Insecticides and Soil Collembola: An Overview

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ABSTRACT

Collembola or springtails are considered to be good model organisms for determining ecological toxicity and are used as non-target bio-indicators in environmental assessments. The susceptibility of these micro-arthropods to different edaphic perturbations is remarkable. One significant element leading to the degradation of soil quality in modern times is the indiscriminate use of insecticides in agricultural fields. Even while using insecticides in agriculture might be profitable, the harmful consequences of these chemicals affect not just the targeted pests that are intended to harm but also a variety of important soil fauna. The adoption of sustainable farming methods is the key to cultivating and conserving a diversified soil community, which plays critical roles in supplying functions and services throughout ecosystems. The goal of this review is to thoroughly explain the negative effects of insecticides on these vital micro-arthropods. An examination of the effects of several insecticides on various Collembola species reveals that collembola is among one of the most vulnerable soil fauna to insecticide contamination. This susceptibility endangers these organisms’ well-being and emphasizes the significance of recognizing their ecological responsibilities in the context of sustainable agricultural management.

Key words: Collembola, Bio indicator, Pesticides, Insecticides, Threats to the ecosystem

Introduction

In the contemporary world, the environment is under increasing stress from a variety of man-made sources, resulting in negative consequences on biodiversity, air, soil, and water quality, habitat loss, and community dynamics (Johnsons et al., 2017; Nielsen, 2019; Sala et al., 2000; Scheffers et al., 2016; Evenrud, 2020). The intricate nature of the soil, constituting nearly a quarter of the planet’s biodiversity, emphasizes its role as the most complex and heterogeneous ecosystem on Earth (Ram, 2019). When soil organisms are subjected to several stressors at once, this complexity is increased, making it more difficult to predict and comprehend the subsequent repercussions (Holmstrup et al., 2010; Evenrud, 2020).

The function of earthworms in soil is now well understood, and they are frequently utilized in studies as a biological model. However, smaller-sized organisms also play a role in the operation of agro ecosystems, and their susceptibility to pesticides and insecticides makes them useful bio-indicators of soil quality, and collembola in particular exemplifies this (Cortet et al., 1999). Collembola or springtails are hexapods, wingless micro-arthropods that belong to mesofauna (Gunstone et al., 2021) and perform arrays of ecosystem services, beneficial for maintaining soil health as well as agricultural sustainability.
(Kibblewhite et al., 2007). They help to transport nutrients by converting the rotting material and minerals into usable forms. Microbial activities are also influenced by them and thus increase soil fertility (Hopkin, 1997). Being a key member of the soil ecosystem, the total biomass of soil invertebrates can be constituted significantly by the springtail. They mainly feed on fungal hyphae and propagate the same during feeding (Sahana and Joy, 2016). However, these microarthropods are very much sensitive to any kind of perturbations in the soil as they are detritivores in nature, and through the food, they are directly exposed to various xenobionts (Joimel et al., 2022). Because most Collembo lacks a tracheal apparatus, gas exchange occurs by diffusion across the body surface (OECD, 2016). Apart from the gas exchange, additional molecules are going to be moving through the cuticle, including hazardous and toxic ones (Evenrud, 2020). Due to their sensitivity to different kinds of pesticides and insecticides, collembola are considered good bio-indicators to assess soil quality. Moreover, they can be cultured easily in the laboratory, and also for their heterogeneity and abundance in the soil make them very useful model organisms for eco-toxicological purposes. Collembo species Folsomia candida has been used as a “standard” test organism for evaluating the effects of insecticides and environmental contaminants on nontarget soil arthropods for over 40 years (Fountain and Hopkin, 2005). In addition to Folsomia candida other collembola species are also suggested and utilized as test species for chemicals (OECD, 2016). Collembola is a good model organism for research with a life-history approach, and this method, combined with toxicological studies, can help us understand the underlying primary and secondary impacts of chemicals (Evenrud, 2020). Nonetheless, interpreting the impacts of insecticides on a soil community based on eco-toxicological experiments remains difficult. The scarcity of important information for terrestrial invertebrate species impedes not only the development of environmental soil quality criteria for pollutants in surface soils but also a comprehensive risk assessment of the soil invertebrate community (Princz et al., 2018).

The objective of the study is to evaluate the significance of soil collembola in both ecosystem functioning and soil health. The research highlights potential significant risks arising from the widespread application of insecticides for agricultural purposes, which adversely impact these non-target, beneficial soil micro-arthropods and compromise their ecological functions. This, in turn, has cascading effects on the overall well-being of the ecosystem. Consequently, collembola emerges as a promising indicator for assessing the intrinsic vitality of soil, especially in the contemporary scenario where soil contamination from insecticides poses a complex challenge similar to other forms of environmental pollution.

**Pesticides and its types**

Pesticides play a vital role in modern agricultural practices, significantly impacting crop yields and

<table>
<thead>
<tr>
<th>Types of Pesticides</th>
<th>Use and Action</th>
<th>Examples</th>
</tr>
</thead>
<tbody>
<tr>
<td>Herbicides</td>
<td>Substances that are used to manage weeds that grow alongside the intended species and hamper plant growth.</td>
<td>Glyphosate, Atrazine, Pendimethalin</td>
</tr>
<tr>
<td>Insecticides</td>
<td>Substances are introduced to regulate or prevent insect attacks that destroy plants or animals.</td>
<td>Imidacloprid, Chlorpyrifos, Cypermethrin, Dimethoate</td>
</tr>
<tr>
<td>Fungicides</td>
<td>Chemicals that prevent or kill the growth of fungi affect animals and plants.</td>
<td>Carbendazim, Mancozeb, Difenoconazole, Carbofuran</td>
</tr>
<tr>
<td>Nematicides</td>
<td>Substances are employed to deter or prevent nematodes from affecting different crops.</td>
<td>Aldicarb</td>
</tr>
<tr>
<td>Rodenticides</td>
<td>Chemicals that are introduced to kill rodents i.e. rats and mice.</td>
<td>Arsenous oxide, Warfarin</td>
</tr>
<tr>
<td>Molluscicides</td>
<td>Substances are employed to slow down the growth and kill slugs and snails.</td>
<td>Copper sulfate</td>
</tr>
<tr>
<td>Plant growth regulators</td>
<td>A chemical that either slows down or speeds up the plant growth process or maturation.</td>
<td>Acibenzolar</td>
</tr>
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</table>
economic returns. However, their widespread and indiscriminate application also leads to soil degradation (Önder et al., 2011). Widespread use of pesticides is one of the primary reasons for soil biodiversity decline, based on the Food and Agricultural Organization’s (FAO) 2018 Soil Biodiversity Survey (FAO, 2018). Pesticides are classified into several groups and each group is specifically designed to target pests, but they put undesired toxic effects on non-target organisms. Table 1 lists the major classes of pesticides and their uses.

Among the different classes of pesticides, insecticides are known as one of the major classes that contribute greatly to pest control and are further divided into different groups. Under the Insecticide Resistance Action Committee IRAC 2016 (IRAC, 2016), insecticides can be classified into five main groups based on their chemical nature (Table 2).

Use of pesticides and insecticides in world-wide and India

In recent years there has been an increasing demand for pesticides and when it comes to the most pesticide used in countries in the world, the United States of America (USA) is placed at the top (FAO, 2022). In 2020, the USA was the largest pesticide-using country with 408 kilotons (kt) of pesticides used for agricultural purposes. Brazil and China placed at 2nd and 3rd position with 377 kt and 273 kt of pesticides used respectively. India has placed 9th in the list with 61 kt of pesticides used (Figure 1).

In a developing country like India, pesticide pollution is a prevalent problem as agriculture is a major source of revenue. In India, insecticides are dominant (Fig. 2) among all the pesticides that are used for various agricultural purposes (FICCI, 2015). Cotton pest management receives 50% of the pesticides used for overall pest management in India (Mooventhan et al., 2020). According to Research and Markets, the Indian pesticide business was worth Rs 214 billion in 2019. By 2024, the market is anticipated to increase by 8.1% annually, to reach

| Table 2. Classification of insecticides based on their chemical nature (IRAC, 2016) |
|-----------------------------------------------|-------------------------------|
| Main Groups | Action | Example |
| Organochlorines | bind to the GABA receptor and stop the influx of chloride into the neurological system of the intended organisms | Chlordane, Endosulfan, Aldrin |
| Organophosphates | impede AChe activity in target organisms’ neural systems | Carbafuran, Carbaryl, Aldicarb |
| Pyrethroids | inhibit the activity of acetylcholinesterase (AChe) in the neural systems of target organisms. | Chlorpyrifos, Diazion, Phorate, Parathion |
| Carbamates | acts on the nervous system that alter the permeability of neuronal membranes to potassium and sodium ions | Pyrethrins, Cypermethrin, alpha-Cypermethrin, beta-Cypermethrin, theta- Cypermethrin |
| Neonicotinoids | efficient against a variety of insects because it acts as an acetylcholine agonist. | Imidaclopid, Thiaclopid, Clothianidin, Acetamiprid |
Rs. 316 billion (TAAS, 2020). Organophosphates are the insecticides that are used the most, followed by neonicotinoids and pyrethroids. The organophosphate insecticide chlorpyrifos is the most often used (Figure 3), with its use increasing from 471 MT (Metric Tonnes) in 2014-15 to 1431 MT in 2019-20 (Nayak and Solanki, 2021).

Soil environment and insecticides

Soil biodiversity is enormous, with an estimated 10-100 million species from over 5000 taxa living in a handful of soil (Ramirez et al., 2015). Numerous macro invertebrate and nematode species, as well as a large array of microorganisms, including hundreds of fungal and thousands of bacterial species, make up a typical functional soil community (Bardgett and van der Putten, 2014; Ram, 2019; Singh et al., 2019). Soil communities are basically graded systems (Figure 4) and are differentiated mainly into five classes; microbes are 20 nanometers (nm) to 10 microns (µ) in size including viruses, bacteria, fungi, etc. and microfauna include soil protozoa and nematodes ranging from 10 micrometers (µm)- 0.1 millimeters (mm) in sizes. Mesofauna (0.1 mm - 2 mm) includes mites, springtails, apterygota, etc., and large soil invertebrates (earthworms, termites, etc.) ranging from 2 mm to 20 mm in size are considered macrofauna lastly, megafauna those are larger than 20 mm, comprises the vertebrates (Wallwork, 1970).

Soil invertebrates play a significant part in soil formation and fertility management, and are frequently important components of terrestrial ecosystems, providing breakdown of organic matter, nutrient recycling, and general soil health maintenance (Stork and Eggleton, 1992). Soil organisms’ burrowing activity alters soil porosity by improving aeration, water infiltration, and retention, and decreasing compaction (Pisa et al., 2015; Ram, 2019). Tunnelers, foragers, and ground-nesting insects like beetles, ground-nesting ants, bees, and termites transport nutrients through various soil layers (Stork and Eggleton, 1992; Willis Chan et al., 2019) detritivores, such as springtails, earthworms, nematodes, millipedes, and woodlice, convert decomposing matter and minerals into usable forms, cycle nutrients, and increase soil fertility (Stork and Eggleton,1992; Kibblewhite et al., 2007; Ram, 2019). Nematodes and mites, for example, promote nitrogen mineralization by feeding on fungal roots and promoting and controlling microbial activity, whereas dead invertebrates decompose and add nitrogen to the soil (Stork and Eggleton, 1992). A healthy soil community has a diverse food web, can keep pests and illnesses under control through predation and competition, and contains a wide range of faunal species (Barrios, 2007; Widenfalk et al., 2016). Soil biota are critical to soil processes and functions, and soil communities are frequently utilized as bioindicators for soil conditions, providing quantitative assessments of physical or chemical qualities in their natural context (Stork and Eggleton, 1992; Barrios, 2007).

The use of insecticides in traditional agricultural practices worldwide to protect plants is a concern, given their damaging impacts on soil biodiversity and the ecosystem functions of live organisms.
The organisms of the soil often come into contact with insecticides, which are applied by sprays, seed coaters, leaching, fumigating, and crop cultivation practices (FAO, 2018). Insecticides may cause direct toxic and sub-lethal effects on soil invertebrates even at concentrations commonly found in the field (Pelosi et al., 2013; Pisa et al., 2014) and persistent chemicals like these can be absorbed by a large number of soil invertebrates in them (Beaumelle et al., 2017; Pelosi et al., 2021; Römbke et al., 2017). Several responses at individual and population levels are associated with direct toxic effects. For instance, insecticides can damage DNA by altering the enzyme activity, growth rates, forage conditions, and reproduction of soil invertebrates (Gunstone et al., 2021; Pelosi et al., 2013). In general, insecticides are marketed with other ingredients that are often considered to be inert substances in the final formulation. The addition of these substances is intended to increase the stability and action of an active substance, but their effects on overall activity are not often known (Mesnage et al., 2015; Simões et al., 2019). Therefore, the role of an active ingredient (a.i.) is to be assessed about its formulation and overall effects on soil biota as well as chemical properties like the rate of degradation in the soil after application.

During insecticide spraying, about 0.1% of it applied to soil and environmental surfaces reach the targeted organisms and the remainder pollutes the soil and the environment (Meena et al., 2020). Numerous insecticides may remain in the soil for a long time, years, or even decades (Navarro et al., 2007; Cabidoche et al., 2009; Hladik et al., 2018). Processes including mobilization, immobilization, bioavailability, and transport are significantly affected by the build-up of insecticides in organo-mineral components of complex structures (Gevao et al., 2003; Piccolo et al., 1998; Hussain et al., 2009). The microbial diversity, biochemical processes, and enzymatic activity are changed by the degraded insecticides (Hussain et al., 2009; Munoz-Leoz et al., 2011). There is always a potential that these xenobiotic compounds will enter different food chains and food webs because soil bacteria typically find them difficult to digest, which could lead to biococoncentration and bioaccumulation (Maurya and Malik, 2016; Dureja and Tanwar, 2012; Edwards and Bohlen, 1992; Paoletti, 1999).

**Impact of insecticides on soil Collembola**

Collembola live on the soil’s surface, rendering them vulnerable to the direct influence of insecticides on their population levels (Bitzer et al., 2002). They not only contribute considerably to soil processes but also serve as a helpful indicator for assessing soil quality (Briones, 2014).

The organophosphates and carbamates insecticides inhibit the essential neurotransmitter, acetylcholinesterase (AChE) and act as a potential neurotoxicant, while organochlorines disrupt the chloride flow at the nervous system by binding to the gamma-aminobutyric acid (GABA) site (Migliani and Bisht, 2019). Even though organophosphates have a shorter persistence than organochlorines, their widespread use has caused concern among government officials and environmentalists (Ajiboye et al., 2022).

Migliani and Bisht (2019) reported that pyrethroid insecticides affect the neuronal membrane permeability to sodium and potassium ions, which interacts with ecological factors impacting soil-dwelling Collembola populations. Choi et al. (2006) studied temperature and moisture as critical factors influencing the ecology of soil-dwelling Collembola. Expanding on this, Top of Form Bandow et al. (2014) stated that temperature has a substantial effect on the toxicity of the insecticide lambda-cyhalothrin on two Collembola species, Folsomia candida and Sinella curviseta. Higher temperatures increase the insecticide’s toxicity to F. candida while decreasing toxicity to S. curviseta.

Fipronil, a phenylpyrazole insecticide, is substantially more effective against insects and targets the GABA-gated chloride channel (Cole et al., 2006; Bloomquist, 2003). Toxic effects of recommended fipronil doses are experienced by terrestrial invertebrates, including collembola, and the survival and reproduction of the organisms were significantly impacted by soil composition, particularly at high soil moisture contents (Triques et al., 2022).

Another group of insecticides, neonicotinoids work by binding to nicotinic acetylcholine receptors (nAChR) on the post-synaptic membrane of insect neurons. They engage in agonistic binding, also known to compete with acetylcholine (Ach) neurotransmitters, to bind to and activate the nAChR. Irreversible binding causes excessive ion fluxes (Na+, K+, Ca2+) via cellular membranes and extended action potentials, resulting in neuron overexcitation.
Exposed animals exhibit signs of confusion and paralysis, and finally die (Buckingham et al., 1997; Matsuda et al., 2001; Sheets, 2001; Millar and Denholm, 2007; Goulson, 2013; van Gestel et al., 2017). Due to their effectiveness against a variety of plant-eating insects like aphids, leafhoppers, and whiteflies, these compounds are the most popular and commonly used class of insecticides (Jeschke et al., 2011). Imidacloprid is the most widely used neonicotinoid, with a wide range of applications (Nauens et al., 2008). Its high water solubility makes it easier for it to be transported with water runoff (Bonmatin et al., 2014) and more than 90% of imidacloprid on treated crops normally enters the soil (Goulson, 2013). Because imidacloprid is highly soluble in water and may rapidly permeate via the ventral tubes of springtails, soil pore water is the principal route of exposure for these organisms (Ogunbemi and van Gestel, 2018). There is growing evidence that soil-dwelling collembola is vulnerable to neonicotinoid insecticides, with consequences on both survival and reproduction (van Gestel et al., 2017).

**Impact of insecticides on growth and survival of Collembola**

Scientists have identified several life history parameters in collembola that have proven to be potential biomarker indices. These biomarker characteristics are sensitive to many insecticides and can respond swiftly to the negative impacts of such environmental pollutants (Sahana, 2018). In the soil of wheat and mustard fields, aldrin and endosulfan (organochlorine) consistently reduced the density of collembolan (Joy and Chakravorty, 1991). Dimethoate, an organophosphate group of insecticides, impacts collembola survival and reproduction; both F. fimetaria and F. candida are susceptible to it, with F. fimetaria being more so (Krogh, 1995). Both the organophosphates, chlorpyrifos, and dimethoate caused a strong decline in the density of total collembola, with chlorpyrifos reducing collembolan density to a greater extent than dimethoate (Endlweber et al., 2006). While another study found that when given alone, chlorpyrifos did not affect springtail growth, it dramatically lessened the growth retardation caused by nickel (Broerse and van Gestel, 2010). Al-Haifí et al. (2006) reported the population of non-target arthropods like collembola is drastically reduced by organophosphates dimethoate and omethoate. In field research, Fountain et al. (2007) found that the insecticide chlorpyrifos had negative impacts on the richness, diversity, and evenness of twelve species of Collembola. The survival of F. candida was significantly harmed by profenofos (organophosphate) (Liu et al., 2012). Jenkins et al. (2013) observed a significant drop in springtail populations after the application of omethoate (organophosphate) and bifenthrin (pyrethroid) when investigating the effect of broad-spectrum insecticides on soil organisms. The survival of Isotoma decorate (Collembola) was below 1% even at the recommended doses of endosulfan and chlorpyrifos (Ahmed et al., 2021). A pyrethroid group of insecticide cypermethrin significantly reduced springtail survival rates and reproduction at its various concentrations (Zortéa et al., 2015). Whereas Wiles and Frampton (1996) have reported, that among three insecticides such as cypermethrin, pirimicarb, and chlorpyrifos, the third one showed the highest toxicity to four species of springtails (Isotoma viridis, Isotomurus palustris, F. candida and Sminthurus viridis) with S. viridis was the most susceptible one. On a field trial, they discovered that cypermethrin had a low toxicity to F. candida (3-10% mortality) within 48 hours of spraying. When the manufacturer’s recommendations were followed, another pyrethroid group of insecticides, etofenprox, did not cause persistent damage in F. candida populations, although it reduced the parent generation’s capacity for reproduction (Szabó, 1902). According to a study by Walker et al. (2016), the populations of collembola were significantly reduced after the application of fipronil in a eucalyptus forest, and these reductions persisted for up to 79 days. Jennig et al. (2021) reported depending on the kind of soil, exposure to fipronil at high temperatures posed a hazard to F. candida populations. Asad et al. (2020) also reported that the use of fipronil considerably reduced this soil-dwelling arthropod, hence its application should be curtailed and a substitute method should be sought out. Fipronil and carbofuran were shown to significantly diminish the Collembola population (Shyamrao, 2020). Along with imidacloprid, another neonicotinoid insecticide thiacloprid was found to be toxic to F. candida, with severe impacts on survival (for imidacloprid) and reproduction (for thiacloprid), potentially leading to population collapse over time (Mabubu et al., 2017). Imidacloprid has been proven to have both lethal and sub-lethal effects on Hypogastrura viatica (collembola) populations in the Arctic (Evenrud, 2020). Imidacloprid
de Lima e Silva et al., 2023). The findings demonstrate the diverse and frequently detrimental impacts of insecticides on the reproductive characteristics of Collembola.

Impact of insecticides on moulting of Collembola

The molting process in Collembola has been identified as a potential biomarker for assessing the ecotoxicity of insecticides and gauging the condition of the soil. This assertion is based on observations of how certain insecticides impact the molting behavior of Collembola. The toxicity of heptachlor resulted in fewer molts and a wide range of instar durations in C. javanus (Joy et al., 2005). During food exposure, the total number of molts decreased with increased imidacloprid concentration for H. viatica. When H. viatica was exposed to imidacloprid at soil-relevant concentrations, it matured later, molted less frequently, and became smaller overall (Kristiansen et al., 2021). After treatment with the insecticide cyfluthrin prolonged molting period has been observed for C. javanus compared to the control (Bhavya and Kumar, 2022).

Monitoring molting behavior provides a measurable endpoint for evaluating insecticide ecotoxicity. Alteration in molting can affect collembola population dynamics, potentially affecting reproductive success, population size, and overall contribution to the ecological balance of the soil ecosystem.

Impact of insecticides on different biochemical parameters of Collembola

The biochemical stress responses of Collembola to various xenobionts constitute a viable avenue in the search for effective soil pollution monitoring. This method is also emphasized as a potential biomarker, providing novel ways for monitoring the influence of environmental contaminants on soil ecosystems (Sahana et al., 2014).

Chakravorty et al. (1995) investigated the organophosphate and carbamate pesticide groups, specifically methyl parathion and carbaryl, and found that these compounds inhibited acetylcholinesterase activity in Collembola species, C. javanus. This finding highlights the biochemical influence of insecticides on important enzymatic pathways in Collembola, providing insights into the stress response systems in the organism. Sillapawattana and Schäffer (2016) reported that imidacloprid increased glutathione-s-transferase (GST) activity in Collembola species, F. candida, when investigating the influence of neonicotinoid insecticides. Simultaneously, the study reported a decrease in reduced glutathione (GSH) content in Collembola treated with imidacloprid. These opposing responses, an increase
in GST activity and a decrease in GSH content, show the complexities of metabolic changes in collembola in response to neonicotinoid exposure. Springtails have a unique biochemical tolerance to the phenylpyrazoles class of insecticides, implying a limited risk assessment for this specific group under natural conditions (San Miguel et al., 2008). In contrast, Bakker et al. (2022) found that neonicotinoids can disrupt detoxification mechanisms in F. candida by blocking cytochrome P450 enzymes. These findings shed light on the intricate connections that exist between specific insecticide classes and the biochemical pathways involved in the Collembola response. In summary, the studies collectively emphasize that insecticides exert a wide range of negative effects on Collembola, with some effects being concentration-dependent. The findings contribute valuable insights to the ongoing discourse on the ecological consequences of insecticide use. Some commonly used insecticides and their harmful effects on collembola are enlisted in Table 3.

Discussion

Among the several types of pesticides examined in the field of pesticide research, insecticides have received the majority of attention. Not surprisingly, considering their specialized targeting of invertebrates, insecticides were found to have the most harmful impact on soil invertebrates when compared to other types of pesticides studied (Gunstone et al., 2021). This study is consistent with existing literature (Pekar and Benes, 2008; Pekar, 2012), which generally depicts terrestrial invertebrates as being extremely vulnerable to the impacts of insecticides.

A comparative study conducted by Martin et al. (2023) provides vital insights into the variable sensitivity of Collembola, notably F. candida, to several kinds of insecticides. The study focused on the toxicological effects of six insecticides, including two neonicotinoids, diamide, keto-enol, pyridine, and butanolide, on the reproduction and survival of F. candida. The results of this investigation confirmed that F. candida is more sensitive to neonicotinoids and diamide than other insecticide classes. Imidacloprid exhibited more toxicity to Folsomia within the neonicotinoid subgroup than thiaclorpid (de Lima e Silva et al., 2017). Furthermore, Lopes et al., 2023 observed that, when compared to imidacloprid and fipronil, clothianidin posed the maximum toxicity to F. candida among seed-dressing insecticides. Panico et al. (2022) found a more comprehensive view of the effects of insecticides on soil functionality and biodiversity. Their study brought to light the risks connected to several insecticide classes when using conventional farming methods. Notably, azole and imidacloprid fungicides were found to pose significant risks to soil functionality and biodiversity. Under certain environmental conditions, such as exposure to dry soil or elevated temperature, F. candida and Sinella curviseta were more sensitive to pyrimethanil (Bandow et al., 2014). Conversely, at the recommended application doses, cypermethrin and pirimicarb did not appear to cause harm to Collembola communities engaged in arable agriculture (Frampton and Brink, 2007). These varied results highlight the need for nuanced approaches in insecticide management for the preservation of soil biodiversity and highlight the significance of taking into account both the particular insecticide class and the environmental factors when evaluating the effect of the same on Collembola populations.

Significant interspecific variations in Collembola reactions to insecticides are revealed by different studies. A notable instance, documented by Tomlin in 1975, demonstrates the divergent susceptibilities of F. candida and Onychiurus justi porter to the insecticide fensulfothion. While fensulfothion exhibited almost no toxicity to Onychiurus justi porter, it proved to be severely toxic to F. candida. This disparity in reaction highlights the fact that even closely related Collembola species can have varied degrees of sensitivity to specific insecticides. Krogh (1995) investigated the effects of dimethoate on the reproduction of two closely related microarthropods, F. candida, and F. fimetaria, to provide further light on the complexities of interspecific variability. It’s interesting to note that F. fimetaria showed greater sensitivity to dimethoate than F. candida.

Moving to more recent research, the LC50 values of imidacloprid showed that, in comparison to F. candida, this insecticide had more detrimental effects on Hypogastrura viatica (Kristiansen et al., 2021). This indicates that, even within a diverse group such as Collembola, each species may react differently to the same insecticide, needing a tailored approach to toxicity studies. Konestabo et al. (2021) added another degree of complexity by demonstrating that surface-living springtails were more strongly affected by imidacloprid treatment than their soil-dwelling
Table 3. Effect of some commonly used insecticides on soil *Collembola*

<table>
<thead>
<tr>
<th>Insecticides</th>
<th>Affected Collembola</th>
<th>Effects</th>
<th>References</th>
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</thead>
<tbody>
<tr>
<td>Aldrin, Endosulfan, Dimethoate,</td>
<td><em>Cyphoderus javanus,</em> <em>Xenylla welchi</em></td>
<td>The density of (<em>C. javanus</em>) has declined but in the case of another</td>
<td>(Joy and Chakravorty, 1991)</td>
</tr>
<tr>
<td>Imidacloprid</td>
<td><em>Hypogastrura viatica</em></td>
<td><em>Xenylla welchi</em>, a lower effect has been recorded.</td>
<td></td>
</tr>
<tr>
<td>Imidacloprid</td>
<td><em>Folsomia candida</em></td>
<td>Complete stoppage of reproductive cycles at higher concentrations</td>
<td>(Kristiansen <em>et al.</em>, 2021)</td>
</tr>
<tr>
<td>Fipronil</td>
<td><em>F. candida</em></td>
<td>A reduction in the size of the <em>F. candida</em> has been recorded.</td>
<td>(Hennig <em>et al.</em>, 2021)</td>
</tr>
<tr>
<td>Rynaxypyr, Cartap hydrochloride,</td>
<td><em>Collembola</em></td>
<td>No significant deleterious effect has been recorded.</td>
<td>(Ghosal and Hati, 2019)</td>
</tr>
<tr>
<td>Ethoprophos</td>
<td><em>F. candida</em></td>
<td>A reduction in the <em>F. candida</em> population has been observed in a</td>
<td></td>
</tr>
<tr>
<td>Chlorpyrifos</td>
<td><em>Isotomus palustris,</em> <em>Isotoma anglicana,</em></td>
<td>Reproduction in <em>collembola</em> has been affected.</td>
<td></td>
</tr>
<tr>
<td>Chlorpyrifos</td>
<td><em>Isotoma palustris,</em> <em>Parisotoma notabilis,</em></td>
<td>The <em>Species richness of springtail</em> has reduced.</td>
<td>(Fountain <em>et al.</em>, 2007)</td>
</tr>
<tr>
<td>Chlorpyrifos</td>
<td><em>Isotoma viridis,</em> <em>Isotoma viridis,</em></td>
<td>Exerts toxic effect on <em>collembola</em></td>
<td>(Wiles and Frampton, 1996)</td>
</tr>
<tr>
<td>Chlorpyrifos</td>
<td><em>Isotoma viridis,</em> <em>Isotoma palustris,</em></td>
<td>The survival and reproductive capacity were hampered</td>
<td>(Santos <em>et al.</em>, 2012)</td>
</tr>
<tr>
<td>Chlorpyrifos</td>
<td><em>F. candida</em></td>
<td>Locomotor irregularity in <em>collembola</em> has been observed</td>
<td>(Szabó <em>et al.</em>, 2018)</td>
</tr>
<tr>
<td>Endosulfan, Chlorpyrifos, Bifenthrin,</td>
<td><em>Isotoma decorata</em></td>
<td>All possessed a negative effect on <em>collembola</em> at their recommended</td>
<td>(Ahmed <em>et al.</em>, 2021)</td>
</tr>
<tr>
<td>Chlorantraniliprole</td>
<td><em>F. candida,</em> <em>F. fimetaria,</em> <em>Proisotoma minuta</em></td>
<td>All <em>collembolas, except for S. curviseta,</em> have shown sensitivity to</td>
<td>(Ferreira <em>et al.</em>, 2022)</td>
</tr>
<tr>
<td>Chlorantraniliprole</td>
<td><em>Sinella curviseta</em></td>
<td>the insecticide</td>
<td></td>
</tr>
<tr>
<td>Chlorantraniliprole</td>
<td><em>F. candida</em></td>
<td>Survival and reproduction were severely affected</td>
<td>(Lavtizar <em>et al.</em>, 2016)</td>
</tr>
</tbody>
</table>
counterparts. This emphasizes not only species-specific variations but also the impact of habitat preferences on the reactions of Collembola to insecticides.

In the Indian subcontinent, Joy and Chakravorty found that the collembola species Cyphoderus javanus showed a high level of sensitivity to specific insecticides. In particular, it was discovered that endosulfan, dimethoate, and aldrin were highly toxic to Cyphoderus, but phosphamidon was somewhat less hazardous to this species of collembola. However, it has been noted that Xenylla welchi, a different species of collembola, is less susceptible to many of these insecticides (Rajagopal et al., 1990) evaluated the impact of four insecticides- carbosulfan, chlorpyrifos, isofenphos, and phorate-on non-target soil arthropods with a particular focus on Collembola and soil mites (Sharma, 2005) found that the number of collembola reduced as a result of treatment with γ-BHC, quinalphos, and cypermethrin. Anbarashan and Gopalswamy (2013) demonstrated the significant negative impact of insecticide use on non-target arthropods, particularly collembola, in conventional fields. Collembola, on the other hand, was found to be safe from the insecticides thiodicarb and emamectin benzoate in a 2017 study by Alam et al. (2017). These studies highlight the diverse responses of different Collembola species to various insecticides in the Indian subcontinent, underlining the importance of developing a more subtle understanding of the ecological interactions between these organisms and chemical inputs in agricultural ecosystems.

The data reported above support the proposition that soil Collembola can be utilized as an effective index for measuring the toxicological effects of insecticides, as highlighted by Joy and Chakravorty in 1995. Numerous researchers have identified the significant potential of soil Collembola as bioindicators; nevertheless, there are significant gaps in biomarker or bioindicator studies involving soil collembola, particularly in the context of Indian tropical edaphic conditions (Sahana, 2018). While the use of various classes of insecticides is critical for maximizing agricultural productivity, it is also critical to evaluate the potential detrimental side effects of these compounds. Recognizing and resolving these negative impacts is critical for minimizing soil contamination, which is necessary for the maintenance of soil biodiversity. All of the data emphasize the necessity of a well-rounded strategy that maximizes agricultural output while reducing environmental impact and protecting soil ecosystems over the long run.

Conclusion

The study emphasizes the contradictory character of contemporary farming methods, which are both necessary to increase crop yield and harmful to soil fauna since they frequently employ toxic chemicals. The negative impact of insecticides on collembola populations, a non-target micro arthropod, is widely documented, demonstrating that these organisms are under substantial stress. The study underlines the critical role of sustainable farming methods in supporting a diversified soil community, highlighting the complicated relationships and ecological roles of this micro-arthropod. Recognizing the susceptibility of Collembola to insecticide contamination, the study recommends for a paradigm shift in agriculture management toward sustainable approaches to ensure the continuing functionality and benefits of the soil ecosystem. In essence, the important message is the critical necessity to combine agricultural productivity with soil biodiversity conservation for long-term ecological sustainability.

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Conflict of interest

The authors declare that they have no conflicts of interest in this work.

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