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Special Collection: Perspective on Biology and Management of Bed Bugs

Perspective on Biology and Management of Bed Bugs: Introduction

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Abstract

Bed bugs are an important group of medical and urban insect pests. They are obligate blood-feeders. Their bites may cause skin irritation and allergic reactions and, under some circumstances, may lead to mental and other health issues. Despite numerous discoveries on the biology of these obnoxious pests and progress in control strategies over the last two decades, bed bugs continue to preferentially plague those from low socioeconomic communities because the poor generally could not afford effective control options. As a result, such infestations in poorer communities serve as a reservoir for wider society. This Special Collection of the Perspective on Biology and Management of Bed Bugs presents nine original research papers on bed bug detection, insecticide performance and resistance, nonchemical treatment, fungal biopesticides, and pest management procurement and contracts. We hope that these investigative findings will spur research on safer, more affordable, and effective control options in the future.

Key words: *Cimex lectularius*, *Cimex hemipterus*, chemical control, nonchemical control, detection

The global resurgence of bed bugs has been a significant challenge to the pest management industry and a public health concern globally over the last two decades (Doggett et al. 2018). Bed bug infestations are no longer limited to homes, hotels, and motels; these days, infestations also are found in commercial buildings, health care facilities (Sheele et al. 2017), offices (Sked et al. 2019), libraries (Salter 2019), and mass transportation including trains (Anders et al. 2010), ships (Lilly and Jones 2018), and airplanes (Juson and Juson 2018). Many people bitten by bed bugs experience skin irritation and allergic reactions (Hwang et al. 2018). Scratching may lead to secondary bacterial infections (Sheele et al. 2019), although this is uncommon in otherwise healthy individuals. Bed bug bites may result in mental (Ashcroft et al. 2015, Wang et al. 2016a) and other health impacts, including blood loss and respiratory issues due to exposure to bed bug allergens (Doggett 2018).

The current bed bug global resurgence involves two species, the common bed bug *Cimex lectularius* Linnaeus and the tropical bed bug *Cimex hemipterus* (Fabricius) (Doggett et al. 2018). *C. lectularius* is most prevalent in temperate regions, whereas *C. hemipterus* is found mainly in tropical and subtropical areas. Despite the importance of *C. hemipterus*, research on this species has been limited compared to *C. lectularius*, due mainly to presence of fewer researchers in countries where tropical bed bugs are prevalent, and less money in countries where vector-borne diseases take the majority share of entomological research funding. With modern building design and indoor climate control systems, the indoor environment is becoming progressively more uniform worldwide. This will inevitably increase the number of localities where both species may be found. For example, over the last five years, tropical bed bugs have been reported in various regions of Europe, including Central Europe (Balvin et al. 2021), France (Bèrenger and Pluot-Sigwalt 2017, Chebbah et al. 2021), Sweden (Naylor et al. 2018), Italy (Masini et al. 2020), Spain (Pradera and Ruiz 2020), and Russia (Gapon 2016, Prisniy 2020).

The resurgence of bed bugs is hypothesized to be due to several reasons, including globalization and the ease of human travel, changing pest management strategies from residual sprays to more target-specific treatment along with poor pest management procedures, and insecticide resistance (Doggett et al. 2018). The latter has been primarily incriminated for the initiation of the resurgence (Davies et al. 2012, Koganemaru et al. 2013, Dang et al. 2017, Romero 2018).

Over the past 15 years, there has been a marked increase in research interest in bed bug biology and management. The availability of various modern techniques has allowed us to advance our knowledge of this cryptic species, particularly insecticide efficacy, insecticide resistance mechanisms (Dang et al. 2017), population monitoring and trapping (Cooper and Wang 2018), population genetics (Booth et al. 2018), microbiome (Goodman 2018), chemical ecology (Gries 2018), and potential control technologies such as RNAi (Moriyama et al. 2016, Basnet et al. 2018). In addition, there are significant interests in novel treatment strategies such as the use of botanical insecticides (Gaire et al. 2020), fungal agents (Barbarin et al. 2017), bed bug baits (Sierras and Schal 2017, Sierras et al. 2018), nonchemical approaches including heat (Pereira et al. 2009, Loudon 2017, Wang et al. 2018, Ramos et al. 2022) and cold treatment (Olson et al. 2013), vacuuming (Liu and Haynes 2016), fumigants (Zheng et al. 2013, Todd et al. 2021), desiccant dust (Akhtar and Isman 2016, Lee et al. 2018b), and nanomaterials (Szyndler et al. 2013).

In this Special Collection, we have nine original bed bug papers covering the topics of detection (Wilson and Miller 2022), insecticide performance and resistance (Dang et al. 2021, 2022; Kells and Kells 2022, Leong et al. 2022), nonchemical treatment (Kong et al. 2022, Ramos et al. 2022), fungal biopesticides (Dery and Choe 2022), and pest management procurement and contracts (Rukke et al. 2022). Four of these papers deal with *C. hemipterus*.

Despite widespread insecticide resistance, chemical control remains the mainstay of bed bug method. Dang et al. (2021 of this collection) investigated insecticide resistance mechanisms in *C. hemipterus* populations collected from Malaysia and Australia. All *C. hemipterus* strains possessed high resistance to DDT and pyrethroids, and moderate to high resistance to malathion. Synergism studies showed that deltamethrin resistance in all strains was inhibited by piperonyl butoxide, indicating the involvement of cytochrome P450 monooxygenases in pyrethroid resistance. It was also found that malathion resistance was reduced by *S,S,S*-tributyl phosphorotrithioate [DEF] in all strains, indicating the involvement of elevated esterases. Molecular detection revealed three *kdr* mutations, M918I, D953G, and L1014F, with M918I + L1014F mutations conferring *super-kdr* characteristics in *C. hemipterus*.

Pyrethroid-neonicotinoid mixture formulations have recently become available as a resistance management tool against bed bugs. Although many previous studies have reported excellent performance of mixture formulations (Potter et al. 2012; Wang et al. 2015, 2016b), Gordon et al. (2014) demonstrated the performance of a beta-cyfluthrin + imidacloprid mixture could decline after just one generation with insecticide selection. Dang et al. (2022 of this collection) evaluated the performance of two pyrethroid-neonicotinoid mixtures, Temprid SC (Bayer Environmental Science, Cary, NC) (containing beta-cyfluthrin + imidacloprid), and Tandem (Syngenta Crop Protection LLC, Greensboro, NC) (containing lambda-cyhalothrin + thiamethoxam) on two substrates (glass and filter paper) against eight *C. hemipterus* strains collected from Malaysia and Australia. All strains showed low mortality (<37%) after 120 h exposure to Temprid SC-, or Tandem-treated filter paper. In contrast, Temprid SC and Tandem residues on glass provided 43–100% and 100% mortality, respectively.

While most insecticides against bed bugs are in residual spray, aerosol, or dust formulations, they are also available in a resin strip, total release foggers, and pyrethroid-impregnated fabrics (mainly permethrin) used as mattress covers or liners (Lee et al. 2018b). In a multi-country collaborative study, Leong et al. (2022 of this collection) evaluated a permethrin-impregnated mattress liner, ActiveGuard (Allergy Technologies LLC, Ambler, PA), against 24 bed bug strains (consisting of *C. hemipterus* and *C. lectularius*) with varying levels of pyrethroid resistance in a series of experiments. They recorded incomplete knockdown for most modern bed bug strains, with many strains still having no mortality even after seven days of constant exposure on the liner. The authors concluded that the pyrethroid-impregnated mattress liners might have limited efficacy in managing most modern infestations of *C. hemipterus* and *C. lectularius*.

Earlier studies revealed that the effectiveness of a halogenated pyrrole, chlorfenapyr, commonly used against bed bugs, was highly variable, ranging from poor (Moore and Miller 2006, Doggett et al. 2012, Ashbrook et al. 2017), to moderate performance (Potter et al. 2008), to highly efficacious (Wang et al. 2016b). Variation in performance was found between spray and aerosol formulations (Lee et al. 2018b). Kells and Kells (2022 of this collection) investigated chlorfenapyr uptake in *C. lectularius* using aerosol and suspended concentrate (SC) formulations and reported that the chlorfenapyr uptake increased with time. Still, the rate of external chlorfenapyr adsorption between the two formulations did not differ significantly. On the contrary, there was greater chlorfenapyr internal uptake from aerosol application than from the SC spray. The absorption of chlorfenapyr residues inside the insects was considerably lower than external adsorption.

Heat treatment is a nonchemical option to control insecticide-resistant bed bugs. Ramos et al. (2022 of this collection) conducted a simulated study to compare the performance of steam application and an insecticide mixture spray (containing 0.05% acetamiprid and 0.06% bifenthrin) against *C. lectularius* in the laboratory. They found both treatments were highly effective, with no significant difference between the steam and spray treatments based on visual inspection or bed bug trap counts. However, the steam treatment reduced the bed bug numbers faster.

Kong et al. (2022 of this collection) monitored *C. hemipterus* in 125 dormitories in two buildings in Guangzhou, China, using pitfall traps and found that 20% of the dormitories were infested. The infested dormitories exhibited an aggregated pattern which means that the neighboring rooms of the infested rooms (sharing walls) had a greater probability of being infested. They treated the infested rooms with a combination of steam and diatomaceous earth (DE) dust and eliminated bed bugs in 44% of the infested rooms 14 weeks post-treatment. The mean number of bed bugs caught per room also decreased by 94.1%. They concluded that combining steam and DE dust treatment effectively reduced *C. hemipterus* in dormitories, although further work was required to eradicate infestations.

Beyond heat treatment, entomopathogenic fungi can be used as a biopesticide to control bed bugs. Since 2017, a liquid spray formulation of *Beauveria bassiana* has been available for bed bug treatment in the United States. Dery and Choe (2022 of this collection) reported that synthetic aldehydes blend similar to those found in freshly-shed 5th instar exuviae could reduce or delay the performance of fungal biopesticides against *C. lectularius* in the laboratory. Further studies also revealed that the growth of *B. bassiana* in culture was reduced and delayed by the bed bug aldehydes confirming their antifungal properties as reported in previous studies (Fallik et al. 1998, Archbold et al. 1999, Ulrich et al. 2015).

The task of successfully eradicating bed bugs is always thought to be the sole responsibility of pest management professionals. Purchase and supply management theory, however, suggests that buyer–supplier relations are crucial in achieving the final objective of pest eradication. Rukke et al. (2022 of this collection) investigated the cost and quality of bed bug control services by implementing a systematic framework aided by information and good knowledge of control and monitoring procedures in a large-scale study involving 11,000 apartment units in Oslo, Norway. Bed bug eradication success increased with the number of visits to the infested apartments and the greater duration of control efforts. They also found the implementation of bed bug preventive measures and building-wide inspections improved control outcomes, while at the same time reducing the cost per infested apartment.

Finally, Wilson and Miller (2022 of this collection) quantified the fecal spots that a *C. lectularius* population produced over time. They found that adults and different instars of *C. lectularius* produced visible fecal spots (dark and light) and clear spots (detectable only under UV light), with the latter produced in greater quantities. The findings from this study successfully quantify bed bug fecal production and will allow researchers to predict infestation duration in the field.

A recent study found that bed bug complaints in New York City decreased from 2014 to 2020, compared to those of other insect pests such as cockroaches and flies (Hacker et al. 2022). However, the authors found high bed bug infestations continued to be prevalent in certain areas. Building-wide surveys revealed an average 9% bed bug infestation rate in low-income apartments in New Jersey (Abbar et al. 2022).

It remains vague how much bed bug infestations are costing the world economy. In the United States alone, the financial impact of bed bug management is estimated to be at a staggering US$1 billion per year (Lee et al. 2018a). While we have made some progress in managing the present resurgence of bed bugs, the light at the end of the tunnel remains unseen. Unfortunately, bed bugs mainly affect people of lower socioeconomic status who cannot afford expensive and effective control options (Lee et al. 2018a). In many situations, when bed bug eradication is not achieved, infestations in low-income houses can become massive and serve as an insecticide-resistant bed bug reservoir for spread throughout the community. It is anticipated that bed bugs will continue to be a significant urban pest for many years to come. We hope this Special Collection will stimulate more research and better processes for managing this group of medically and economically important urban pests in the future.

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