Chapter

Challenges for the Control of Poultry Red Mite (*Dermanyssus gallinae*)

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Abstract

The Poultry Red Mite, *Dermanyssus gallinae*, is an ectoparasite which is considered the major pest for the egg-laying industry. The mite hides in crevices and cracks during daylight and feed on the blood of the hens in the darkness. It can also parasitize other bird and mammal species, including man that can develop gamasoidosis when bitten at work or private residences. The control of the mite infestations has relied in synthetic acaricides, but the development of resistances and the restricted list of authorized products make fundamental the development of novel control measure. The combination of alternative control measures, such as monitoring of the mite infestation, plant-derived products, inner dusts, biological control and vaccines, poses as the best way for achieving satisfactory results.

Keywords: *Dermanyssus*, poultry, mite, zoonosis, control, vaccines

1. Introduction

The poultry red mite (PRM), *Dermanyssus gallinae* (De Geer, 1778), is a hematophagous mite that affects mainly poultry [1] but also parasitizes other avian [2] and mammalian hosts [3–5], including humans [6]. PRM has a worldwide distribution and it constitutes a serious problem for the European egg-laying industry where the average prevalence is 80% with some countries reaching a prevalence higher than 90% of the farms affected [1]. PRM infestation is associated with severe economic losses in the egg production industry [7], also causing health and welfare issues in the hens [7–9]. Additionally, the PRM has shown to be a mechanical vector for multiple pathogenic viruses and bacteria [1].

The control of PRM is mainly based on the use of synthetic acaricides. However, synthetic acaricides have important limitations such as the development of resistant mite populations, environmental contamination and limited efficacy for controlling already settled infestations [1, 10]. Thus while research focused on *D. gallinae* was previously scarce, it increased significantly in recent years probably due to the support received due to the growing impact of mite infestations on the egg-laying industry [10]. The limitations of the conventional control measures make research on alternative control measures as one of the leading research topics in recent years. Amongst those control measures, vaccination poses a promising effective and environmentally sound intervention.

The aim of the present review is to show the current knowledge about the PRM, the challenges it poses from the One Health perspective for both human and animal health and the future possibilities for the control and prevention of PRM infestations.

2. Biology

Dermanyssus gallinae is taxonomically assigned to the Dermanyssidae family englobed in the order Mesostigmata of the Arachnida Class. There are 14 other mite species that affect birds and are morphologically very similar to *D. gallinae* which may be misidentified when identification is solely based on morphological characteristics [11]. Recent advances in molecular tools as gene sequencing or DNA barcoding, combined with morphological features is allowing a proper mite identification, including *D. gallinae* identification [12–14] (**Figure 1**).

Dermanyssus gallinae is an obligatory ectoparasite that feeds on the blood of the host. It has a global distribution [15]. In contrast with other *Dermanyssus* spp., *D. gallinae* is a generalist species with a low host specificity [16]. The PRM is a pest in the egg-laying farms [1], but can also be found parasitizing more than 30 wild and domestic bird species [11] and mammals [3–5], including humans [6]. The life cycle for *D. gallinae* includes five developmental stages: egg, larvae, protonymph, deutonymph and adult (**Figure 2**). Larvae have three pairs of legs while the rest of the stages have four pairs of legs. The PRM requires a blood meal for molting from protonymph to deutonymph, to adult and for egg-laying [17] (**Figure 2**). The color of the fed stages varies from bright red to brown, depending on the digestion of the blood inside de mite, while unfed stages are white. Adults and fed deutonymphs are

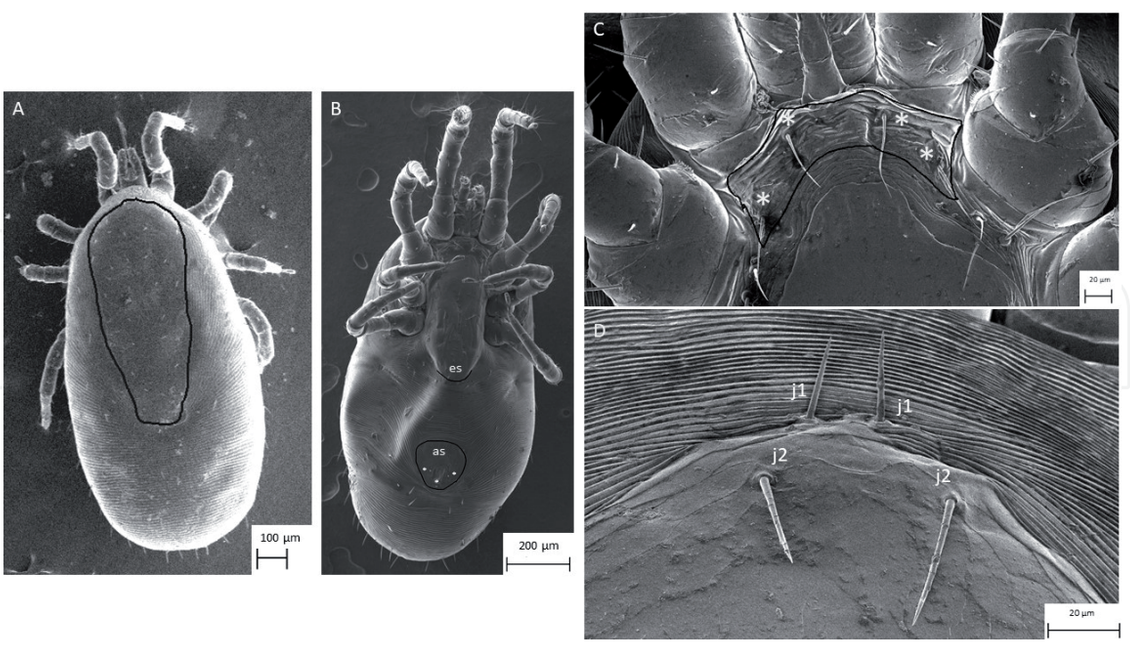

Figure 1.
SEM images from several morphological characteristics useful for the identification of D. gallinae *and differentiation from other similar species. Morphological characteristics shown are present in adult females according to Di Palma et al. [14]. (A) Dorsal overview. Dorsal shield (outline traced) with prominent shoulder. (B) Ventral overview. Epigynal (es) and anal (as) shields are rounded posteriorly. Anal shield with three anal setae (*). (C) Detail of the sternal shield. The sternal shield is wider than long and containing two pairs of setae (*). (D) Detail of dorsal shield. The two pairs of setae (j1 and j2) are on the dorsal shield. See methodology for additional information.*

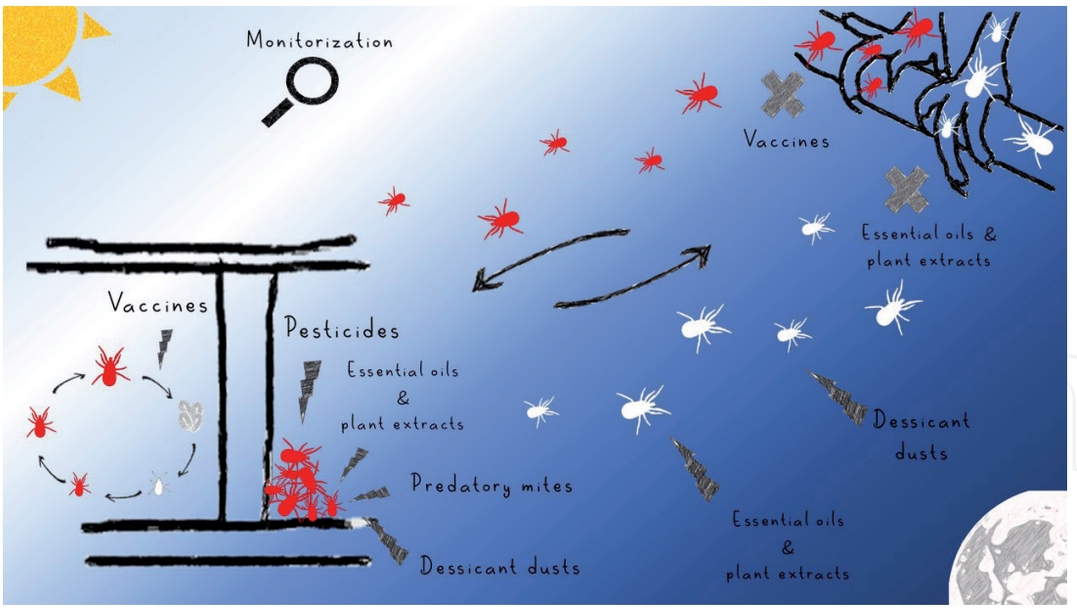

Figure 2.
Graphical representation of the PRM biological cycle and points of action for different control measures. Iconography explanation: large red mites = fed adult mites; small red mites = fed nymphal stages; large white mites = starved adults; small white mites = starved nymphal stages; cross = points where the treatment can interrupt the mite cycle; thunderbolt = points of action for the different treatment options. New control interventions such as vaccination, predatory mites or plant extracts are shown. See methodology for information source.

visible with the naked eye. Life cycle usually takes 2 weeks to complete, but it can be shorter when ideal conditions are provided (25–27°C and high relative humidity) [17–19]. Long-time emptied hen houses have been reported to remain infested. This finding is justified by the ability of the mite to survive without any blood meal for up to 9 months if the environment is suitable. However, desiccation and high temperatures (>45°C) are lethal [19]. Oviposition is carried out only by adult female mites. A maximum of approximately 30 eggs can be laid by a single female in her lifetime, usually in clutches of 4–8 eggs after a blood meal [20].

The PRM lacks real eyes and it can senses changes in the luminosity of the environment with photocells [21]. During daylight hours, mite is usually hidden in cracks and crevices where it is out of the reach of the hen. In these shelters, it gathers with more mites until they can form a cluster of hundreds of mites of different stages. This behavior is driven by aggregation pheromones [22]. It is in the darkness when the PRM comes out of their refuges to feed on the host. The host-seeking process is multifactorial, but temperature has been proven to play an important role as the PRM is highly sensitive to even minor changes in temperature and starved mites have an increased sensibility [23, 24]. *D. gallinae* increases its activity when exposed to substrate vibrations which are supposed to be used for host localization [23]. Surface skin lipids are also involved in the host identification and stimulation [22, 25]. These lipids are used to improve feeding rates in artificial feeding devices when synthetic membranes are used [26] and have provided possibilities for the use of essential oils in the control of PRM infestations in layer houses. In contrast with other hematophagous ectoparasites that utilize CO_2 to identify their hosts, CO_2 did not induce any host seeking response in *D. gallinae* under laboratory conditions but induced immobility under light conditions, which is interpreted as a survival strategy to avoid being eaten by the host [23]. Nymphal and adult stages stay on the host for feeding for 30–60 min [27]. According to this behavior, PRM can be considered as a micro predator [16].

3. One health: poultry industry, environment and human health

3.1 Poultry industry

The PRM is not a significant issue in the broiler industry, mainly due to its short production cycle, but it poses a substantial threat to the egg-laying industry worldwide, except for layer farms in the USA where *Ornythonyssus sylviarum* is the main mite species affecting layer hens [28]. However, recent reports suggest significant increase of *D. gallinae* infestations in the USA [15]. Although *O. sylviarum* is also present in wild birds of European countries, *D. gallinae* is the specie responsible for farm infestations. However, mixed infestations have been reported in countries out of Europe [29]. Infestations can reach high prevalence in Europe, where the average prevalence is more than 80% with several countries reaching higher than 90% [30]. However, PRM prevalence can be more related to certain areas rather than a country as different prevalence has been observed in different regions of the same country [31]. PRM infestations have been described in every production system. Less-intensive farming systems present higher risks of infestation which usually is inversely proportional to the level of intensification [32]. Therefore, PRM prevalence is generally higher in backyard and free-range units, followed by barns and, ultimately, by enriched systems [33]. Enriched cages usually show higher levels of infestation when compared to traditional pens in those countries where they are still allowed [32]. These systems improve mite survival by providing more safe areas to the mite far from the reach of the hens and the treatments at the same time as they promote hen welfare.

Temporal dynamics of PRM infestations vary greatly between laying hen houses. Specific environmental conditions and differences in laying hen house management are responsible for these variations. The age of the flock is another modulating factor according to a model developed for forecasting the population dynamics in a hen house [34]. The age of the flock has a negative effect on the growth of the mite population as mite populations decline as the age of the hens increases despite the fact that the immune response of the hen against a PRM infestation has not been well characterized. An experimental infestation developed an increase of the serum amyloid-A [35], but hens do not generate natural potent immunoprotective responses [36]. The development of an immune response by the bird after a chronic exposure is a plausible explanation which has been proposed that requires further research [34, 37]. The type of hen hybrid and how they were raised as pullets seem to have some effects on the vertical distribution of the mite infestation in aviaries, which is explained by differences in the space use by different hybrids [38].

Infestation levels vary seasonally [38]. Seasons prone to more severe infestations also differ depending on the climate of each region [38]. Usually, seasons with mild temperatures and high relative humidity can be correlated with lower fluctuations of these parameters inside the layer house, providing more ideal conditions for the mite to grow and therefore show more severe infestations. In this way, in northern countries the infestation peak usually happens in summer months while in more temperate climates the most prevalent seasons are spring and autumn.

Moderate and low infestations do not seem to have an effect on the production parameters independently of the layer hen productive system [39]. Instead, severe infestations are associated with important production losses albeit variations between housing systems [21]. Therefore, PRM has been demonstrated to negatively affect the proportion of laying hens, egg weight and the amount of first-choice eggs in enriched cages facilities while detrimental effects have been observed on egg mass, first-choice eggs and bodyweight of hens housed in aviary

systems [39]. The impact on egg production can cause reductions of up to 20% [8]. PRM infestations are also responsible for devaluation of eggs when these are blood spotted. The spots are the result of fed mites getting crushed beneath the eggs while walking or hiding on the conveyor belt [40].

PRM is also responsible for health and welfare issues for egg-laying hens. When asked, most egg-producers commonly state that PRM is the major issue concerning hen welfare [41]. The main sign of a severe infestation is the anemia observed in the birds. An adult mite can ingest 0.2 μl of blood in a blood meal [42]. It is described that a laying hen can lose more than 3% of its blood volume every night [8]. In cases of severe infestations, increased bird mortality is observed due to exsanguination. The mortality due to a PRM infestation has been estimated to increase between 4 and 50% [43], and correlates with an increased mite burden. Several studies find significant relationships between PRM infestation and hen mortality [7, 44]. PRM infestation increases food and water intake. Hens under infestation suffer restlessness, agitation, sleep deprivation and increased preening and feather pecking [9, 45]. Thus, the infestation puts the hens into chronic distress making them more susceptible to diseases and reducing vaccine efficacy.

Many dermanyssoid mites are confirmed vectors of bacterial and viral pathogens. Several pathogens have been isolated from *D. gallinae*, thus confirming its role as mechanical vector. Several reports have detected pathogenic bacteria in PRM such as *Coxiella burnetii*, *Erysipelothrix rhusiopathiae*, *Listeria monocytogenes*, *Pasterella multocida Mycoplasma gallisepticum, Chlamydophila psittaci* and Spirochetes [46–48]. However, its role as a biological vector for these pathogens is not yet fully elucidated and requires further research. The PRM has been demonstrated under laboratory conditions to act as a vector for *Salmonella enteritidis* where they showed the oral transmission after ingestion of washed mites contaminated by cuticular contact or during blood meal [49]. Additionally, *S. enterica* subsp. *enterica* serovar gallinarum biovar gallinarum (*S. gallinarum*), the etiological agent of the fowl typhoid, was found to survive for up to 4 months in infected mites [50]. Recently, Pugliese et al. [51] showed the maintenance of *S. gallinarum* in two different productive cycles where after an outbreak of fowl typhoid, the mites remained infected even after a sanitary break and vaccination of the second flock. An interesting finding of this work was that the number of bacteria found in the mites varied according to the antibody titers of the vaccinated hens. This finding illustrates the complex relationship between host, parasite and bacterial pathogen. PRM has an experimentally confirmed potential capacity for acting as a mechanical vector of avian influenza virus after a bloodmeal on infected hens [52]. Other viral agents such as avipox virus, fowl adenovirus, Marek's disease virus, avian paramyxovirus type I and the Eastern, Western and Venezuelan equine encephalomyelitis viruses have been isolated from PRM [7].

In summary, PRM is responsible for economic losses of around 231 million Euros annually in Europe considering the combination of the production losses, health issues and cost of mite infestation control [53]. Other reports estimate the economic impact of PRM infestations in Europe between 0.5 and 0.6 Euros per laying hen [54].

3.2 Environment and wildlife

Historically, wild birds were considered as the main source of the mite infestation in the poultry houses. However, mitochondrial cytochrome oxidase I *(mt-COI)* gene sequencing, which allowed secured *Dermanyssus* species identification, demonstrated that none of the *Dermanyssus* species that specifically parasitize wild birds were found in poultry farms and concluded that only *D. gallinae*

harbored synanthropic populations [11]. Additionally, the same research described that the *D. gallinae* populations associated with poultry farms belong to different genetic lineages [11]. In addition, recent research on genetic differences between *Ornithonyssus sylviarum* present in wild sparrow nests and layer houses in the USA indicated the absence of mite exchange [55]. However, wild bird nests located in the proximities of the hen house can act as a reservoir of mites and thus allow re-infestation. Mul et al. [56] performed a risk analysis in which poultry farmers and employees, followed by hen cadavers and manure aeration, represented the highest risks of introduction and spread of PRM in the farm. If the manure belts are shared amongst barns, they constitute a severe risk of spreading the PRM [56]. Rodents and insects are potential carriers of mites, and although the role of pests in the introduction and spread of PRM in layer farms has not been fully elucidated, a case of phoresy of *D. gallinae* has been described in a beetle [57].

In a recent questionnaire by free-range farmers in the UK, antiparasitics were reported as one of the three most commonly used medicines against PRM [41]. A recent scandal on the discovery of an unauthorized product in food-producing animals (Fipronil, $C_{12}H_4Cl_2F_6N_4OS$) in contaminated eggs from farms in 45 countries worldwide. The concentration in the contaminated product did not reach toxic doses for humans, but a mediatic Public Health alert was raised, and a food fraud investigation was started by European authorities [58]. Only two compounds are specifically labeled to control PRM infestations while birds are present (Phoxim, $C_{12}H_{15}N_2O_3PS$ and Spinosad, $C_{41}H_{65}NO_{10}$ (A); $C_{42}H_{67}NO_{10}$ (D)) by the European Union (EU), and recently a new compound (Fluralaner, $C_{22}H_{17}Cl_2F_6N_3O_3$) has been approved [59, 60]. Authorized products do not penetrate the whole egg but improper handling when breaking the shell can lead to food contamination [61]. Risks of residues of traditional and unlabeled pesticides entering the food chain are due to its presence in body tissues of hens that are slaughtered for human consumption [60]. A withdrawal period has been suggested for the skin tissue after application of Spinosad and Abamectin ($C_{48}H_{72}O_{14}$ (B_{1a}); $C_{47}H_{70}O_{14}$ (B_{1b})), an acaricide with available formulations for spray application in some European countries, due to the detection of residues in this tissue [62]. The chemicals used to control PRM may also have adverse effects for workers directly exposed while applying the treatment. The limited availability of tools and the increase of resistance are forcing the farmers to turn to non-authorized products to face PRM infestations and underline the necessity for alternative control methods.

3.3 Zoonotic risks

D. gallinae is known as a bird ectoparasite but it has low host specificity [16]. This lack of specificity allows the mite to feed on mammals, including humans, when the natural host is not available [6]. Human parasitosis due to PRM is called gamasoidosis or dermanyssosis. Skin erythematous papules are the usual clinical signs for gamasoidosis and urticarial lesions have been also described [6]. Skin lesions are usually pruriginous and can be distributed throughout the entire body, but are more frequently located in the arms, legs and the upper trunk [6]. Regarding human gamasoidosis associated with *D. gallinae*, two epidemiological scenarios are described: urban cases and occupational cases [6]. *D. gallinae* is the most commonly ectoparasite identified as the causal agent of gamasoidosis, but the cases assigned to *D. gallinae* can be misdiagnosed due to the difficulty of species determination for non-trained practitioners. The geographical expansion of other similar mite species such as *Ornythonyssus* spp. [63] due to climate change, host expansion and globalization will require more precise analysis.

Occupational cases are those related to poultry workers. The infestation can occur both in professional workers and hobbyists. These mite attacks usually happen during the daytime, while the workers are handling birds, cages or collecting eggs or when cleaning the premises. High levels of mite infestation and lack of proper protective clothing increases the risk of mite bites. Despite the high prevalence of infestation in egg-laying farms and continued exposure of the workers to the PRM, the number of reports of occupational cases is limited [6, 64]. The low number of reported cases can be explained by the fact that the attacks occur under specific conditions (severe infestation and lack of protection) or because workers do not report the attacks.

Urban cases are not associated with poultry workers. These cases are usually linked to familiar homes or public buildings such as hospitals and halls. In these cases, synanthropic birds, generally pigeons, are the source of the infestation [6]. Most of them occur when the host has left the nest after the breeding season. At that moment, the mites search for a new host to obtain a bloodmeal. Recent investigations suggest the existence of a pigeon specific lineage (*D. gallinae* L1) that is more frequently involved in human gamasoidosis [65]. Skin lesions in urban cases tend to be more severe than those in occupational cases, basically due to extended exposure.

Reports of gamasoidosis are scarce but their frequency has increased in the recent years [6]. PRM gamasoidosis is still an underdiagnosed parasitosis mainly due to un-specific signs which do not lead the practitioners to a certain diagnosis and, generally, the fact that PRM bites cause only light to mild clinical symptoms, indistinguishable from other bug bites and do not put the patient in need of seeking medical assistance. Recently, the bacterial genera *Tsukamurella* has been identified as part of the microbiome of the PRM with an endosymbiotic relationship suggested [66]. *Tsukamurella* species are foremost saprophyte bacteria that have occasionally been identified as opportunistic organisms associated with postoperative infections [67]. This, and the avian pathogens listed earlier, together with reports of *D. gallinae* infestations in hospitals [68] highlight potential zoonotic risks associated with PRM. Thus, because of the potential vector role of PRM for zoonotic pathogens it should be included in routine medical differential diagnosis for skin lesions.

4. Control measures

Treatment and control of PRM infestations have until recently relied on the spraying of chemical acaricides in infested premises, and mostly still occurs despite the limited list of products licensed to be used against the PRM in the EU. In general, traditional control actions achieve only temporary effects and mite populations return to levels prior to treatment soon after treatment application. One of the main limitations in the use of pesticides is the incapacity to apply the product to a degree that does not allow the target to escape from exposure by hiding in cracks and crevices [38]. Another significant problem in the use of pesticides is the emergence of resistances [69]. The number of PRM populations with reduced sensibility to traditional pesticides as λ-Cyhalothrin or Amitraz has grown especially after 2012. In the case of Phoxim, which has been considered a highly effective compound, highly resistant populations have been detected since 2015 [70]. This is probably related to withdrawal of most of the labeled compounds from the marked and subsequent overuse and misuse of the only remaining products available. The single chemical pesticide that shows satisfactory results is a recent labeled to be used as poultry isoxazoline, Fluralaner. Fluralaner has demonstrated a nearly

100% efficacy after two applications in poultry farms [71]. The key for this product is that with the oral administration the treatment reaches the whole mite population when the mites feed on the hens. This delivery method avoids the necessity to spray the product, a way of administration that has been proven of low efficacy for the control of PRM as there are mites that escape from the treatment.

An often-neglected tool for the control of PRM infestations in a layer hen house is the monitorization of the population. Many treatments do not show the expected results because they have not been applied at the right moment. The decision for applying treatment is traditionally taken when the farm employees announce a severe infestation, which is usually too late to allow successful control [72]. A proper monitorization routine can promote early detection and quantification of the infestation level and thus allowing proper programming of control measures. There are multiple methodologies that can be used for monitorization, including both quantitative and qualitative techniques. A description of the most commonly used monitoring methods has been recently reviewed [73]. Many monitoring systems are based on the placement of traps that emulate the hiding places of the mites and that are checked periodically. In this way, depending on the technique the farmer can obtain an estimate of the mite population in the hen house and/or a trend for the mite population evolution. There appears not be a single best choice for a monitoring method as it depends on the time and resources available in the farm. However, farms with monitoring programs in place can improve their capacity of PRM control [74].

Development of new control interventions is currently a priority in PRM research as a consequence of the severe impact of the mite in the egg-laying industry and the scarce resources for its control (**Figure 2**). Amongst those novel methods, treatments with essential oils and plant extracts have received significant attention. There are many studies on the effects of essential oils against PRM, but variable efficacy is observed [75]. Benefits of plant extracts and essential oils include their low mammalian and bird toxicity and short environmental persistence [75]. Several plant-based products are already commercialized against veterinary pests, and many others are in research phase. Essential oils are traditionally used for their repellence of pest arthropods [75]. The effect of essential oils can be due the influence of a number of volatile organic compounds (VOCs) in the host-recognition process [20]. Recent research found that the odor emitted by the hens can be modified through addition of plant-originated VOCs to the food and that some of those VOCs showed repellent activity against the PRM, making the hens less attractive to the mites [76]. The other approach for the use of plant derived compounds is using its insecticide properties for treating the hen house environment. Amongst those substances, neem oil is receiving special attention from researchers [75, 77]. Neem oil preparations are made of essential oil obtained from an Indian tree (*Azadirachta indica*) and have shown promising effects in PRM population reductions [77]. A disadvantage of neem oil application is the possible effects of the oily film on the farm installations and eggs, but technological improvements such as reducing the volume of solution or the droplet size can be applied to reduce these adverse effects [77].

Mite communities constituted by different mite species are able to establish themselves in layer farm buildings, mainly associated with manure [78]. These communities include mite species that are predators of free-living nematodes and arthropods, including mites [78]. Some *Hypoaspis* species identified in starling nests are considered putative predators of *D. gallinae* [79] and two mite species are already commercialized to be used in layer farms: *Androlaelaps casalis* (Androlis, APPI-group Koppert. France) and *Cheyletus eruditus* (Taurrus,

APPI-group Koppert. France). *A. casalis* have shown to control, but no to eradicate, PRM populations under laboratory conditions but was more efficient at temperatures under 30°C [80]. The authors suggested that predation can occur over other mite species when *D. gallinae* is hiding in safe places, basically at different heights (*D. gallinae* was on high areas of the cages while predators remained on the floor) [80]. Predatory mites are already effectively used in the control of phytophagous mites in greenhouses and in pig farms for the control of non-hematophagous arthropods. Biocontrol of PRM in layer farmhouses is based upon the massive release of predatory mites. The effectivity of predatory mites to control PRM infestations is variable, probably due to variations in environmental conditions [79]. The main disadvantage of using predatory mites as a control tool of *D. gallinae* is their high sensitivity to acaricides used to treat PRM infestations [78]. Thus, biocontrol using predatory mites is not compatible with the use of acaricides.

Another control method is based upon a perch design (Q-perch), which prevents the mite from reaching the hens by an electrified wire placed just beneath the perch where the bird is roosting [81]. Various desiccant dusts, diatomaceous earth and synthetic silica products are commonly used in commercial layer farms [74]. Generally, it is a measure used as a temporal constraint of PRM infestation and to reduce the number of treatments with synthetic acaricides. Inert dust kills the mite by dehydration and probably, by cuticle damage by destroying its protective wax layer [82]. The main limitation of the use of inert dusts is the limited efficacy in environments with high levels of relative humidity [82]. A synergistic effect between inert dusts and entomopathogenic fungi have been described [83]. The use of entomopathogenic fungus for the control of PRM is recent and there is limited research. Laboratory tests show promising results, and some have been tested with some success in field trials [84].

Vaccination against ectoparasites is not solely focused on the prevention of the infestation but also on the reduction of the parasite population [85]. Vaccination have demonstrated to provide high levels of protection against blood-feeding ectoparasites by reducing cattle tick populations and prevalence of certain tick-borne pathogens [86]. The only commercial vaccines against ectoparasites (TickGard and Gavac) were developed with recombinant tick midgut antigens Bm86 and Bm95 and registered for the control of cattle tick infestations [87]. This vaccines demonstrated their efficacy for the control of tick infestations while reducing the use of acaracides and encourage further research for the identification of new effective protective antigens using different approaches [88].

Vaccine development relies on the identification of proteins that can act as protective antigens to which the host develops an immune response. The identification of protective antigens in *D. gallinae* has been limited by the lack of molecular research about the mite. The description on the mite transcriptome [89] and, more recently, its genome [90] can enhance the understanding of the host–parasite relationship and the identification of protective antigens. Two approaches have been followed for PRM vaccines development, testing of mite extracts and the production of vaccines based on recombinant proteins (**Table 1**). Vaccination against PRM recombinant proteins has induced antigen specific IgY responses but variable results have been obtained when mites fed in *in vitro* tests on blood from immunized hens or blood enriched with antibodies extracted from egg yolk. Another limitation for the assessment of efficacy of a candidate antigen has been the high background effects observed in the *in vitro* tests due to the feeding physiology of the PRM. A recent optimization of an on-hen feeding device allows a more physiological evaluation of the vaccine effects allowing a better

Antigen	Type	Species	Adjuvant	Test	Effects (%)	Reference
Soluble protein mite extract	Native	*D. gallinae*	Incomplete Freund's	In vivo [92]	↑ 0.1 M	[92]
Soluble protein mite extract			QuilA	In vitro [93]	↑ 24 M	[94]
IEX Group 4					↑ 23.5 M*	[94]
IEX Group 5					↑ 11.4 M*	[94]
IEX Group 2					↓ 4.2 M	[94]
IEX Group 1					↑ 19.5 M*	[94]
IEX Group 3					↑ 13 M*	[94]
PBS soluble mite extract					↑ 10.1 M*	[93]
Membrane associated					↑ 2.2 M	[93]
Urea soluble					↑ 0.2 M	[93]
Integral membrane					↓ 1.5 M	[93]
Mite extract			ISA 50 V	In vitro [95]	↑ 50.7 M*	[95]
Soluble protein mite extract			ISA 207 VG	Field	↓ 78 Pop*	[96]
Akirin	Recombinant	*Aedes albopictus*	ISA 50 V	In vitro [95]	↑ 35.1 M*	[97]
Bm86		*Rhipicephalus microplus*			↑ 23 M*	[97]
Histamine release factor		*D. gallinae*	QuilA	In vitro [98]	↑ 4.1 M*	[99]
Cathepsin D-1				In vitro [93]	↑ 6.9 M*	[100]
Cathepsin L-1					↑ 2.6 M*	[100]
Unknown function protein 1					↑ 18.4 M*	[94]
Unknown function protein 2					↑ 0.6 M	[94]
Aspartyl proteinase					↑ 5.6 M	[94]

Antigen	Type	Species	Adjuvant	Test	Effects (%)	Reference
Phosphoglycerate dehydrogenase	Recombinant	*D. gallinae*	QuilA	In vitro [93]	↑ 4.1 M	[94]
Serpin-1					↑ 12 M*	[94]
Hemelipoglycoprotein-1					↑ 18.9 M *	[94]
Vitellogenin-1					↑ 21.9 M*	[94]
Peptidase C1A-like cysteine proteinase					↑ 14.5 M	[94]
Serpin-2					↓ 8.2 M	[94]
Unknown function protein 3					↑ 3.5 M	[94]
Paramyosin					↑ 20.1 M*	[101]
Tropomyosin					↑16.5 M*	[101]
Deg-SRP-1 + Deg-VIT-1 + Deg-PUF-1			ISA 70 VG	Field	—	[96]
Calumenin			ISA 71 VG	On hen [79]	↓ 35 O*	[102]
Akirin					↓ 42 O*	[103]
Cathepsin D-1					↓ 50 O*	[104]
Subolesin		*Rhipicephalus microplus*			↓ 44 O*	[102]
Cathepsin D-1	DNA	*D. gallinae*	chicken IL-21		—	[104]
Cathepsin D-1			*Eimeria tenella*		—	[104]

Abbreviations: M, mortality; O, Oviposition; ↑, increase; ↓, reduction.
**The effects are statistically significant.*

Table 1.
Antigens tested as vaccine candidates against infestations by D. gallinae.

assessment of novel antigens [91]. Vaccines can be considered as an alternative and complementary intervention for PRM control, which can reduce the use of acaricides.

5. Conclusions and future directions

The negative impact of the PRM infestations have become more relevant with recent changes in the production systems, and it is expected to become worse as the market demands more welfare focused systems that reduce the options for controlling poultry infestations. These changes in the production procedures should include increased concerns in biosecurity and monitorization in order to achieve a better understanding of the mite ecology on each farm. PRM infestations constitute a challenge for the modern industry to guarantee hen welfare and prevention of risks for the workers.

Omics are a promising tool for enhancing the understanding of the mite-host interactions. These techniques are needed to resolve questions that are yet to be answered such as the determination of the role of the PRM as biological vectors for both poultry and human pathogens and the different mechanisms involved in the immune response in hens or if there are any on the mite side to modulate its host response. Alternative control methods and particularly vaccine are urgently needed for the effective and sustainable control of PRM infestations with the optimization and combination of different interventions.

See methodology for bibliometric analysis.

6. Methodology

6.1 Bibliometric analysis

A bibliometric analysis was performed in the web database Scopus (https://www.scopus.com) with the search code "dermanyssus AND gallinae" (date accessed: Sep 16, 2019). The search generated a total of 418 entries, from which 56 entries (14.4%) were published in the last 2 years (2018 and 2019). After the search was completed, we selected those references that addressed the main topics reviewed in this work.

6.2 Scanning electron microscope (SEM) imaging

Images obtained by scanning electron microscope (SEM) were used in **Figure 1** to show morphological characters that are useful for species identification [14]. The adult female mite used for SEM photography was dehydrated in absolute ethanol for 24 h. Specimens were mounted onto standard aluminum SEM stubs using conductive carbon adhesive tabs. Mites were observed and photographed with a field emission scanning electron microscope (Zeiss GeminiSEM 500, Oberkochen, Germany) operating in high vacuum mode at an accelerating voltage of 2 kV in the absence of metallic coating.

6.3 Points of action for control measures

The determination of the points of action for the different control measures was obtained based on the data available in previous works [1, 20, 22, 74–77, 79, 82, 103, 104].

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