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Emerging technology-driven bird deterrence methods for agricultural crop protection: a systematic literature review

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ABSTRACT

Bird damage is a persistent challenge in food production agriculture, causing substantial economic losses worldwide. Conventional deterrent methods (e.g., scarecrows, reflective tapes, and propane cannons) are labor-intensive and prone to bird habituation. In recent years, advances in sensing, automation, robotics, and artificial intelligence have enabled the development of technology-driven bird deterrent systems that offer targeted, adaptive, and scalable alternatives. However, a well-documented and critically evaluated synthesis of the literature is lacking. Therefore, we present a systematic literature review of advanced and emerging bird deterrence technologies for crop protection. A total of 33 peer-reviewed articles were selected and analyzed. Each study was critically reviewed based on deterrent platform type, sensing modality, control strategy, target crop system, targeted bird species, reported effectiveness, and limitations. Drone-based hazing emerged as the most used approach, followed by laser deterrents and sonic net systems. The reviewed studies primarily focused on high-value agricultural systems known to suffer from bird damage, including row crops ($n = 10$), vineyards ($n = 8$), orchards/fruits ($n = 6$), and poultry farms ($n = 2$). The studies that compared technology tools to conventional deterrents were summarized, and only one study evaluated the impact of a sensor-triggered deterrent system. In general, deterrent systems integrating sensor feedback, and automated actuation can outperform conventional methods, achieving rapid flock dispersal, significant reductions in bird activity, and decreased crop damage. Despite these advances, challenges remain related to scalability, long-term effectiveness, regulatory constraints, sensor robustness, and economic feasibility. We also synthesized current trends, highlighted critical research gaps, and outlined future directions for the development of cost-effective, adaptive, and farmer-centric bird deterrent solutions that harness advanced technologies for the benefit of growers. The findings provide a well-documented knowledge base to support researchers, extension specialists, and producers in adopting next-generation deterrent technologies for sustainable food production systems.

1. Introduction

Birds are an integral part of agricultural ecosystems and provide beneficial services, including pest control, pollination, and seed dispersal, while maintaining biodiversity and ecosystem health [1,2]. However, birds are also a source of ecosystem disservices to agriculture, including crop damage and contaminating crops with food-borne diseases. Bird damage is one of the most significant factors to yield loss, affecting producers across the globe [3–5]. In the United States, estimated annual bird damage exceeds $4.7 billion USD [6]. The magnitude of damage varies geographically and can be influenced by bird species, crop types, and landscape context. For example, the annual damage caused by European starlings (*Sturnus vulgaris*), blackbirds (Icteridae), and crows (Corvidae) to grain, fruit, and berry crops in the United States is estimated to exceed $150 million USD [7]. Moreover, birds pose a significant food safety risk through direct contact with crops. Birds can carry foodborne pathogens (e.g., *Campylobacter spp*., *Escherichia coli* and *Salmonella* spp.), which contribute to foodborne diseases around the world [8–12]. The possible routes of contamination involve fecal droppings deposited directly onto the crop or indirectly deposited via soil, dust, or irrigation water [13].

Several measures are available to deter birds from the field,

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including habitat modification, exclusion, and frightening techniques [14]. Habitat modification aims to alter preferred habitats and disturb feeding behavior to reduce bird density. However, habitat modification may result in negative impacts, including biodiversity loss, ecosystem imbalance, soil degradation, and adverse public perceptions [15,16]. Other methods include exclusion techniques, which restrict entry by creating a physical barrier (e.g., netting) or a discomfort zone (e.g., chemical application). Exclusion techniques are the most reliable in deterring birds when fields are small, but are still labor-intensive and expensive, requiring upfront costs [17–20]. Birds primarily rely on vision and auditory senses to locate food, mate, and avoid predators. Thus, frightening devices employ various auditory and visual stimuli to frighten birds. Commonly used auditory tools include bioacoustics, such as bird distress and predator calls, as well as artificial sounds, such as propane cannons and pyrotechnics [21]. Likewise, reflective ribbons, balloons, kites, inflatable tube-men, effigies, and artificial predatory birds are common and widely used visual tools. These frightening techniques are relatively cheap, standardized, fixed, applied uniformly to all bird species, and often triggered at set intervals without any feedback on bird presence [17–20]. Unfortunately, this leads to habituation, causing the hazing tool to be ineffective after a certain period, leading to a waste of resources, money, and time. Moreover, not all devices have been scientifically tested, leaving farmers to rely on product claims and logic to determine efficiency and applicability.

Additionally, bird species respond differently to various frightening or dispersal methods [17,20,22] and there is not a single solution to mitigating bird damage [17–20,22,23]. Although, a combination of acoustic and visual deterrent methods may provide the most effective solution for bird control [17–19,22], using multiple methods together is costly, time-consuming, and labor-intensive, as these units must be rotated in the field at regular intervals with implementation costs increasing proportionally with the production area [24].

With recent advances in sensing technologies, data processing, and computational capabilities, bird deterrence methods have steadily evolved from fixed, stationary, and repetitive systems to intelligent, adaptive, and automated tools that are increasingly adopted by farmers. Novel deterrent systems integrating low-cost sensors or Internet of Things (IoT) device feedback [25–27], data processing units, and automated actuation have been developed in recent years, with examples including the use of an aerial drone for bird monitoring and deterrence [28]. In this study, we define an advanced technology-driven bird deterrent as a system that utilizes modern technologies beyond conventional scare tactics to prevent bird damage. These advanced deterrents leverage sensors, electromechanical systems, automation, and data intelligence to provide more effective, nonlethal, and adaptable solutions. Examples of technology-driven deterrent systems include flying drones [29–33], robotic laser deterrents [34,35], sonic nets [36], and feedback-driven acoustic devices [37]. These technology-driven approaches are emerging and continuously evolving within agricultural systems for bird deterrence. However, to the best of our knowledge, well-documented, systematic, and synthesized information on advanced technology-driven bird deterrent methods remains limited. Therefore, the objective of this study is to systematically review technology-driven bird deterrent methods used in agricultural systems. We conducted a systematic literature review (SLR) using established research questions, comprehensive literature searches, document screening, and structured summarizing. The review focuses on sensor feedback, artificial intelligence (AI) integration, evaluation metrics, targeted bird species, experimental outcomes, system limitations, and future research needs. The established research questions (RQ) that guide this systematic literature review are as follows:

RQ1. What technology-based bird deterrents have been implemented/tested in agriculture?

RQ2. What are the agricultural use cases, targeted bird species, and study types?

RQ3. What sensors, actuators, and control mechanisms are used in advanced deterrent systems?

RQ4. What is the effectiveness/measurable impact of deterrent systems in reducing crop damage?

RQ5. What advantages, challenges, and limitations are reported in practical deployment?

This study examined a comprehensive range of technology-driven approaches for deterring birds from agricultural fields, including AI-enabled deterrent systems, automated or intelligent platforms (e.g., motion-activated systems and drones), electromechanical systems (e.g., lasers, robotic scarecrows, and sonic devices), and IoT-enabled or remotely controlled solutions. The working principles of these technologies are discussed, including the types of sensors and actuators used and their system-level integration. If available, we documented research that directly compares these technologies with conventional bird deterrent methods to evaluate their relative effectiveness and practical applicability. Overall, we compiled and synthesized experimental findings across different species and summarized conclusions to highlight current progress on technology-driven bird deterrent systems to guide future research.

2. Materials and methods

Systematic literature reviews are a well-established and commonly used scientific research method that identifies, evaluates, and synthesizes relevant existing research on specific research questions. It provides an unbiased, reproducible, and well-documented summary of current knowledge. Therefore, we conducted the SLR in accordance with the PRISMA-Preferred Reporting Items for Systematic Reviews and Meta-Analyses guidelines. The review process consisted of four main stages, as depicted in the PRISMA flow diagram (Fig. 1).

(1) Identification: A comprehensive literature search was conducted on the “Web of Science”, “IEEE Xplore,”and “Scopus” databases to identify relevant studies on technology-driven bird deterrent systems in agriculture. A structured keyword search strategy was developed using Boolean combinations derived from the established research questions. The search was applied to titles, abstracts, and keywords. The search terms included “bird”, “deterrent”, “repellent”, “scare”, “exclusion”, “control”, “agriculture”, “farm”, “orchard”, “crop”, “technology”, “automated system”, “automation”, “artificial intelligence”, “AI”, “computer vision”, “machine learning”, “IoT”, “drone”, “UAV”, “sonic”, and “laser”. The search was conducted in June 2025. This search strategy identified a total of 532 articles. All identified records were exported to an MS-Excel (.csv) file containing metadata, not limited to title, authors, publication year, keywords, abstracts, and institutional affiliations, which were subsequently used for the screening stage.

(2) Screening: Next, the identified articles were first filtered by excluding non-English publications, as well as conference papers, review articles, and book chapters, to retain only peer-reviewed research articles. This initial screening reduced the dataset to 81 articles. The remaining records were then checked for duplicate entries across the two databases, resulting in the removal of repeated articles. After this process, 58 unique articles remained for further full-text evaluation.

(3) Eligibility: A predefined set of inclusion and exclusion criteria was applied to ensure the relevance of the selected studies. Articles were included if the full text was available, the study was directly related to agricultural applications, the work was peer-

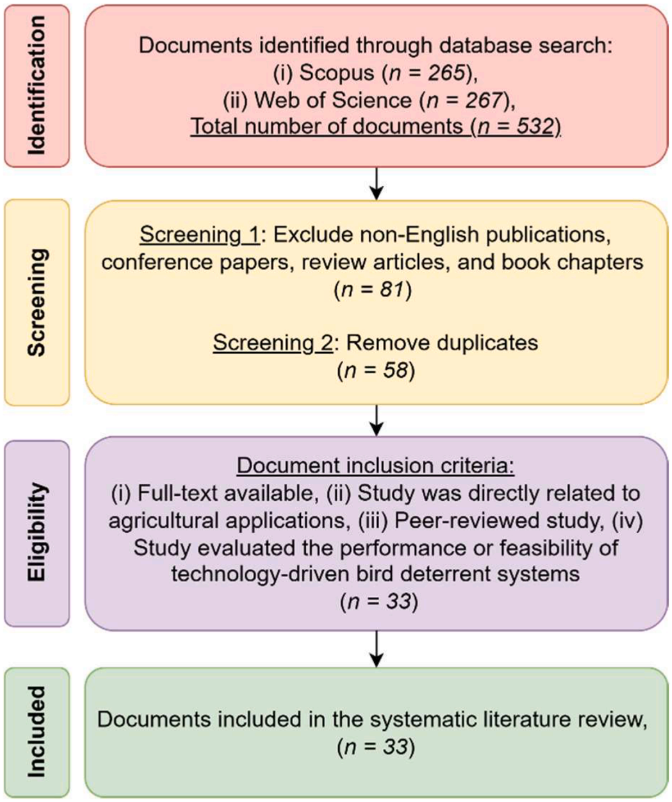

Fig. 1. Overview of the literature review procedure according to the PRISMA flow chart.

reviewed, and the study evaluated the performance or feasibility of technology-driven bird deterrent systems. During this stage, the abstracts were carefully examined to determine whether each study met these criteria and aligned with the established research questions. Articles that did not satisfy these requirements were excluded from further analysis. A total of 33 studies met the eligibility criteria.

(4) Inclusion: A total of 33 studies met all inclusion criteria and were selected for the final qualitative synthesis and documentation. For each included study, a structured data extraction form was used to systematically capture relevant information. Extracted variables included reference identifiers, authors, publication year, article title, source, and country or region of study. Technical attributes of each study were recorded, including the type of deterrent technology used, sensor type, actuator or output mechanism, control type, AI methods employed, power source, and the area covered. We also collected information related to study performance, including evaluation metrics, reported effectiveness, deployment duration, and comparisons with conventional deterrent methods. Finally, each study was assessed for reported challenges or limitations, key findings, and future research directions.

3. Results and discussion

3.1. Technology-based bird deterrent systems

In the SLR, we grouped the technology-based deterrent methods into four categories (Fig. 2). The drone category, which is often used to scare birds by mimicking natural threats, was the most used strategy implemented in the studies ($n = 17$). This was followed by sound-based deterrents, which included bioacoustics (e.g., predator or distress calls; $n = 7$), impulsive and other threatening sounds (e.g., cannon and pyrotechnics or other sounds; $n = 6$), and sonic nets (pink noise; $n = 4$). The next most common were visual deterrents, which included lasers ($n = 7$) and light ($n = 2$), followed by deterrents that combined more than one method ($n = 11$) (Fig. 2).

Drones: Drones are aerial platforms capable of operating without an onboard pilot, either through manual remote control or autonomous flight along pre-programmed paths using onboard flight controllers. Aerial drones mimic the behavior of avian predators (e.g., hawks, eagles) to elicit fear or flight response, particularly in small bird species. Birds perceive flying drones as a potential threat, impacting their behavior (e.g., feeding, foraging), leading to abandoning the area or displacement [30,38,39]. Drones offer several advantages, including task versatility, high mobility, large coverage, and customization. Therefore, they are used in multiple agricultural operations. Over 17

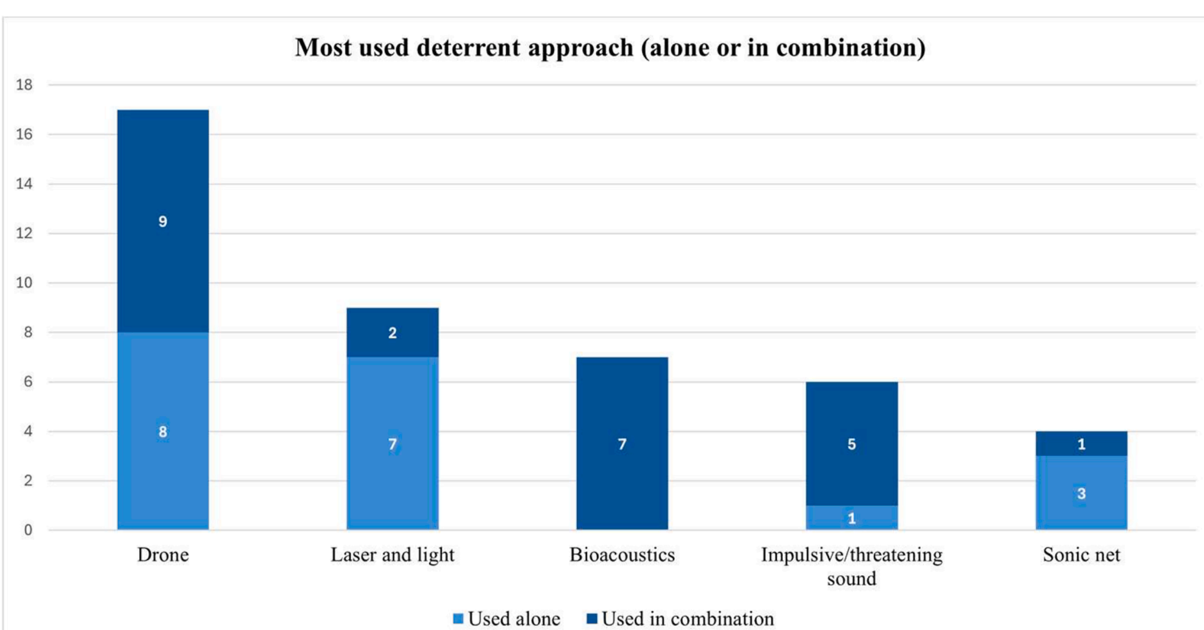

Fig. 2. Overview of technology-based bird deterrent systems used in agriculture ($n = 33$).

studies employed drones as a bird-repelling tool [40,41] either as a standalone deterrent or combined with other deterrent modules [40,41]. Birds instinctively flee when they perceive a threat or danger. Therefore, a standalone flying drone may scare birds through its visual appearance, operating noise, flight pattern or sudden movement. These features of drone mimics predatory behavior [32,39,40,42]. Moreover, drones can be combined with other deterrent modules, including sound and visual methods. For example, loudspeakers installed on drones are used to broadcast auditory threats (e.g., alarm calls, loud noises, and distress calls), mimicking predatory attacks, which were found to trigger fear in birds, resulting in birds leaving the area [30,33,39]. Likewise, some studies combined drones with visual deterrents, including reflective surfaces such as rotor blades, reflective tapes, or boards, to disturb birds through high-intensity light exposure, which interacts with avian visual systems to elicit avoidance responses [43]. Moreover, Wang et al. [44] employed upside-down crow taxidermy mounted on flying drones, this approach incorporated avian behavioral psychology by making birds perceive the drone as a predator that had captured a conspecific, which resulted in strong avoidance behavior.

Small bird species perceive falcons as active predators; thus, falconry has been practiced for many years as an effective deterrent method. However, falconry requires specialized training, intensive labor, and is costly, limiting its large-scale adoption. Consequently, novel approaches were developed using drones to mimic falcon behavior. For example, Storms et al. [45] developed the RobotFalcon to visually resemble a peregrine falcon (*Falco peregrinus*) and behaviorally mimic its hunting strategy when approaching bird flocks, inducing fear, and driving birds away. Likewise, Grimm et al. [32] modified a fixed-wing drone to resemble a Cooper's hawk (*Accipiter cooperii*), a common predator in the region, to control pest bird populations in vineyards. In addition, automated drones can continually patrol agricultural fields, which may be perceived by birds as a territorial threat, thereby preventing them from entering crop fields [42,45,46].

We observed that spraying drones are used simultaneously as frightening devices and for the targeted application of chemical avian repellents (e.g., methyl anthranilate) [31]. Avian repellents are considered safe for birds and humans, and do not cause long-term environmental damage; however, contact with the chemical irritates the mucus membranes of birds, prompting them to leave the treated areas. Drone-based applications enable improved spray deposition, real-time deployment, and spot treatment, thereby effectively reducing overall chemical usage and associated costs [29,47]. Most studies included in this SLR employed multi-rotor drones for bird deterrence because they provide key operational advantages such as precise hovering, targeted maneuvering, easy takeoff and landing, and simplified control [38,39,48]. In contrast, only two studies used a fixed-wing drone, which was modified to visually resemble a hawk to enhance predator-mimicry effects [45,48].

Sound-based deterrent system: Birds rely on acoustic signals for communication, mate attraction, territorial defense, and alarm signaling. Avian hearing is most sensitive to sounds in the range of approximately 1 to 4 kHz, although birds can perceive both lower and higher frequencies [49]. Sound-based deterrents exploit this dependence by broadcasting pre-recorded distress or predator calls to confuse or frighten target species, thereby inducing birds to vacate protected areas [37,39]. In addition to fear, certain sound stimuli can generate physical discomfort in birds. Recently, sonic net technology has emerged as an innovative sound-based repellent that disrupts bird communication by emitting pink noise with a frequency range of 2 to 10 kHz [50]. Unlike conventional loud noises, pink noise is a broadband signal that specifically masks the acoustic frequencies used in bird alarm calls and social vocalizations. This auditory masking interferes with effective communication, leading to confusion, increased stress, and eventual area abandonment [50,51]. The basic architecture behind sonic net involves ultrasonic parametric arrays, which produce a highly directional sound beam of 2–10-kHz range at an amplitude of approximately 80 dB sound pressure level emitted through directional speakers, and the beam starts out as a mixture of two ultrasonic frequencies. A nonlinear conversion interaction between the sound waves results in an audible sound that is the difference between the two ultrasound frequencies, and that remains highly directional [37,39,51]. Although a variety of ultrasonic sound repellents are commercially available, their effectiveness remains inconsistent and is often poorly supported by empirical evidence, with several studies indicating that most bird species are unable to perceive ultrasonic frequencies (>20 kHz) [49].

Visual-based deterrent system: Birds are often described as "a wing guided by an eye" [34] reflecting the central role of vision in their behavior. Birds have well developed vision, with retinal organization having cones containing visual pigments and visual cells with photosensitive material to absorb striking light. This enables them to see a wider light spectrum and sharp changes in light motion [43]. Vision is therefore critical for predator avoidance, navigation, communication, and resource selection [43]. The avian retina functions within a spectral sensitivity range of approximately 300–700 nm [52]. Thus, birds exhibit strong avoidance responses when exposed to rapidly moving laser beams, likely due to visual distraction, discomfort, and perception of threat [35,52]. Thus, several studies have employed both handheld [53] and automated laser systems (i.e., laser scarecrows) for bird deterrence [52,54] with positive outcomes reported when laser beams were directed at bird flocks [34]. The use of commercially available off-the-shelf lasers is the most common approach in bird deterrence studies. Reported laser specifications include: (1) green lasers with power output <500 mW and wavelength 532 nm [53]; (2) 400 mW green lasers with wavelengths ranging from 505 to 530 nm [54]; and (3) green lasers with wavelength 532 nm and power output <500 mW [52]. These lasers fall under the Class 3B category, with power outputs ranging from 400 to 500 mW and wavelengths of approximately 500–532 nm.

In addition, exposure to flickering LED lights (red or red–blue combinations) has been shown to act as an aversive stimulus, inducing discomfort and escape behavior in birds [55]. The flickering light concept is based on neurophysiology, which is very similar to how the human brain reacts to flickering light, which can trigger headaches, nausea, or dizziness [56].

Combined approach: Existing literature on bird deterrents consistently emphasizes that no single method is sufficient for effective bird deterrence; therefore, employing multiple complementary techniques is often recommended. Several studies have adopted combined approaches integrating visual stimuli, auditory signals, and predatory mimicry [33,40,44]. We observed that drone-based hazing is frequently paired with additional deterrence strategies, including auditory cues (e.g., distress and predator calls via onboard speakers), application of avian repellents using spray drones, and visual deterrents such as reflective materials, tapes, and bird taxidermy [29,33,40,44]. In addition, some ground-based systems employ modular, IoT-enabled architectures that combine lasers, bird repellent gun and speakers into a unified platform [27]. The overarching goal of these combined approaches is to enhance efficacy by reducing habituation and increasing behavioral unpredictability.

3.2. Use cases, targeted bird species, and study type distribution

Each study included in the SLR was categorized by geographical region, crop type, and study type distribution (Fig. 3). Technology-driven bird pest management research is concentrated in developed agricultural systems, with most studies originating from North America (40.6%, $n = 14$), Europe (21.9%, $n = 7$), and Australia (12.5%, $n = 4$). The geographic distribution indicates that bird pest problems represent a global challenge, although research efforts are concentrated in relatively advanced agricultural regions (Fig. 3b).

The reviewed studies primarily focused on high-value and specialty cropping systems (Fig. 3a), including row crops (27.8%, $n = 10$),

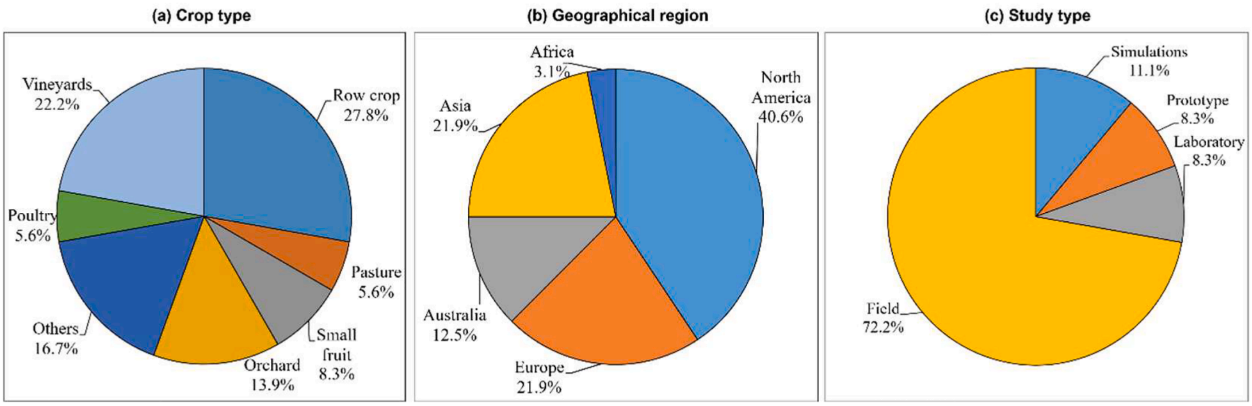

Fig. 3. Distribution of technology-driven bird deterrent studies by (a) crop type, (b) geographical region, and (c) study type included in the systematic literature review.

vineyards (22.2%, $n = 8$), orchards (13.9%, $n = 5$), and small fruits (8.3%, $n = 3$), reflecting the high economic losses associated with bird damage in these systems. Crop losses in cash row crops (e.g., sunflower [*Helianthus annuus*] and sweet corn [*Zea mays*]) are among the strongest drivers of research in this area. For example, North Dakota supports a historically large population of blackbirds, which are responsible for extensive damage to sunflower fields [57], with estimated annual damage of >$15 million in sunflowers alone [58]. Thus, over the years a variety of technologically advanced approaches have been tested to mitigate blackbird damage in sunflower including drones [31,38,48,59] and sonic nets [36]. Likewise, European starlings are major agricultural pests that damage sweet corn, particularly during kernel ripening, rendering entire ears unmarketable and contaminating crops with droppings. Consequently, advanced deterrent systems have also been tested in sweet corn to mitigate bird damage [34,35,60].

Fruit loss due to bird damage is a common, persistent, and costly problem for farmers worldwide, with per-hectare losses varying by region and crop type. Losses include direct damage through fruit consumption, which reduces marketable yield, along with indirect damage, where pecking creates entry points for secondary infections, leading to produce degradation and food contamination risks. Estimated bird damage ranges from approximately $104 per hectare in Oregon tart cherries (*Prunus cerasus*) to as high as $7267 per hectare in Washington Honeycrisp apples (*Malus domestica*) [61]. Therefore, over 50% of the reviewed studies focused on developing advanced bird deterrent systems to mitigate fruit losses in vineyards [30,32,39,40,44,46], orchards (e.g., apple and peach) [29,41], and berry crops (e.g., strawberry [26], blueberry [46], and cherry [41]). We provide a detailed overview of the crop types, targeted bird species, and corresponding deterrent technologies evaluated in the literature (Table 1).

In free-range poultry operations, wild birds pose significant risks by spreading diseases, contaminating feed and water sources, and causing physical damage through direct contact or environmental contamination. For example, free-range poultry farms located near grass pastures, waterways, and natural habitats face elevated risks of low-pathogenic (LPAIV) and highly pathogenic avian influenza virus (HPAIV) transmission through contact with or visitation by wild birds [52]. Thus, Elbers and Gonzales [52] and Chen et al. [54] have developed automated laser-based deterrent systems to reduce the number of wild birds visiting free-range poultry farms.

In pasture and grassland systems, geese (Anatidae) pose a significant pest problem because they are well-adapted to these habitats and primarily feed on grass, sedges, and agricultural crops. Intensive goose grazing in pasture systems creates significant competition for forage, leading to economic losses and necessitating management strategies such as deterrence or habitat modification. Accordingly, two studies conducted in Sweden and Denmark employed drone-based approaches [62] and handheld laser devices [53] to deter geese from pasture and farmland areas.

The “others” category (16.7%) included studies conducted in silage storage environments [50], and controlled aviary experiments [51], while two studies did not specify the crop type [39,45]. Silage storage systems on dairy farms in the United Kingdom involved outdoor maize silage, where wild birds consumed feed intended for livestock, damaged farm infrastructure, and contributed to the spread of pathogens that can affect both animal and human health. Therefore, a sonic net was developed to protect silage storage areas from bird intrusion [50].

Targeted bird species varied by region and crop system, with commonly reported pests including crows, starlings, blackbirds, sparrows, geese, gulls, and waterfowl (Table 1). Most studies were field-based trials (72.2%, $n = 26$), indicating a strong emphasis on the real-world validation of bird deterrent technologies. While relatively few studies were limited to simulations (11.1%, $n = 4$), laboratory experiments (8.3%, $n = 3$), or prototype development (8.3%, $n = 3$), which aims at the initial development and testing of the system in a controlled environment. Laboratory (i.e., lab) experiments often included experimental pens or aviaries where bird deterrents were tested under controlled conditions.

3.3. Sensors, actuators, and control mechanisms in advanced or automated deterrent systems

Unlike conventional deterrent systems, which are either fixed-frequency-activated or stationary (e.g., scarecrows or reflective tape), technology-driven bird deterrent systems employ multiple electromechanical components, including sensors, actuators, and control mechanisms, to enable semi-automated, automated, and intelligent operation. An overview of the core functional components commonly observed in these systems is presented in Fig. 4, which will be subsequently discussed.

Modern bird deterrent systems employ bird surveillance and monitoring modules to enable feedback-driven deterrent actions. In this SLR, the most frequently used sensing units include Red-Green-Blue (RGB) cameras, microphones, and motion sensors for detecting bird presence and activity (Table 2). Among these, RGB cameras are the most widely adopted and are typically mounted on ground-based stations or directly on the deterrent platform. A detailed list of employed sensors is presented, including their use for detecting bird presence or flock size across diverse settings, such as vineyards, orchards, and poultry farms (Table 2). Most camera-based systems are mounted on ground-based stations to monitor the field. In addition to visual sensing, acoustic detection approaches have been used to identify bird presence [25,37], and at least one study employed a passive infrared sensor for bird detection [26].

Table 1
Studies in the systematic literature review (SLR) including location and type (P = prototype, S = simulation, L = lab or aviary, F = field), target resource type (NS = not specified), target bird species or group (NM = not mentioned), and if additional tools were evaluated in the same study (T = tool comparisons or C = combined stimuli); and if the tool was operated manually (M) or autonomously (A) without an operator and if it was triggered by sensors (S).

Reference	Location & type	Resource	Target birds	Tools or stimuli
[29]	California, USA P,S	Orchards (NS)	NM	Drones; threatening sounds (not specified); repellent spray C,A,S
[40]†	Washington, USA F	Vineyards	American robins/ European starlings	Drones; reflectors; flight pattern; bioacoustics (distress calls) T,C,M
[30]	Washington, USA F	Vineyards	NM	Drones; flight pattern; bioacoustics (distress calls) C,A,S
[31]†	North Dakota, USA F	Sunflower	Blackbirds (Icteridae)	Drones; repellent spray (methyl anthranilate) C,M
[48]†	North Dakota, USA F	Sunflower	Blackbirds (Icteridae)	Drones; platform shape (raptor, multirotor, fixed wing) C,M
[46]	Washington, USA P	Vineyards/ blueberries	NM	Drones A
[32]	Oregon, USA P	Vineyards	NM	Drones A
[62] †	Sweden F	Pasture/ farmland	Graylag geese	Drones; walking human T,M
[41]	Portugal S,F	Orchards (peach)/ corn	NM	Drones A
[33] †	Malaysia F	Rice paddies	Sparrows	Drones; altitude; reflective boards; bioacoustics (predator calls) T,C,M
[45] †	Netherlands F	(NS)	Corvids/ gulls/ lapwings/ starlings	Drones; platform shape (raptor, multirotor) T,C,M
[63]	Australia S	Vineyards	NM	Drones (tethered) A,S
[38] †	North Dakota, USA L,F	Sunflower	Blackbirds (Icteridae)	Drones; altitude M
[39] †	Australia F	Vineyards	Ravens/ cockatoos/ silvereyes	Drones; effigy (crow); bioacoustics (distress calls) C,M
[44] *†	Australia F	Vineyards	Mynas/ silvereyes/ friarbirds/ miners/ starlings	Drones; effigy (crow); bioacoustics (distress calls); netting; reflectors T,C,M
[64]	Australia S	(NS)	NM	Drones A
[59] †	North Dakota, USA F	Sunflower	Blackbirds (Icteridae)	Drones M
[34] *	Rhode Island, USA F	Sweet corn	Blackbirds (Icteridae)/ starlings	Laser (50 mW, 14 mm, 532 nm) A
[54] †	Taiwan F	Poultry	Sparrows/ mynas/ bulbuls/ doves/ pigeons	Laser (400 mW, 505–530 nm) A,S
[53] *†	Denmark F	Pasture	Barnacle geese/brent geese	Laser (<500 mW, 40–50 mm, 532 nm) M
[52] †	Netherlands F	Poultry	Waterfowl/ songbirds/ falcons/ cranes/owls	Laser (50–499 mW, 532 nm) A
[35]*†	Florida, USA L	Sweet corn	European starlings	Laser (50 mW, 14 mm, 532 nm) A
[65]	Czech Republic F	Vineyards	NM	None tested (Proposed a detection mechanism that can trigger one or more deterrents)
[60] *†	Florida, USA L	Sweet corn	European starlings	Laser (50 mW, 14 mm, 532 nm) A
[27] †	China P	Farmland	NM	Laser (specifications not provided), threatening sounds (not specified)C, A,S
[26] †	Thailand F	Strawberries	NM	Flood light, threatening sounds (not specified) C,A,S
[55] †	Japan F,L	(NS)	Carrion/ large-billed crows	Flickering white/ blue/green/red lights (15 Hz) M
[25]	Rwanda P,S	Farmland	Weavers/ waxbills/ bulbuls/ cisticolas/ canaries/ queleas/ robin chats	Bioacoustics (dogs barking), impulsive (gunshots, sirens, noisemakers, car horns, vuvuzelas), ultrasonic sounds A,S
[66]	China F	Orchards (pear)	Crows, magpies, tits, pheasants	Bioacoustics (distress/predator calls), impulsive (explosions)A,S
[37]	Turkey P,S	Orchards (NS)	NM	Threatening sounds (not specified)
[51] †	Virginia, USA L	(NS)	European starlings	Sonic net (2–10-kHz at 80 dB SPL at food) A
[36] *	North Dakota, USA F	Sunflowers	Blackbirds (Icteridae)	Sonic net (1–8 kHz at 80 dBA SPL at 10 m) A
[50] †	Cornwall, UK F	Silage	European starlings	Sonic net (2–10-kHz at 80 dB SPL at pile opening) A

Studies that evaluated crop damage (*) or bird activity or behavior (†) in response to the technology-based management tool.

Processing sensor data acquired from cameras and microphones is essential, as raw signals alone cannot support automated decision-making. Therefore, advanced machine learning (ML) algorithms and models are primarily developed or utilized to accurately determine bird presence and activity. In the case of visual sensing, several studies have employed ML-based computer vision techniques to analyze images and estimate bird presence or flock size. For example, YOLOv5, an object detection model, was developed for bird detection in vineyards, which achieved a 94.3% recall rate [65]. Similarly, YOLOv5, SSD, and RetinaNet models were applied to monitor birds in pear orchards, reporting detection accuracy over 92% [54]. In a poultry farm setting, Mask R-CNN, a type of object detection model, was used to detect wild birds [54]. For acoustic signal processing, a DenseNet-201 model was employed for bird sound recognition tasks [37]. Once bird presence is

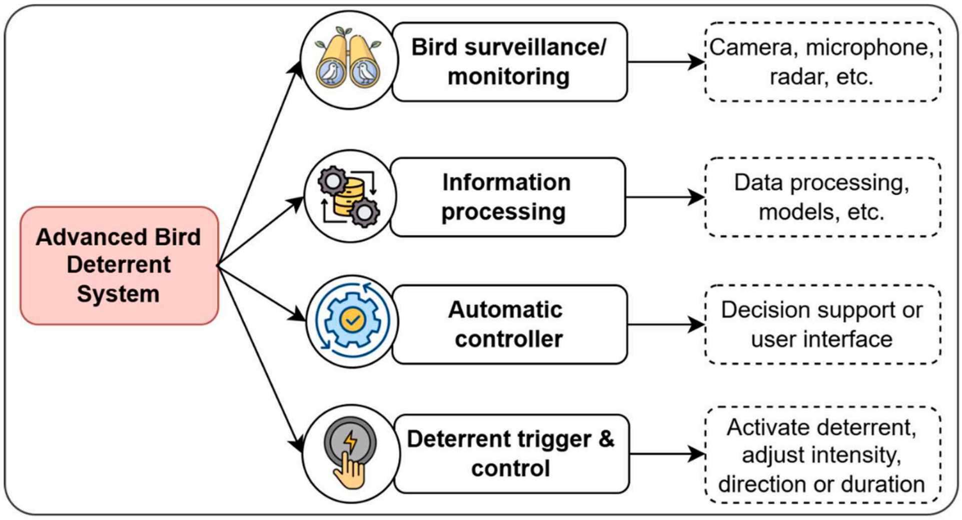

Fig. 4. An overview of the core functional components commonly observed in these systems is presented.

Table 2
Monitoring devices (V = visual, A = acoustic, M = motion, T = thermal) used to automate surveillance or monitor pest birds, along with deterrents employed and protected resources (NM = not mentioned). Some studies may have used on-board drone cameras, but did not report the specifications. A few studies were excluded because no sensor-based monitoring system was used for bird monitoring.

Reference	Monitoring device specifications	Deterrent	Resource
[29]*	Wireless Ground Sensor Network (WGSN) using microphones, lasers or motion detectors[A,M] (in study bird detection simulated using a digital button)	Drone	Orchard
[40]	Video (GoPro Hero 4, 1080P) [V]	Drone	Vineyard
[30]*	ZED Stereovision (Stereolabs Inc, 2 RGB 1/3″ CMOS sensors, 4MP each) [V]	Drone	Vineyard
[46]	Stereo webcams (Logitech C290 [ground]) [V]	Drone	Vineyard
[45]	Video (Runcam Micro Swift2 [drone]; Sony FDR-AX53,4 K [ground]) [V]	Drone	NM
[63]*	Virtual ground cameras; UAV sensor model	Drone	Vineyard
[54]*	Webcam (Logitech C922 Pro Stream) [V]	Laser	Poultry
[27]*	Optical and laser detection units[V]; Radar calibration unit[M]; Infrared detection unit[T]	Laser	Farmland
[52]	Video camera (Hikvision low-light Turret 4MP) [V]	Laser	Poultry
[66]*	Webcam (Dahua Technology Corporation P40A2-WT, 1080P,2 K) [M]	Acoustic	Orchard
[37]	Microphone (in Arduino Nano 33 BLE) [A]	Acoustic	Orchard
[65]*	RGB camera (Sony IMX477R); Webcam (Arducam 8 MP) [V]	Ultrasonic	Vineyard
[25]*	Microphone (in Arduino Nano 33 BLE Sense nodes; XIAO ESP32S3 Sense base station)[A]	Acoustic	Farmland
[26]*	Passive Infrared Sensor (PIR) [T]	Acoustic	Strawberry

* Device used to trigger deterrent tools, not just monitor bird numbers or assist drone pilots..

established, the automatic control system delivers targeted deterrent actions. For example, in drone-based studies, detection of birds within the field-of-view triggers drone deployment [29,30,46]. Likewise, in poultry farm settings, detection of wild birds initiates automated laser activation, directing the laser beam toward the identified bird zone [54]. With this active, real-time feedback framework, the controller not only activates the deterrent but also dynamically adjusts its intensity and duration, introducing a level of automation and intelligence that is largely absent in traditional bird deterrent systems.

As emphasized in the literature, proximity, unpredictability, and adaptiveness are key characteristics of effective long-term bird deterrent systems [67]. Unlike stationary devices such as scarecrows, drones are mobile platforms that continuously move and can approach birds closely to introduce proximity. Drones can perform diverse actions or movements that enhance unpredictability and adapt or chase birds if required, making them highly effective deterrents. However, drone use as a bird deterrent is not fully “autonomous” in some regions. For example, in the United States, drones must be operated or actively monitored by a human pilot within visual line of sight under FAA Part 107 regulations [68]. Operations beyond the visual line of sight or fully automated deployments are typically subject to additional waivers or operational approvals. Similarly, dynamic visual systems, such as automated lasers, can leverage feedback from sensing units to focus on selected regions for targeted deterrence, which is currently lacking in conventional visual deterrent devices (e.g., flashing tape or fixed lights). Likewise, traditional propane cannons produce repetitive, loud acoustic noise, offering limited automation or intelligence [21]. On the other hand, digital acoustic deterrent systems can vary sound types, intensity, and duration based on bird species and behavior, thereby enhancing unpredictability and adaptability.

3.4. Reported effectiveness/measurable outcomes of advanced deterrent

The reviewed SLR studies consistently reported that technology-driven bird deterrent systems were significantly effective in reducing bird activity and crop damage (Table 3). Measurable outcomes and effectiveness were evaluated using several metrics that quantified bird behavioral responses (i.e., flock abandonment, flock reduction, flock time to dispersal, bird response percentage, and flock return rate) or crop damage percentage with deterrent treatment.

Drone-based deterrents have shown rapid and strong responses across a variety of bird species and crop systems. For example, the RobotFalcon, which mimics peregrine falcon morphology and hunting behavior, cleared entire fields within 5 min, while conventional multi-rotor drones dispersed approximately 80% of bird flocks within the same duration [45]. Drone type and operational characteristics also influence deterrence effectiveness. Studies measuring flight initiation distance (FID) demonstrated that blackbird flocks responded sooner to fixed-wing airplanes (98 m), followed by predator-model fixed-wing drones (90 m) and multi-rotors (55 m), confirming that predator mimicry enhances perceived threat [48]. Wandrie et al. [38] reported that rotary-wing platforms elicit stronger behavioral responses when operated at lower altitudes.

Although drones spraying an avian repellent did not show

Table 3
Reported effectiveness metrics and performance outcomes of technology-driven bird deterrent systems tested in the field as a function of bird behavioral responses or crop damage. Simulations and prototypes are not included.

Reference	Deterrents used	Evaluation metrics	Effectiveness
[40]	DJI Phantom 3 drone, reflective propellers, flight patterns, distress calls	Bird number hour^{-1}, Incoming/ outgoing birds per flight interval	Bird activity was >300% higher without UAS; Distress calls with random flights showed strongest reduction, while reflective propellers have minimal effect.
[30]	Tello EDU programmable drone, flight patterns, distress calls	Automated UAV mission success rate	92% and 90% success for independent and sequential/longer missions, respectively.
[31]	DJI Agras MG-1P drone, avian repellent (methyl anthranilate)	Abandonment, flock reduction (%), latency to return	Drone spraying repellent slightly increased abandonment and flock reduction (methyl anthranilate ~47%, water ~44%)
[48]	Flight Test FT Explorer (fixed-wing airplane drone), raptor model (fixed-wing), DJI Phantom 4 Pro multirotor drone	FID, abandonment	FID: fixed-wing airplane = 98 m, raptor silhouette model = 90 m, multirotor = 55 m. 9/53 abandoned fields after 2-min hazing.
[62]	DJI Phantom 4 drone, walking human	Distance after scaring, return probability	Distance after scaring: 990±56 m after 5 min No difference in responses depending on the scaring technique Reduced return/field use for ~4 h; no effect after 24 h.
[33]	DJI Phantom 3 drone, reflective board, ultrasonic/predator sound broadcast	Bird numbers (%)	Deterrent combination on the drone is effective; Lower effectiveness at 10 m altitude
[45]	RobotFalcon, DJI Mavic Pro	Abandonment	Predator mimic cleared all flocks, multirotor cleared 80% in 5 mins
[38]	Fourthwing Vireo (fixed-wing), DJI Inspire drone (rotary-wing)	Flocks alerting/ flying (%)	Responded to multirotor at 30 m AGL; no response to fixed wing at 52 m AGL.
[39]	Custom multirotor with speaker and crow taxidermy	Response distance, settle distance from initial position, time to return	Large birds responded at 50–300 m, ravens resettled ~450 m away, most flocks did not return before dark, except one starling flock.
[44]	Custom multirotor with speaker and crow taxidermy; netting; reflective visual scaring devices	Mean grape bunch damage (%)	UAV reduced grape damage to 0.9–1.6%, similar to netting (0.5–1.2%) and better than visual scaring (1.8–4.8%)
[59]	DJI AgrasMG-1P spraying drone	FID, abandonment, flock reduction, return rate	FID: 40 m, 52% flocks abandoned, 50% flock reduction, 81% return rate
[34]	Laser (URI Laser Scarecrow)	Bird damage to sweet corn ears (%)	Protected plot has 33% less damage than unprotected plots under relevant bird pressure.
[54]	Laser (Quarton VLM-520)	Repulsion rates (hourly, daily)	Highest repulsion rate was 97.1% (hourly) and 40.3% (daily)
[53]	Laser (Agrilaser 500, handheld)	Displacement distance	Displaced 70% of flocks <1 min, and 98% displaced in 5 min
[52]	Laser (Avix Autonomic Mark II)	Bird numbers with/without laser	Bird visitation reduced by 98.2%
[55]	Flickering white/blue/ green/red lights (Acebeam L18, Archer M Pro, modified Maxtoch Owleyes W2)	Escape behavior /time before flight, FID	Red flickering light induced crow escape behavior, Treated area FID (137 m) > untreated area FID (12 m). Strongest response at 15 Hz, crows fled in ~8.1 s when illuminated from 100 m.
[35]	Laser (URI Laser scarecrow)	Crop damage (sweet corn)	Damage reduced <20 m but damage increased with distance
[60]	Laser (URI Laser scarecrow)	Probability of feeding (sweet corn)	Feeding probability reduced on sweet corn
[27]	Laser, strobe, sounds	Bird numbers	Rejection rate 97.6% during the day and 94.2% at night (<500 m^2), but decreased when the range was >950 m^2
[36]	Sonic net (Midstream Technology Inc)	Crop damage (sunflower)	Damage reduced by 28.6%, 64.6% & 22.6% at 3 fields
[51]	Sonic net (Holosonics Audiospotlight parametric array speaker)	Bird numbers	Bird presence reduced by 46%
[50]	Sonic net (using Faital Pro HF100/WG101 loudspeaker + SMSL SA-98E amplifier)	Bird presence, flock size	Bird presence reduced by 94% over 2 days and 89% over 14 days
[66]	Bioacoustics (distress/ predator calls), impulsive (explosions)	Fruit pecked (pears)	Pecking reduced by 53.8% with and 44.2% without computer vision

significantly greater flock abandonment or flock reduction rates compared to drones spraying water, birds exposed to the repellent took longer to return to the field, indicating some benefit to combining chemical repellents with drone hazing [31]. Likewise, drones combined with additional visual and auditory modules were more effective than drones alone. For instance, drones equipped with reflective propellers, random flight patterns, and distress calls significantly reduced bird activity in fruit crops [33,40]. However, Månsson et al. [62] found no significant differences in greylag goose (*Anser anser*) responses to an approaching drone or human. Thus, the effectiveness of drones as deterrents may vary by species.

Laser-based deterrents, particularly automated laser systems, demonstrated high effectiveness. Automatic laser deterrents achieved 97.1% hourly repulsion and 40.3% daily repulsion rates [54], while Elbers and Gonzales [52] reported a 98.2% reduction in wild bird visits at free-range poultry farms. Handheld laser devices displaced 70% of barnacle geese (*Branta leucopsis*) and dark-bellied brent geese (*Branta bernicla*) flocks within one minute and 98% within five minutes [53]. In addition, an aviary study demonstrated reduced feeding probability of European starlings on corn ears and decreased overall crop damage, although effectiveness declined with increasing bird–laser distance, highlighting the importance of tool proximity [35,60]. Brown and Brown [34] showed that automated laser scarecrows were able to reduce bird damage to sweet corn in a field setting. We observed that the most laser deterrent systems employed fixed-position platforms.

Acoustic deterrents, particularly sonic net systems, are capable of providing strong long-term suppression of bird activity. Sonic net reduced starling presence by 46% [51] and up to 94% during short-term deployments, maintaining 89% suppression over 14 days [50]. In another study, sunflower crop damage was significantly reduced by 28–65% across three different fields [36]. Multi-modal platforms, which combine lasers, bird deterrent gun, and acoustic deterrents, have demonstrated consistently high performance. Zhou and Mughees [27] reported bird rejection rates of 97.6% during daytime and 94.2% at night within a 500 m^2 area, although effectiveness declined beyond 950 m^2, indicating range limitations. Drone systems augmented with reflective propellers, distress calls, and randomized flight patterns significantly decreased bird movement compared to single-mode deterrents [33,40].

Deterrent systems integrating AI-based detection and automated response demonstrated superior performance. For example, an acoustic deterrent system with computer vision feedback reduced fruit pecking by 53.8%, whereas continuous operation without feedback achieved only a 44.2% reduction [54]. Likewise, an automated laser deterrent system reduced wild bird visitation rates by 98.2% [52]. Across all technologies, systems incorporating sensing, control, and multi-modal deterrent strategies have achieved sustained reductions in bird activity or crop damage. While static and repetitive deterrents often showed diminishing returns due to habituation [44,65]. Collectively, these suggest that automation, proximity, unpredictability, and feedback-driven adaptation can improve the effectiveness of bird deterrent systems.

3.5. Advantages, challenges, and limitations to field deployments

Modern bird deterrent systems equipped with surveillance and monitoring capabilities can enable targeted hazing and reduce bird habituation by varying the intensity and duration of deterrent actions. This adaptive and unpredictable nature of deterrence can substantially improve the overall effectiveness and efficiency of bird deterrent systems. However, the use of AI-driven camera-based vision systems as primary sensors presents several challenges, including high computational cost, limited field of view, and dedicated hardware and expertise are required in model development [69]. Additionally, environmental variability, differences in species behavior, and changing field conditions can limit the robust and reliable performance of the vision system [65]. For example, identifying the exact species and creating adequate acoustic datasets from recordings are some of the other identified limitations for the sensing system [25].

Drones have emerged as a modern and effective tool for bird deterrence [40,44,61], with several studies reporting a rapid and strong bird response over large areas, up to 25 ha [39]. Nevertheless, drones only provide a temporary deterrent effect, as birds are often observed returning to the field once the perceived threat subsides [39]. Additionally, the results obtained in the field trial with drone-based deterrents are limited to the specific drone models or configurations used, and therefore cannot be generalized to other platform types [38]. A major limitation is restricted flight endurance, with most platforms operating for 10–30 min due to battery constraints [29,32,44]. For example, White et al. [59] suggested that ten minutes of drone hazing in a large sunflower field was insufficient to reduce crop damage. To address this, researchers have developed energy-efficient path-planning algorithms (e.g., particle swarm optimization algorithm) to optimize flight trajectories and conserve power [41]. More recently, a grid of autonomous, ground-tethered drones has been proposed to overcome endurance limitations by supplying continuous power from ground stations, enabling nearly indefinite operation [63]. Simulation models have been used to evaluate the feasibility of different tethered drone configurations and deployment strategies; however, this approach introduces operational and spatial constraints imposed by the tether [63]. Although drones can operate autonomously using predefined flight plans, most studies have still relied on manual piloting, which often results in increased labor costs due to the need for continuous human supervision and active maneuvering to maintain effective deterrence [44,48]. This reliance on manual control is largely because bird responses depend on the drone's approach pattern, since birds are more likely to react strongly when the drone approaches directly and head-on rather than tangentially or from above. Therefore, real-time pilot adjustments are often required to maximize (drone) deterrent effectiveness. Furthermore, drone-based systems face additional challenges, including regulatory restrictions, training requirements, safety concerns, high initial costs, periodic maintenance, and limited scalability for large commercial farms. Moreover, drone operation can be stalled under rain or strong wind conditions [41,45].

Sonic net systems are designed to minimize bird habituation by operating in landscapes where natural predator risks persist, and alternative food resources are available. Repeated exposure to the masking signal diminishes predator detection abilities, thereby sustaining avoidance behavior over time [36] along with no new bird recruitment owing to a lack of communication [50]. Unlike conventional acoustic deterrents, sonic net creates a spatially contained “deterrent bubble” that protects specific target areas of fixed size, depending upon the speaker array range. However, system performance can decline in dense or well-established crop canopies, where acoustic attenuation and scattering degrade sound propagation, limiting effective coverage to the output capacity of the speaker array [36]. It was suggested that a sonic net can be useful in reducing damage by foraging birds during the early crop stage, with limited acoustic degradation [36] without any new bird recruitment [50]. Despite these constraints, sonic bird repellent offers several practical advantages, including a large range with multiple speaker arrays, independence from time or geographic constraints, low cost, and minimal risk to humans, animals, or the environment, making it a promising and scalable solution for bird deterrence [51,54]. Experiments that determine the species-specific effectiveness of sonic net systems could bolster deterrent effectiveness.

Laser deterrents exploit the visual sensitivity of birds by projecting rapidly moving light beams that create visual disturbance. Most systems employ green Class 3B lasers (i.e., 500–532 nm, 400–500 mW) due to their high visibility under low-light conditions. Both handheld and automated laser platforms, often referred to as laser scarecrows, have been widely evaluated in agricultural and poultry settings. Automated systems outperform static devices by enabling dynamic targeting and region-specific activation based on real-time sensor feedback [53]. Field studies have demonstrated high deterrence efficacy; however, laser effectiveness is strongly influenced by proximity, beam movement patterns, and bird-laser distance, and interactions of the laser beam with crop foliage and structure, with significantly reduced impact when birds are beyond 20 m [35,53]. Despite their effectiveness, laser deterrents face several limitations, including restricted coverage area, efficacy based on ambient light conditions (e.g., bright or sunny day), and strict safety requirements due to ocular hazards associated with Class 3B lasers, which often comes with operator training and installing warning signs at the facilities [53]. Furthermore, most current systems are stationary, limiting spatial flexibility, and direct exposure to the bird's eye may create a long-term detrimental effect on the bird’s vision [35].

In general, the included SLR studies are often limited to short-term, and small field trials, with relatively few to no investigations evaluating long-term performance, economic feasibility, or bird habituation over multiple seasons. For example, in one multi-season experiment, it was observed that the probability of geese returning and using the agricultural field was higher in spring than in other seasons [62] when scared by a drone. Habituation, a process that leads to decreased responsiveness to a stimulus [70] has been established as a primary challenge to long-term deterrent efficacy [71]. However, quantifying/measuring habituation within a human-wildlife context is rare [72]; a primary limitation exists in that to measure habituation (or sensitization) individual animals need to be identified and their behavioral response to deterrents measured over an appreciable temporal span [70]. In an aviary experiment, Manz et al. [35] observed European starling damage to sweet corn increased from day 2 to day 5, but they could not determine if this was attributed to habituation of the laser deterrent, the birds learning to be more effective at foraging the sweet corn, or a combination thereof. Technology-driven deterrents have the potential to make aversive stimulus less repetitious, which in theory should reduce habituation. Future emerging technology-driven deterrent investigations that incorporate measures of bird response to stimulus over time will be poised to quantify and deepen our understanding of habituation.

Effectiveness is also dependent on multiple factors, not limited to species, crop type/structure, landscape, flock size, and context. The structure and amount of associated crop foliage can influence deterrent efficacy. For example, Manz et al. [35] measured laser efficacy in artificial sweet corn (ripe sweet corn placed on wooden stakes) and a sweet corn crop, and determined that the laser was more effective in the actual crop; they argued that the sweet corn foliage made the laser more visible to the birds, enhancing the aversive stimulus. Similarly, in mature sunflower fields, the highly three-dimensional crop structure creates pockets that shield or muffle the sonic net sound, whereas sonic net may perform better during crop establishment when sparse vegetation allows sound to travel farther and provides fewer refuges [36]. To gain a better understanding of the role crop structure plays in deterrence efficacy, an effort should be made to test the same emerging technology-driven deterrent(s) across crop types. In addition, the systems that perform well for one bird species or crops may fail in another setting. For example, in drone hazing in large sunflower fields, White et al. [59] suggested that the probability of bird abandonment was higher in smaller flock sizes than in larger ones, as more eyes watching (i.e., the many-eyes hypothesis) affects perceptions of safety [73,74] . Similarly, the study observed that the abandonment probability was greater in the late afternoon compared to mornings, as bird energy needs were met [59,62]. Lighting conditions can also influence sensor performance, thereby affecting the efficiency of automated deterrent systems. For example, a passive infrared (PIR) sensor showed reduced detection accuracy under the strong sunlight and during large simultaneous flock entries [26]. Likewise, in the context of landscape, Månsson et al. [62] reported that scaring alone tends to move the problem around, with other studies reporting that drones deter birds to another location ~450 m away [39]. Thus, this suggests that scaring needs to be repeated across the landscape, including fields where birds (e.g., geese) do not cause damage.

Technology-driven bird deterrence systems may improve bird deterrence efficiency, but their practical adoption is constrained by cost, complexity, and on-field reliability. Such systems often require components including microcontrollers or single-board computers, high-definition cameras, advanced sensors, actuators, etc., which are costly; some constraints, such as limited camera field of view and deterrent coverage, means larger farms may need multiple camera-deterrent modules, increasing installation complexity, power demand, and cost [65]. Connectivity is another barrier because reliable internet access is not available on many farms. However, some IoT systems require internet connectivity to send warning notifications [26], while real-time bird detection systems demand continuous Wi-Fi, a dedicated computer server to coordinate cameras, routers, and repellent units [54]. Field reliability is also affected by weather, power limitations, and chances of technical faults. For example, UAVs may be grounded during rain, strong winds, or extreme temperatures, while battery-powered systems have limited operating duration and may require solar panels or other supporting instruments for continuous use [34,38,44]. Technical issues, such as reduced MP3 sound output or false bird detection can further reduce system performance [50,52]. Drone-based deterrents add further challenges because limited battery life restricts flight duration, and large fields require longer and repeated hazing flights, often with a trained operator available all the time to fly the drone and replace batteries [39, 59]. In addition, drone and auditory deterrent noise may disturb nearby residents, so deployment may be more suitable in areas away from residential zones [33]. Regulatory requirements can also add complexity in adoption, as drone and laser operation often require permissions, hazard reduction for low-flying aircraft, and safety signage [38,52]. Furthermore, most technologies protect limited spatial ranges, and scalability to large commercial farms remains a key research gap.

4. Conclusions

In this study, we adopted a systematic literature review to document and critically evaluate the current state of technology-driven bird deterrent systems in food production and agricultural environments. The study observed that bird deterrent systems are continuously evolving with technological advancements. Emerging and advanced deterrent platforms now incorporate sensor-driven, automated, and adaptive mechanisms that utilize advanced models and control strategies to overcome the limitations of traditional static, fixed, repetitive, and labor-intensive systems. We observed that emerging deterrent systems integrating real-time surveillance, AI-based models, and automated actuation offer targeted, proximity-based, and unpredictable responses compared to conventional deterrents, which may enhance their potential to reduce bird activity and crop damage. However, rigorous comparative evaluations are limited, and the long-term effectiveness of these systems, particularly regarding bird habituation, remains insufficiently explored.

Among the reviewed technologies, drones, automated laser systems, and sonic net deterrents emerged as the most frequently studied solutions. Drone platforms provided strong aversive responses through predator mimicry, rapid maneuvering, and close-proximity intervention, while automated laser deterrents achieved high repulsion rates in low-light and fixed environments, including poultry farms. Sonic net offered a non-invasive acoustic masking mechanism that disrupted avian communication, maintaining sustained reductions in bird presence with minimal environmental disturbance. Importantly, studies employing multi-modal deterrence strategies that combine visual, acoustic, chemical, and robotic methods reported superior performance compared with single-modality systems, highlighting the value of integrated deterrence modules.

Despite these advances, significant challenges remain before widespread commercial-scale adoption can be achieved. Vision-based detection systems still lack scalability and robustness for unstructured and continuously varying agricultural environments. Drone platforms are restricted by battery endurance, regulatory barriers, safety risks, and high maintenance costs, and laser-based systems require strict adherence to ocular safety standards. Moreover, most studies were short-term and geographically concentrated, with limited evaluation of long-term economic feasibility, system scalability, and cross-species adaptability.

Future research should prioritize the development of scalable, cost-effective deterrent ecosystems that unify AI-driven perception, closed-loop control, and multi-modal actuation within a robust cyber-physical framework. Long-duration, multi-season field trials with study designs capable of yielding strong inference (e.g., Before-After-Control-Impact) are needed to quantify habituation dynamics, economic return on investment, and operational reliability. Similarly, extension-driven deployment studies will be critical for validating these systems under real-world farm conditions and ensuring technology transfer to producers. Ultimately, the integration of adaptive intelligence, automation, and ecological understanding represents the most promising pathway for transforming bird pest management into a sustainable, data-driven component of modern agriculture

Statement for studies in humans/animals

This study did not involve Humans or Animals.

CRediT authorship contribution statement

Tanmay G. Jalgoankar: Conceptualization, Data curation, Formal analysis. **Chetan M. Badgujar:** Conceptualization, Data curation, Funding acquisition, Investigation, Methodology, Writing – original draft, Writing – review & editing. **Bryan M. Kluever:** Supervision, Writing – review & editing. **Page E. Klug:** Methodology, Resources, Writing – review & editing.

Declaration of competing interest

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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Data availability

Data will be made available on request.

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