes or audit requirements. However, trials require prior agreement from the same manufacturers, customers and assurance personnel whose confidence they are intended to establish. One potential route would be a graduated programme beginning in a segregated, lower-risk area, supported by a prospective risk assessment, defined efficacy and contamination endpoints, stopping criteria and comparison with the existing pest management programme. Museum and heritage applications of *L. distinguendus* provide partial operational precedent (Querner et al., 2019; Querner & Biebl, 2011), although differences in product exposure, pest pressure, regulation and contamination sensitivity substantially limit their direct transferability to food manufacturing. These findings also inform research priorities. For entomopathogenic fungi, the principal development need relates to formulation because current evidence indicates superior efficacy in dust and spray applications compared with baits (Lopes & Alves, 2011). Nevertheless, bait formulations offer advantages including targeted placement, reduced environmental exposure and, in cockroach management, potential for secondary mortality through coprophagy and necrophagy (Hamilton et al., 2023). Research into gut microbiome interactions that may inhibit fungal establishment following bait ingestion (Pan & Zhang, 2020) could inform formulation strategies. For parasitoid wasps, variable outcomes across museum applications (Querner & Biebl, 2011; Schöller & Prozell, 2011) highlight the need to identify factors predicting success or failure. Niedermayer, Krogmann, and Steidle (2016) found reduced host-finding by *L. distinguendus* in empty storage facilities compared with laboratory conditions, suggesting that environmental complexity may impede parasitoid efficacy in ways not captured by controlled studies. Evidence from grain stores similarly indicates that parasitoid activity alone may suppress host populations insufficiently and is better treated as one component of an integrated programme than as a replacement for existing treatments (Harush et al., 2021). Regulatory considerations, although not extensively explored in the interviews, represent an additional implementation barrier. Microbial products marketed for indoor insect control are subject to the applicable Great Britain or Northern Ireland biocidal-product authorisation regime; plant-protection uses are regulated separately, and requirements are specific to the product and intended use (Health and Safety Executive, 2025). The costs and complexity of registration have been identified as impediments to biological control commercialisation

(Barratt et al., 2018; Cook, 1996). The legal route for any microbial or invertebrate agent would therefore need to be confirmed with the competent authority before evaluation in a food facility.

Several limitations constrain interpretation. Convenience recruitment through professional networks may have selected participants who were particularly willing to discuss novel pest management approaches, while the concentration of facilities in northwest England and north Wales limits geographic transferability (Etikan et al., 2016; Robinson, 2014). Although participants represented 15 reported facility contexts and several product sectors, some worked at the same facility or within the same parent company, and several production categories were represented by only one or two individuals. The sample cannot therefore support estimates of attitude prevalence or robust comparisons among roles, facility types or biological control agents. Practices and regulatory frameworks may also differ across jurisdictions (Conter et al., 2025). Retailers, certification auditors and standard-setting organisations were not interviewed, despite being identified as influential gatekeepers; participants' accounts of their likely responses consequently remain perceptions rather than direct evidence. Adaptive probing was appropriate to the semi-structured design but meant that not every participant considered identical location-specific scenarios. The first author's pest management background and prior connections within the recruitment network may have influenced participation or encouraged socially desirable responses. Lexicon-based sentiment analysis cannot fully resolve technical language, irony or context. The sentiment results should therefore be treated only as descriptive triangulation of the thematic findings.

In this sample of UK food manufacturing professionals, biological control was not invariably rejected, but willingness to consider it was conditional on the agent, product, production environment and availability of appropriate safeguards. Entomopathogenic fungi appeared to present fewer perceptual barriers than *B. thuringiensis* or parasitoids, although conditional consideration should not be equated with operational approval. Progress towards implementation would require any necessary legal authorisations or permissions, evidence from carefully controlled manufacturing trials, documented assessments of contamination and worker risks, and early engagement with retailers, auditors and specialist pest management providers. These exploratory findings provide a basis for larger and more diverse studies, including interviews with supply-chain gatekeepers and quantitative surveys capable of estimating how widely these views are held.

ACKNOWLEDGEMENTS

We thank the 17 food manufacturing professionals who generously contributed their time and insights to this research. Rory Hope provided valuable industry context on current stored-product insect management practices.

FUNDING INFORMATION

None declared.

CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

Source recordings and transcripts contain potentially identifying personal and organisational information and are not publicly available. Requests for de-identified supporting materials will be considered by the corresponding author subject to the terms of ethical approval, participant confidentiality and applicable data-protection requirements.

ORCID

Ben J. Clunie https://orcid.org/0000-0003-0078-1778
Tom W. Pope https://orcid.org/0000-0002-3678-2943
Joe M. Roberts https://orcid.org/0000-0002-9576-9239

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SUPPORTING INFORMATION

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How to cite this article: Hadfield, B., Clunie, B. J., Pope, T. W., & Roberts, J. M. (2026). Industry perceptions of biological control in food manufacturing environments: A qualitative analysis of barriers and opportunities. *Annals of Applied Biology*, *189*(2), e70155. https://doi.org/10.1111/aab.70155