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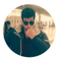

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Conservation agriculture based crop management practices impact diversity and population dynamics of the insect-pests and their natural enemies in agroecosystems

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Human efforts to grow abundant food through the persistent use of resource-intensive farming practices have resulted in declining soil health, and deterioration of ecosystem functions and services. Conservation agriculture (CA) has emerged as a practice to minimize the impacts of conventional resource-exhaustive and energy-intensive agriculture. Minimum soil disturbance, permanent soil cover, and diversification are the key components of CA. Tillage through conventional practices on the other hand has detrimental effects on the soil and environment as it requires deep inversion of soil with instruments such as mouldboard plow, disc plow etc. leaving very less organic matter in soil after establishment of crop. Even though, CA advocates many benefits over conventional agriculture in terms of soil and water conservation, the consequent changes in moisture and temperature regimes due to reduced tillage and surface cover would likely going to influence the biological activity, including insect pests and their natural enemies which dwell within these agroecosystems. The changed crop conditions under CA may favor particular insect communities and their ecological niches. The adoption of such practices may lead to decrease in insect pests with major activity on the crop canopy. However, the activity of the insect pests that spend their maximum life span at the soil surface or beneath the soil surface may increase. Recent insect-pest outbreaks in North-Western India and imbalances reported in Indo-Gangetic Plains point to the need for a better understanding of the inter-relationships between tillage intensity, residue retention, and insect pest population dynamics. The current review analyzes the existing state of knowledge of these dynamics and presents the scenarios that may emerge as CA get more acceptance. This review will help to develop countermeasures to improve performance and ecosystem services of Conservation agriculture (CA) based cropping systems.

KEYWORDS

insect herbivores, conservation agriculture, conventional agriculture, soil tillage, crop residues, soil amendments, crop diversification, IPM

1. Introduction

Climate change, economical uncertainties, and social pressure to produce an ever-greater amount of food have led farmers to adopt new crop cultivation practices (Poppy et al., 2014; Veeck et al., 2020). Extensive tillage, crop residue burning, and the use of high external inputs are some of the recently adopted crop production approaches for increasing productivity (Dey and Karmakar, 2021; Szczepanek et al., 2023). Tillage involves manipulation of the soil into a desired condition by mechanical means such as digging, stirring, and overturning for planting and cultivation. However, the benefits of tillage could be temporary as long-term studies have shown degradation of soil structure, compaction, erosion of top soil, and extinction of soil-dwelling fauna as some of the consequences of it (Bhardwaj et al., 2016; Singh et al., 2020; Dey and Karmakar, 2021; Ghabeish et al., 2023). Other consequences of persistent use of conventional farming practices include depletion of natural resources (Kakraliya et al., 2018), biodiversity loss (Shaxson et al., 2008), environmental pollution (Stevens et al., 2012), and human health hazards (Nderitu et al., 2020). To minimize these negative impacts, particularly on soil and the environment, a new concept of farming called conservation agriculture (CA) took shape in the United States of America first and later spread throughout the world (Bhan and Behera, 2014). There is a growing understanding among farmers that not only high productivity is important but it needs to be environmentally and socially sustainable too. It is pertinent to conserve biodiversity in the soil to get key ecosystem services provided by the microorganisms, and therefore shift from conventional practices to CA is need of hour (Kassam et al., 2019; Hermans et al., 2021). Basically, conservation agriculture is a resource-conserving system of agricultural crop production (Nandan et al., 2018; Lal, 2020) that requires minimum soil disturbance, maintains permanent soil cover, and focuses on diversified crop rotation, all of which contribute to improved soil health and higher productivity (Thierfelder et al., 2018; Figure 1). It is merely a combination of commonly used management principles that can help ensure more sustainable agricultural production (Shrestha et al., 2020; Nandan et al., 2021; Saha et al., 2022). At the same time, it is a noble strategy to address issue of soil quality deterioration (Nyirenda and Balaka, 2021) and climate change impacts on agricultural production (Scopel et al., 2013; Yadav et al., 2017). Besides, CA has been advocated as a key approach for conserving soil from wind and water erosion (Bhan and Behera, 2014; Bell et al., 2018) in addition to minimizing tillage-related production cost through the retention of crop residues on the soil surface. It has also been reported as a crop production strategy that promotes macro faunal diversity while enhancing crop yields (Kertész and Madarász, 2014; Mashavakure et al., 2019a,b). Considering the benefits of CA, it can be promoted as an option to achieve sustainable vertical intensification crop production because of its efficient resources utilization (Nyambo et al., 2022).

Contrarily, planting crops using conventional tillage has been reported to disturb arthropod habitats, and disrupt their life cycle resulting in reduced biological activity (Mhlanga et al., 2020). Agronomic crop management using conventional or CA practices is presumably may lead to shifts in diversity as well as the abundance of insect pests due to changes in their habitats (Jasrotia et al., 2021; Wilson and Fox, 2021). Reduced or no tillage under CA results in reduced soil disturbance, less disturbed soil flora and fauna habitats, and the creation of micro-environments that encourage proliferation of biological activity. Furthermore, more diverse systems (e.g., crop residue retention, mixed cropping, intercropping, and cover cropping) can result in higher niche diversification and provide the predators with shelter and hunting ground (Mashavakure et al., 2019b; Feng et al., 2023). Thus, increased biological activity in CA systems may encourage the emergence of new pest species while also favoring the natural enemies of these pests (Mhlanga et al., 2020). Under CA, both positive and negative shifts in pest attacks, damage, and crop yield consequences have been documented (Chabert and Sarthou, 2020; Kumar et al., 2022). However, the direction of these effects may be influenced by several factors which are not very clearly analyzed and documented in any study. A study of 51 insect pest species around the world found that decreased tillage reduced damage in 43% of the cases, increased damage in 28% of the cases, and had no effect in the remaining 29% of the cases (Abdul-Baki and Teasdale, 1993). Literature on the effects of CA on insect pests and their natural enemies' occurrence, diversity, abundance, and population dynamics is scarce. Hence, the objective of this review is to seek and compile all scattered information on the impacts of CA practices on the population dynamics of detrimental as well as beneficial arthropods.

2. The key drivers of conservation agriculture

Conservation agriculture can be considered as one of the oldest methods of crop cultivation since it could be the only way before the invention of tillage machines, fertilizers, and harvesters. It relies on three fundamental principles which are interconnected and must be taken into account for effective implementation (Figure 1). Underlying all three principles of conservation agriculture (Kirkegaard et al., 2014; Giller et al., 2015) are outlined in the following sections.

2.1. Minimum soil disturbance

Under minimal soil disturbance, two practices, i.e., reduced tillage and minimum tillage are included that are very helpful in maintaining proper soil health (Nunes et al., 2020; Figure 2). Due to minimum soil disturbance (i.e., no inversion tillage), arthropod habitats are less disturbed leading to micro-environments that favor their growth, development, and survival (Jacobsen et al., 2022). It can also be referred to as biological tillage that creates a variety of pore sizes in the soil, allowing increased air and water infiltration leading to easy pupation and adult emergence of soil-dwelling insect pests (Sofo et al., 2020). According to Rabary et al. (2008), no-till systems not only increased the density of white grubs but also increased their biological control due to the conservation of their natural enemies.

2.2. Permanent soil cover

The main practices included under this principle are organic amendments, mulching, and cover crop (Figure 3). Permanent soil cover is essential to protect soil from the harmful effects of changing weather such as intense rainfall and direct exposure to sunlight. It also

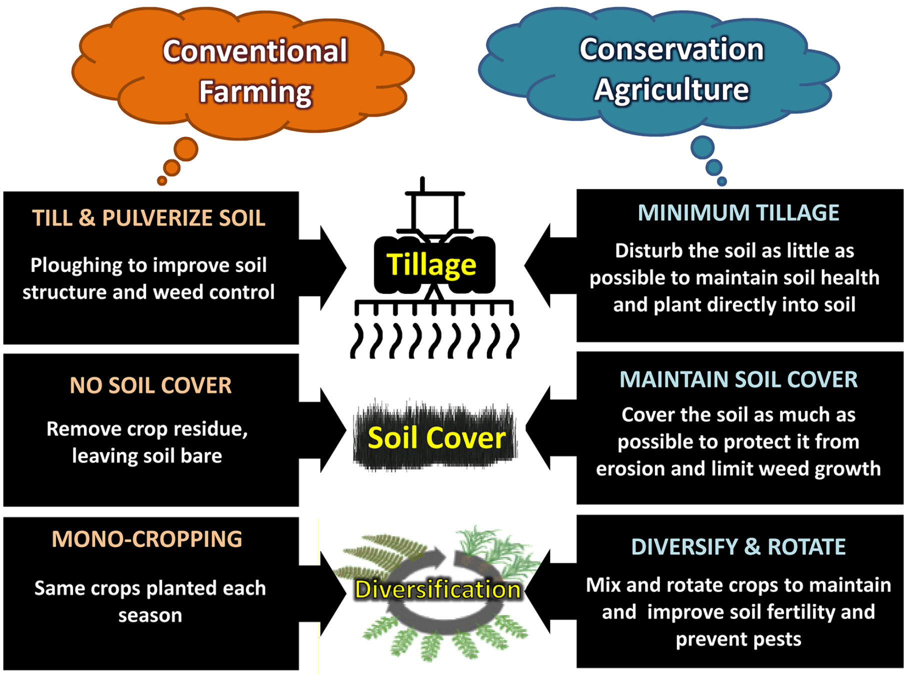

FIGURE 1
Comparison between conventional farming and conservation agriculture.

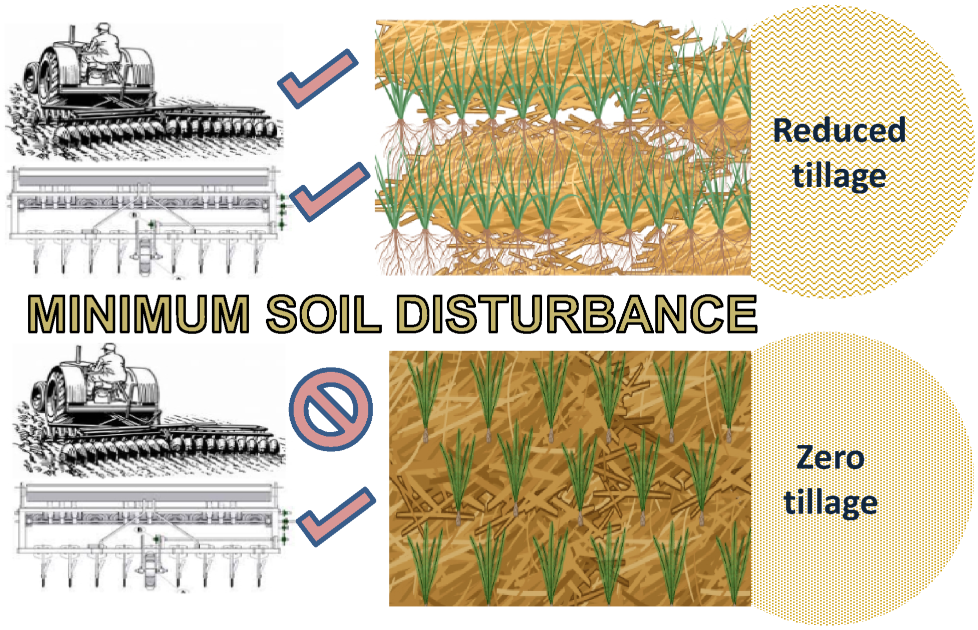

FIGURE 2
Practices followed under the minimum-soil-disturbance principle of conservation agriculture.

alters the microclimate of the soil which provides shelter to micro and macro-organisms in soil and as a result, improves the soil biodiversity (Ghosh et al., 2010; Bhan and Behera, 2014). Ground cover greatly increases the number of ants, spiders, and beetles, which further help in the control of pests like aphids, thrips, bollworms, and grasshoppers (Stewart et al., 2003). In addition, covering the soil with vegetation has been noted to increase the number of predators and parasitoids that attack numerous insect pests (Snyder, 2019) improves soil biodiversity, increases soil biological activity, and carbon sequestration (Ghosh et al., 2010).

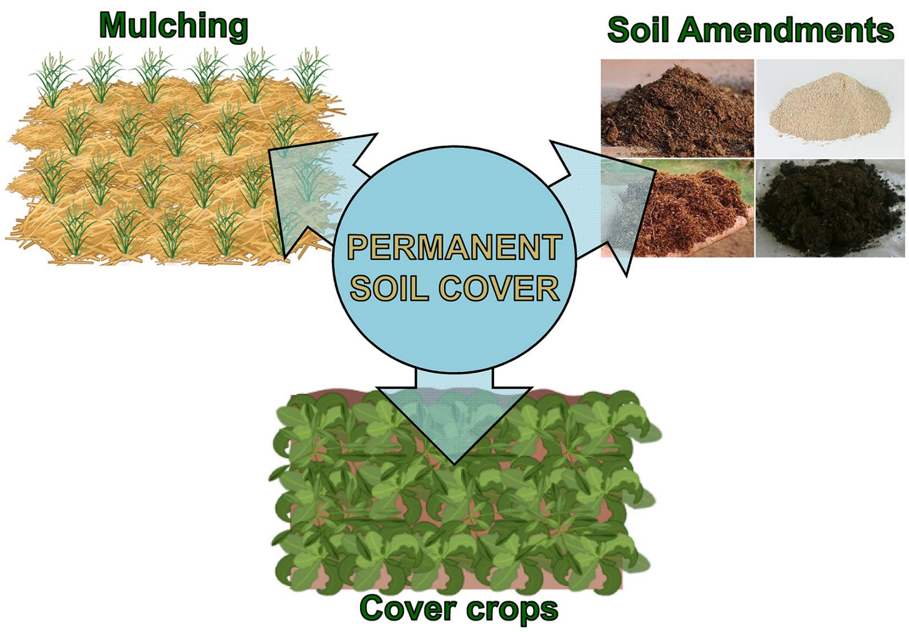

FIGURE 3
Practices followed under the permanent-soil-cover principle of conservation agriculture.

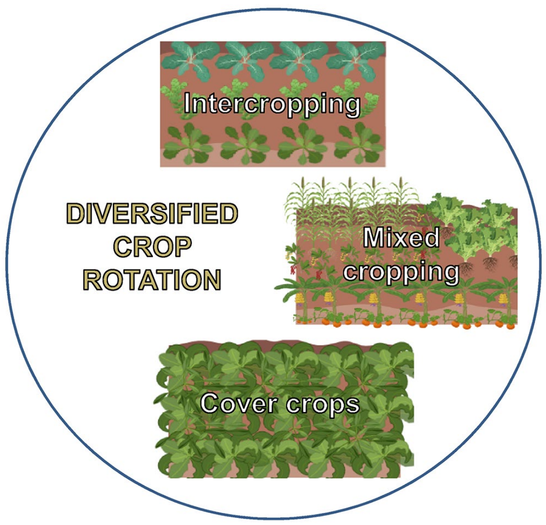

FIGURE 4
Practices involved under the diversified-crop-rotation principle of conservation agriculture.

2.3. Diversified crop rotation

Intercropping, mixed cropping, and cover crops are the main practices under this principle (Figure 4). Diversifying crop rotation refers to a rotation system that comprises three or more crops (Wang et al., 2021). Crop rotations that include a diversity of plants minimize production risk and uncertainty, thus benefiting the farmers by diversifying their source of income (Shah et al., 2021). The rotation of crops not only offers a diverse "diet" to the soil microorganisms but also provides different types of shelters to insects, beneficial as well as pests. Rotations, therefore, need to be strategically designed to avoid providing alternative host plants to insect pests. In principle, because of the distinct structure, function, and relationship of plant communities with soil, it contributes to the long-term improvement of soil health (Li J. et al., 2019). Improved soil health may also aid in decreasing insect pests, weeds, and disease incidences through improved biological control. It may help in minimizing rates of population buildup of insect pest species, through disruption of the life cycle in the absence of host plant (Dumanski et al., 2006; Kassam et al., 2009), releasing secondary metabolites, and enhancing the biodiversity of beneficial insects and thus improved biological control of pests (Mhlanga et al., 2020).

3. Impact of the key drivers of CA on insect pest diversity and population dynamics

3.1. Conservation tillage effects

Tillage can influence insect pest population in two ways (i) First, directly through disruption of soil structure causing the direct exposure of insect pests to their natural enemies or high temperature due to sunlight, and (ii) indirectly by altering the weed population.

3.1.1. Studies indicating increased pest problems due to conservation tillage

Conservation tillage is a technique that retains more than 30% of the preceding crop's stubble on the soil surface (Stinner and House, 1990; Kassam et al., 2019), and it may provide a suitable microclimate for insect pest proliferation. Reduced or minimum tillage can influence insect pests population in two ways: first, it causes less disruption to soil structure and thus causing less disturbance to the habitat of soil-inhabiting insect pests, and second, it leads to prevention of direct exposure of insect pests and their natural enemies to sunlight or high temperature (Figure 5A). For instance, reduced tillage helps tobacco hornworm, *Manduca sexta* pupation in the soil during winter. Also, by altering the weed population, it can indirectly increase pest populations (Figure 5B). Also reduced tillage support in completing the entire life cycle of many soil-dwelling insect pests (Figure 5C). Weeds act as alternate hosts and, provide food and shelter to insects when their host plants are not available. For example, in the early season, *O. nubilalis* use weeds as a habitat and disperse to main crops from surrounding weeds (Weber et al., 1999). In wheat, mealybug [*Brevennia rehi* (Lindinger)] uses grassy weeds (*Echinochloa colona*, *Echinochloa crusgalli, Cynodon dactylon, Leptochloa chinensis*, and *Panicum repense*) as alternate hosts (Kumar et al., 2022). Due to this, insect pests pose a greater threat in fields managed with reduced tillage as compared to high disturbance tillage systems. For example, wireworm (*Conoderus* spp.) population exhibited higher infestation in non-tilled corn fields than in conventionally tilled plots (Gregory and Musick, 1976). Similarly, the black cutworm, *Agrotis ipsilon* (Hufnagel), one of the most devastating insect pests of cotton, was more abundant in reduced tillage than in tilled fields with high soil disturbance (Gregory and Musick, 1976; Gaylor et al., 1984). In contrast, some arthropod pest species such as seed corn maggot, *Delia platura* Meigen, exhibited a higher population in conventionally tilled plots as compared to reduced-tillage systems (Hammond, 1997). Further, in a reduced-tillage system, the abundance of plant residues and vegetation favors some pest species, resulting in higher pest populations [e.g., European corn borer (*Ostrinia nubilalis* Hübner), black cutworm (*Agrotis ipsilon* Hufnagel); Bohnenblust and Tooker, 2010; Mischler et al., 2010]. In comparison to conventionally tilled fields, the infestation of European corn borer in maize was reduced to half in no-till fields. Corn seedling infestation by lesser corn stalk borer, *Elasmopalpus lignosellus*, was observed to be less in no-tillage fields than in conventionally plowed ones (All and Gallaher, 1976). Significantly lower infestation by *Agriotes* wireworm (Coleoptera: Elateridae) in the no-till maize production system was reported than conventional tillage system (Furlan et al., 2021). Similarly, less infestation by black field earwigs (*Nala lividipes*) was observed in the conservation tillage system as it prefers highly disturbed soil rather than undisturbed soil (Dang et al., 2015).

In comparison to deep tillage systems, minimum tillage systems have a higher biodiversity of soil arthropods (Cortet et al., 2002). Conservation tillage is reported to be highly conducive for the growth and development of white grub because less soil disturbance prevents its exposure to parasites and predators (Gregory and Musick, 1976). A serious problem of root aphids in rice and corn (maize) production was reported under reduced and no-tillage as compared to conventional tillage (Gregory, 1974). The oviposition rate of northern corn root worm (*Diabrotica longicornis*) and western corn root worm (*Diabrotica virgifera*) was four times higher in reduced tillage than conventional plowed ones (Brust, 1994). Higher infestation of armyworm (*Pseudaletia unipuncta*) was reported in reduced tillage conditions compared to conventionally tilled plots in rice, corn, and barley cultivation (Gregory and Musick, 1976). The population density of stalk borer (*Papaipema nebris*) was reported to be higher in no-tilled plots as compared to conventionally tilled corn fields (Gregory and Musick, 1976). One of the major constraints in corn production is the southwestern corn borer, *Diatraea grandiosella*

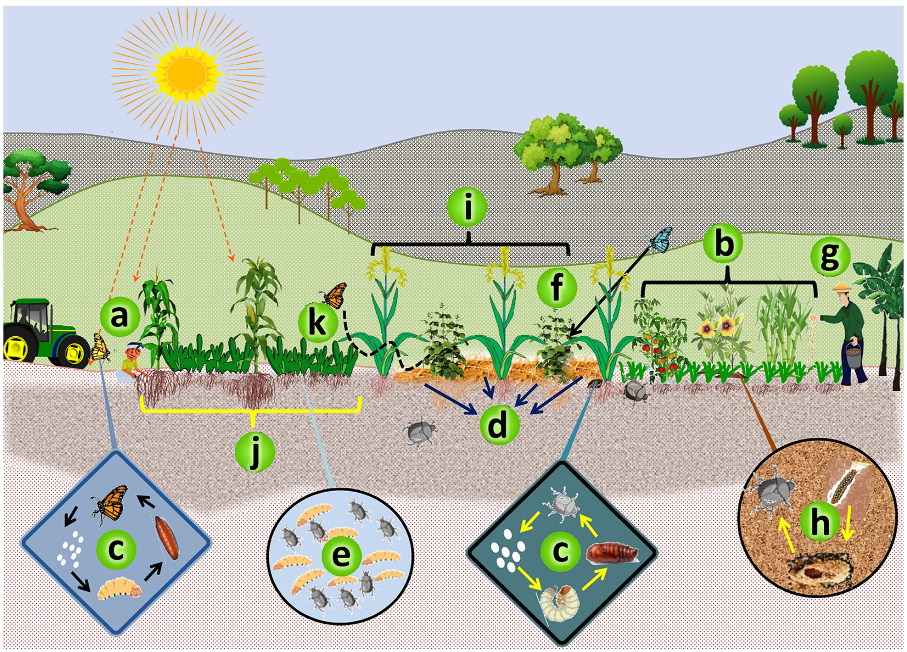

FIGURE 5
Overall pictorial view of impact of conservation agriculture practices on on insect pests and their natural enemies [**(A)** Prevention of different stages of insect-pests to direct exposure to sunlight or high temperature and their natural enemies, **(B)** weed as an alternate host for insect-pests in crop fields, **(C)** reduced tillage supporting life cycle of soil-dwelling pests, **(D)** straw mulch, **(E)** living mulch, **(F)** mulching impairing with insect's ability to locate their host plant, **(G)** organic amendments making soil favorable for pests, **(H)** organic amendments supporting insect migration and pupation inside soil, **(I)** intercropping influence on pests density, **(J)** cover crop influencing pests density, **(K)** intercropping, a barrier to insect- pests to locate host plant].

(Dyar) under the conservation tillage system (Edwards and Berry, 1972). Higher survival of boll weevil (*Anthonomus grandis*) and boll worm (*Helicoverpa armigera*) in cotton cultivation was reported under conservation tillage (Gaylor and Foster, 1987). A higher population density of variegated cutworm (*Peridroma saucia*) was reported under CA practices (Gaylor et al., 1984).

Nemati and Pezhman (2014) observed that wheat brown mite, springtails, spiders, and carabid beetles were the dominant soil arthropod species in the no-tillage system. Singh (2012) reported that the severity and infestation caused by pink noctuid stem borer *Sesamia inferens* were higher in zero tillage conditions when the crop was sown either earlier or later than the recommended sowing time. Investigations on the influence of tillage on the occurrence of root aphids reported that root aphid number was higher in the reduced tillage-unprotected system (Jasrotia et al., 2021). Minimum tillage, which is one of the main principles of CA, was noted to enhance the insect attack, especially by *Hyperodes bonariensis* Kuschel and *Agrotis ipsilon* (Hfn.), in maize seedlings (Carpenter et al., 1978). The incidence of European corn borer, *Ostrinia nubilalis* (Hubner), stalk borer, *Papaipema nebris* (Guenee), black cutworm, *Agrotis ipsilon* (Hufnage), armyworm and *Pseudaletia unipuncta* (Haworth) increased as tillage was reduced, especially in no-till corn (Willson and Eisley, 1992). Oribatids have been noted to be the predominant mites under no-till practices or uncultivated soils, but their number starts decreasing following cultivation (Loring, 1981; Hendrix et al., 1986; Crossley et al., 1992; Neher and Barbercheck, 1998; Menta and Remelli, 2020).

Reduced tillage can help to conserve some soil arthropod groups such as beetles, ants, predatory ants, spiders, and springtails in the sugarcane agroecosystem (Susilo et al., 2018). Kosewska et al. (2014) concluded that an increase in the activity of the carabid beetle was due to the use of non-inversion tillage compared to conventional tillage. An increase in incidence, severity and species diversity of carabids was recorded with a decrease in the intensity of mechanical disturbance (Stinner and House, 1990; Brust, 1994; Digweed, 1995; Heimbach and Garbe, 1996; Krooss and Schaefer, 1998; Kromp, 1999; Brévault et al., 2007; Twardowski, 2010). The armyworm, *Pseudaletia unipuncta* (Haworth), and the black cutworm, *Agrotis ipsilon* (Hufnagel) were documented to be a serious problem in no-till cultivation than conventionally grown corn (Harrison et al., 1980). Edwards and Thompson (1975) reported the increased incidence of wireworms in the no-till system.

The density of wolf spiders (*Pardosa pseudoannulata* and *Pirata subpiraticus*) was significantly higher in no-tilled paddies than in conventionally tilled ones (Ishijima et al., 2004). The black cutworm, *Agrotis ipsilon* (Hufnagel) and armyworm, *Pseudaletia unipuncta* (Haworth) were favored by no-till (Tonhasca and Stinner, 1991). The numbers and biomass of lycosid and salticid spiders were higher in untilled than in tilled plots (Motobayashi et al., 2006). The activity and density of spider, centipede, and rove beetle were higher in the reduced-tillage system (Pretorius et al., 2018).

Because of minimum soil disturbance and retention of crop residues a greater population of termites was reported under CA plots than in conventionally tilled plots in a study by Muoni et al. (2019). Mealybug in wheat [*Brevennia rehi* (Lindinger)] in rice was found to increase abnormally in number in CA-based production systems (Kumar et al., 2022). No-till and residue retention proliferated *Mythimna separata* population in CA based system (Sharma and Davies, 1983). Armyworm (*Pseudaletia unipuncta*) was reported to be the most damaging insect pest of corn seedlings with 15% seeding infestation in reduced tillage (RT) compared to only 1% in conventionally tilled plots (Gregory and Musick, 1976).

3.1.2. Studies indicating decreased or no effects of conservation tillage on pest population

The western corn root worm, *Diabrotica virgifera virgifera* LeConte, and the European corn borer, *Ostrinia nubtlalis* (Hubner), densities were generally reduced in no-till plots (Tonhasca and Stinner, 1991). The density of planthoppers (*Laodelphax striatella*, *Sogatella furcifera*) and leafhoppers (*Nephotettix cincticeps*, *Recilia dorsalis*) was lower in no-tilled paddies than in conventionally tilled ones (Ishijima et al., 2004).

Tillage affects the insect populations due to the disturbance of their natural habitat over and in the soil. The abundance and diversity of carabids were not significantly influenced by the type of soil cultivation (Andersen, 2003; Hatten et al., 2007). Boscutti et al. (2015) concluded that the tillage system used in conservation agriculture does not affect the species diversity of carabids. At the same time, Jalli et al. (2021) reported that tillage did not influence the occurrence of midge (*Sitodiplosis mosellana*), an important pest of spring wheat. The number of tetragnathid and linyphiid spiders was similar in both untilled and tilled plots (Motobayashi et al., 2006). Pretorius et al. (2018) investigated that the ground beetle activity and density were not affected by tillage operation. Tillage has no effect on midge (*Sitodiplosis mosellana*) damage in spring wheat (Jalli et al., 2021).

3.2. Soil cover effects

3.2.1. Mulching

The application of plant residues or other suitable material on the soil surface as a protective cover to improve soil health and suppress weeds is known as mulching (Figure 5D). It is a well-known and approved conservation practice to reduce erosion and runoff, conserve soil moisture, stabilize soil temperature, and enhance soil quality. There are two types of mulches, living mulch, and non-living mulch. Non-living mulches are further divided into organic and synthetic mulches. Living mulch may compete for water, nutrient, space, and light with the main crop and may cause a reduction in yield (Wiles et al., 1989). On the other hand, non-living mulches are expensive as well as not so environmentally friendly as living mulches (Davis, 1994). Therefore, in CA, selection of mulch type should be an important consideration. Mulches have a small but significant impact on insect pests. Some effects of using living mulches include influence on pest density and the population of beneficial insects (Figure 5E), and enhancing soil structure, texture, and health because of adding organic matter to the soil (Frank and Liburd, 2005; Nyoike and Liburd, 2010). Mulch impairs the insect's ability to find a host plant, so in the absence of mulch insect pests easily locate their host plant (Figure 5F). Infestation of aphids was reduced in straw mulch in crops like, canola (Heimbach et al., 2000, 2001), fababean (Heimbach et al., 2002), barley (Kendall et al., 1991), and lupine (Jones, 1994). Straw mulch reduced the Colorado potato beetle larvae population in potatoes (Stoner, 1993; Johnson et al., 2004) and eggplants (Stoner, 1997). A reduced number of 1st and 2nd instars larvae were noted in mulched potato fields than on non-mulched ones (Stoner, 1993). Colorado potato larva defoliates potatoes by 2.5 to 5.0 times less when they are covered with wheat straw mulch. (Zehnder and Hough-Goldstein, 1990; Brust, 1994). A significant reduction in aphid infestation in mulched potato fields was reported by Saucke and Döring (2004). In comparison to control plots, onion thrips numbers were considerably lower in straw-mulched plots Larentzaki et al. (2008). No-till tomato fields covered with hairy vetch (*Vicia villosa* L. Roth) or subterranean clover (*Trifolium subterraneum* L.) showed less Colorado potato beetles infestation (Abdul-Baki and Teasdale, 1993). Intercropping of eggplant with crimson clover (*Trifolium incarnatum* L.) grown as mulch resulted in fewer beetles than eggplant planted on bare ground (Hooks et al., 2013). Lower Colorado potato beetle population was reported when potato plots are planted with herbicide-killed hairy vetch or winter rye (*Secale cereale* L.) as mulch (Szendrei et al., 2009, 2010). Aphid populations are frequently reduced when live mulches are used in crops (Costello and Altieri, 1995; Vidal, 1997; Hooks et al., 1998; Frank and Liburd, 2005). Onion thrips densities were considerably decreased in leeks (*Allium ampeloprasum* L.) when clover was applied as living mulch (Weber et al., 1999).

Several mechanisms may be involved in the reduction of pest populations on mulched plots. First, mulches may make it difficult for some herbivores to locate host plants (Andow, 1991; Costello and Altieri, 1995; Finch and Kienegger, 1997; Vidal, 1997) because when the main crop is hidden in a thick stand of mulch, insect pests may take longer in searching a suitable host plant (Adamczewska-Sowinska et al., 2009; Szendrei et al., 2010). Secondly, mulching may encourage the natural enemy abundance, thus enhancing biological control (Sheehan, 1986; Russell, 1989). Mulching of potato plots with barley strips resulted in three times reduction in aphid infestation (Nakahira et al., 2012). Thirdly, the physical and chemical properties of the mulch may assist in insect pest control. The application of straw mulch on the soil surface may help to control the Colorado potato beetle by altering the microclimate (Zehnder and Hough-Goldstein, 1990; Brust, 1994). Pupation and adult emergence in onion thrips was interfered with by straw mulch (Larentzaki et al., 2008). Allelopathic effects of mulch applied beneath avocado trees interfered with thrips emergence (Hoddle et al., 2002).On the other hand, it was reported that mulching was found to increase the predation of Colorado potato beetle eggs and larvae (Brust, 1994, 1996).

3.2.2. Crop residue

After the harvest of the main crop, keeping crop residue on the soil surface maintains soil structure, texture, moisture, and temperature and enhances soil health (Turmel et al., 2015). After the decomposition of crop residue, it helps in the improvement of nutrient status in soil and increased nutrient availability. Other alterations in soil microclimate include adequate water holding capacity, better aeration, and porosity which together support biological activity in the soil. This favorable microclimate helps in the migration of adults and larvae, and easy pupation in soil. Keeping plant residues in reduced-tillage systems benefits some pest species like European corn borer, *Ostrinia nubilalis* Hübner, and black cutworm, *Agrotis ipsilon* Hufnagel (Bohnenblust and Tooker, 2010; Mischler et al., 2010). Seed corn beetle (*Agonoderus* spp.) and seed corn maggot (*Hylemya* spp.) development and oviposition are promoted by crop residues remaining on the soil surface (Gregory and Musick, 1976). Retention of crop residue on soil surface afforded more number of European corn borers, *Ostrinia nubilalis* (Hubner), in reduced tillage than in conventional tillage system (Gregory and Musick, 1976). TerAvest et al. (2015) reported an increase in termite abundance under substantial residue cover and diversified crop rotations. Application of crop residue in CA led to increased activity and the number of termites in maize (Nyagumbo et al., 2015).

3.2.3. Organic amendment addition

The amount of organic matter present in the soil is an important factor for determining the overall soil health, including the abundance, diversity, and activity of soil-dwelling organisms. Soils rich in organic matter provide a complex food web that usually supports the food and shelter requirements of a variety of insect pests. Application of organic amendments (Figure 5G) in the soil makes the soil porous which help in easy insect migration and pupation in soil (Figure 5H).

Negative impact of potato grown in manure amended soil on infestation by Colorado potato beetles was reported as compared to an unamended soil (Alyokhin and Atlihan, 2005; Alyokhin et al., 2013). A significant reduction in leaf consumption by both larvae and adults collected from manure amended soil was reported (Boiteau et al., 2008). They also reported a reduced rate of development of immature stages reduced female fecundity and higher mortality of 1st instars as an effect of amending soils with manure amended soil. Reduced fecundity of European corn borer on maize plants grown on organically amended soil than on conventionally managed plots has been noted (Phelan et al., 1995). Less number of green peach aphids were observed on manure amended soil as compared to synthetic fertilizer grown cabbage (Staley et al., 2010). Winged green peach aphids prefer landing on control plants compared to plants grown in vermicompost-amended soil (Little et al., 2011). They also observed that wingless green peach aphids produced more nymphs when fed on control plants. There is strong evidence from several plants cultivated on organically amended soils that they become more effective in preventing herbivory by obtaining antibiotic and/or antixenotic characteristics, making them less vulnerable to insect herbivory (Alyokhin et al., 2013). For instance, a significant reduction in defoliation caused by both larvae (Alyokhin and Atlihan, 2005) and adult (Boiteau et al., 2008) of Colorado potato beetle was noted in manure amended potato fields than on plants grown on unamended soils (Alyokhin et al., 2013). Significantly higher fecundity of European corn borer was observed on maize plants grown in conventionally managed soil compared to organically managed soil (Phelan et al., 1995). Higher populations of the green peach aphid on synthetically fertilized cabbage plants than on organic amended plants (Staley et al., 2010). Winged green peach aphids preferred landing on control plants over plants grown in vermicompost-amended soil, whereas more nymphs are produced by wingless green peach aphids while feeding on control plants (Little et al., 2011).

3.3. Impact of crop diversification related practices

Considering the negative effects of conventional agricultural practices, focus has been shifted toward on the biodiversity-friendly agriculture systems that are ecofriendly and provide ecosystem services (Vialatte et al., 2021). Diversification of crops can be helpful in achieving the food and nutrition security through judicious use of land and water resources, sustainable agricultural development and environmental improvement, employment generation, source of income growth and poverty alleviation. However, it is important to identify the mechanisms of crop diversification in agricultural systems which helps in both pest and disease management with increased crop yield (Pan et al., 2020). Contrary to crop diversification, large-scale crop monocultures facilitate the proliferation and increasing prevalence of diseases and pest insects (He et al., 2019).

The impacts of crop diversification on the population dynamics of insects and beneficial organism in agricultural ecosystems are well-documented. These studies provide evidence that habitat manipulation techniques such as intercropping, relay, and rotation can significantly improve pest management. On the other hand, monocropping is found to selectively increase the population of certain groups of arthropod pests resulting in the dominance of only such arthropods thereby reducing their overall diversity (Ramert et al., 2002). However, reduced soil disturbances plus crop diversification in conservation agriculture systems can promote the abundance of various faunal species (Brainard et al., 2016).

3.3.1. Intercropping effects

Growing two or more crops together in the same field at the same time is known as intercropping (Figure 5I). Studies indicate that insects with a narrow host range, are more readily reduced in number when host crops are mixed with non-host crops. This can be an important consideration in the case of the diamondback moth (*Plutella xylostella*), which attacks only cruciferous crops (Andow, 1991; Hooks and Johnson, 2003). Alfalfa has been used as a trap crop to draw Lygus (also known as the western tarnished plant bug, *Lygus hesperus*) away from main crop plantings of cotton and strawberries (Smith and Liburd, 2012). In Florida, collard greens (*Brassica oleracea* var. *acephala* L.) have been used as a trap crop to suppress infestations of diamondback moth larvae in cabbage (Mitchell et al., 2000).

Intercropping investigations on whiteflies (*Bemisia tabaci*) which feed on a variety of crops have shown that intercropping reduces their numbers in some instances but not in others. Frank and Liburd (2005) found that in a more diversified cropping system involving squash, a living mulch, and buckwheat (*Fagopyrum esculentum* Moench) had reduced densities of *Bemisia tabaci* and other several species of aphids. However, Smith and McSorley (2000) and Smith et al. (2000, 2001) found that there was no reduction in whitefly densities when eggplant or squash were used as trap crops, but it was significant when maize was used as a barrier crop. Soybean of the strip-intercropping system showed the highest abundance of the insect pests *Megalotomus* sp. and Maecolaspis sp. and the natural enemies Geocoris sp., Lebia concina, Orius sp., Braconidae, and Scelionidae (Cividanes and Barbosa, 2001).

3.3.2. Cover crop effects

Fast-growing crops planted to prevent soil erosion, increase nutrients in the soil, and provide organic matter are called cover crops (Figure 5J). These are cultivated in between seasons of normal main crops in a rotation to minimize soil erosion by wind and water, promote biological activity, maintain soil temperature, conserve moisture, control weeds, and to reduce soil erosion by wind and water (Fageria et al., 2005). Before or during the planting of the main crop, cover crops are either incorporated into the soil or left on the surface as dead mulches. This approach increases the amount of residue on the soil surface, improves soil structure, and ultimately provides a more stable and diverse agro-ecosystem. As a result, including cover crops in rotation sequences is likely to reduce overall insect pest pressure by reducing plant susceptibility, increasing natural enemy populations, and reducing sunlight exposure (Figure 5K).

Overall, crop-wise effects of various conservation agriculture practices on insect pests has been shown in Table 1.

4. Impact on natural enemies of insect pests

4.1. Tillage effects

Tillage can affect beneficial arthropod survival either through direct mortality or by reducing prey availability or by altering the physical environment (Holland and Luff, 2000; Kendall, 2003; Holland, 2004; Thorbek and Bilde, 2004). Excessive soil tillage is likely to diminish beneficial arthropod numbers, particularly epigeal predators (Patterson et al., 2019). Reduced tillage, which minimizes the intensity or frequency of tillage, can help in pest management by increasing natural enemy populations. It enables crop fields to host a greater number and diversity of natural enemies, such as predators, parasitoids, and entomopathogens, all of which can help to lower pest populations (House and Stinner, 1983; Brust et al., 1986; Stinner and House, 1990; Brust, 1991; Sosa-Gomez et al., 2001). Soil-dwelling predators that spend a part of their life cycle in the soil have been noted to be more abundant in reduced-tillage systems than in conventionally tilled plots (Stinner and House, 1990; Prasifka et al., 2006; Hatten et al., 2007; Shearin et al., 2014; Rowen et al., 2020). The populations of soil-associated predators can be higher in systems that maintain weed cover and crop stubbles on the soil surface from the previous years (Halaj et al., 2000; Rypstra and Marshall, 2005; Woodcock et al., 2010; Kosewska et al., 2014; Shearin et al., 2014; Blubaugh and Kaplan, 2015; Blubaugh et al., 2017). Residue retention with no-tillage and crop rotations (CA) has potential for conserving certain ground-dwelling predators (Rivers et al., 2016).An increase in predatory arthropod population, especially ground beetles (Carabidae) and spiders that inhabit soil and crop debris has been observed in conservation tillage. Greater carabid beetles were reported to be more abundant in conservation tillage systems than in conventionally tilled soybeans (House and All, 1981). A comparison of no-tillage and conventional-tillage soybeans showed that the no-tillage treatments had a mean density of 17.6 carabid beetles per m^2 compared to 0.38 per m^2 in the plowed treatments (House and Parmelee, 1985). Ant attacks on *Heliothis zea* prepupa were much more abundant in no-tillage soils than in plowed soils (Landis et al., 1987).

Reduced tillage system in South Asia resulted in increased beneficial fauna such as predatory beetles, spiders, ants, wasps, and earwigs (Jaipal et al., 2002; Hobbs et al., 2008; Kumara et al., 2020). A significant increase in hunting spiders and soil-dwelling beetles in CA systems was observed in Zimbabwe (Mashavakure et al., 2019a,b). Carabid beetles are effective predators of wireworms, and moth larvae; their population was increased in reduced and non-till systems (Legrand et al., 2011). Tamburini et al. (2016) noted that both the abundance and the aphid predation were higher in conservation tillage (16%) higher than in the fields managed under conventional tillage. Petit et al. (2017) showed that cereal fields that adopted CA over four years prior had a high abundance of beneficial, predatory carabid beetles. The density of wolf spiders tended to be significantly

TABLE 1 Effect of various conservation agriculture practices on insect-pests of different crops.

CA principle	CA practice	Crop	Influence on insect-pest population	Reference
Minimum soil disturbance	No-till	Maize	Suppressed population of Northern corn rootworm beetle *Diabrotica longicornis*	Musick and Collins (1971)
		Alfalfa	Population density of Alfalfa weevil, *Hypera postica* increased	Barney and Pass (1987)
Permanent soil cover	Living mulch	Brassica with tomato and ragweed	Host-finding ability of *Phyllotreta cruciferae* was impaired	Tahvanainen and Root (1972)
	Straw mulch	Onion	Onion thrips population was decreased	Gold (1999)
	Organic amendments	Cabbage	Population of Green peach aphid (*Myzus persicae*) was decreased	Dey and Karmakar (2021)
		Maize	The European corn borer (*Ostrinia nubilalis*) was decreased	
Diverse cropping system	Mixed cropping	Cowpea with maize	Legume bud thrips poupulation (*Megalurothrips sjostedti*) reduced	Kyamanywa and Tukahirwa (1988)
	Intercropping	Brassica intercropped with clover	*Anthomyiid Delia* reduced	Hawkes and Coaker (1976)
		Cabbage with Indian mustard, *Brassica juncea* L.	Reducted population of *P. xylostella* and leafwebber, *Crocidolomia binotalis*	Srinivasan and Moorthy (1991)
		Eggplant intercrop with maize	Pest density of leafhoppers suppressed	Sekhar et al. (1997)
		Eggplant with maize, coriander, marigold	Leafhopper and whitefly population reduced	Fereres (2000)
		white cabbage with tall red clover	Oviposition of *Plutella xylostella* reduced	Åsman et al. (2001)
		Common bean with soybean and groundnut	Termite population reduced	Sekamatte et al. (2003)
		Wheat with onion	Reduced aphid population	Saidi and Itulya (2006)
		Cabbage with garlic and onion	Significantly reduced the population of aphids	Sarker et al. (2007)
		Upland rice with groundnut	Reduction in population of Green stinkbug (*Nezara viridula*) and stem borer (*Chilo zacconius*)	Epidi et al. (2008)
		Cotton with cowpea	Thrips and whiteflies reduced	Chikte et al. (2008)
		Tomato intercropped with coriander.	Population of *Bemisia tabaci* suppressed	Hilje and Stansly (2008)
		eggplant inter-planted into crimson clover	Reduced larval population of Colorado potato beetle	Adamczewska-Sowinska et al. (2009)
		wheat-oilseed rape intercropping	Significantly reduced population of *S. avenae*	Wang et al. (2009)
		Cabbage with onion and tomato	Significantly reduced *P. xylostella* population	Asare-Bediako et al. (2010)
		Cabbage with clover	Turnip root fly (*Delia floralis*) reduced	Björkman et al. (2010)
		Cabbage with onion	Decreased infestation of *Bemisia tabaci, Hellula undalis* and *Brevicoryne brassicae*	Baidoo et al. (2012)
		Wheat with garlic	Aphids Reduced aphid population	Zhou et al. (2013)
		Pearlmillet intercropping with groundnut	Reduced infestation of stem borer	Degri et al. (2014)
		Potato with onion	Reduced plant infestation of whitefly (*Bemicia tabaci*) and aphids' *Myzus persicae* and *Aphis gossypii*	Sharaby et al. (2015)
		Intercropping garlic or carrots in cotton	Reduced cotton aphid population	Xue (2015)
		Lettuce *Lactuca sativa* with onion *Allium cepa*	Reduced infestation of thread caterpillar *Agrotis ipsilon*	Sulvai et al. (2016)
	Crop rotation	Maize and soybean	Pest density of corn rootworm suppressed	Wright (1995)
		Maize and Soybean	Decreased population of Corn rootworm	Derpsch et al. (2011)
	Crop diversification	Brussel sprouts undersown with rye,	Increased eggs and larvae of the hover fly, *Episyrphus balteatus*	Vidal (1997)
		Cabbage *with Trifolium repens*	Reduced the number of *Diaeretiella rapae* pupae/plant	Langer (1996)

TABLE 2 Effect of various conservation agriculture practices on natural enemies of insect-pests in different crops.

CA Principle	CA practice	Crop	Influence on natural enemies of insect-pests	Reference
Diverse cropping system	Cover crop	Forest plantations intercropped with (honey plants *Phacelia* and *Eryngium*)	Attracted more parasitoid population of *Scolie dejeani*	Telenga (1958)
	Intercropping	Cowpea with maize as intercrop	Predator, *Orius* spp. reduced cowpea insect pest population by 23%	Matteson (1982)
	Intercropping	Intercropping groundnuts with pearl millet (*Pennisetum americanum*)	Predators (*Coccinella* sp. and *Menochilus sexmaculatus*) and parasitoid (*Chelonus* sp.) increased coccinellid numbers per plant	Kennedy et al. (1990)
	Crop diversification	Cabbage with tomato	*C. plutellae* increased parasitism of *P. xylostella*	Bach and Tabashnik (1990)
	Intercropping	Eggplant intercrop with maize	Coccinellids and syrphids decreased leafhopper population	Sekhar et al. (1997)
	Strip-intercropping	Eggplant with dill (*Anethum graveolens*)	Ladybird beetles and lacewings increased predation of Colorado potato beetle (*Leptinotarsa decemlineata*)	Patt et al. (1997)
	Intercropping	Lettuce with sweet alyssum (*Lobularia maritima*)	Syrphid flies suppressed aphids	Bugg et al. (2008)
	Intercropping	Wheat-oilseed rape intercropping	Mummy rate of *S. avenae* were significantly reduced by predator, ladybird beetle	Wang et al. (2009)
	Intercropping	Sunflower with pepper	Minute pirate bugs (*Orius* spp.) suppressed western flower thrips	Funderburk et al. (2011)
	Intercropping	Canola–wheat intercropping	No effects on predator populations was observed	Hummel et al. (2012)
Minimum tillage	Reduced and no tilled fields	Potato	Ground beetles, rove beetles, lady beetles and green lacewings decreased Colorado potato beetle eggs and larvae, and aphid population	Alvarez et al. (2013)

higher in no-tilled paddies than in conventionally tilled paddies (Ishijima et al., 2004).

Furthermore, different natural enemy species can respond differently to tillage. For example, Marti and Olson (2007) recorded more ants, and ladybeetles with less tillage, while lacewings, spiders, and fungal pathogens showed no difference between tillage treatments. In another study, it was observed that the populations of coccinellids and wasps decreased with reductions in tillage, while those of generalist arthropod predators such as spiders and rove beetles increased with reductions in tillage (Jasrotia et al., 2021). Sandhu and Cherry (2014) indicated that there are no significant effects of no-tillage and minimum tillage on the population of arthropod ground predators in sugarcane at Florida sugarcane.

4.2. Intrcropping effects

The regulation of pests by natural enemies by their attraction in intercropping fields could be a way to improve the biological control of pests. Moreover, according to the 'enemy hypothesis', the suppression of herbivores by their natural enemies is expected to be more efficient in diversified crop habitats compared with simplified ones, as they may be more abundant in environments offering a greater diversity of prey/host species and microhabitats to exploit (Root, 1973). However, according to the literature available, the number of responses reporting a beneficial effect of intercropping on predators and parasitoids was significantly lower in some studies, may be higher in another studies or may be no effects on natural enemies were reported. Nyoike and Liburd (2010) reported higher populations pressure of beneficial insects when buckwheat was intercropped with squash. Similarly, when buckwheat and squash were intercropped reduced pest pressure and increased beneficial insect populations were found (Frank and Liburd, 2005). The activity of *Encarsia* spp. and *Trichogramma* spp. were found to be greater in cotton intercropped with pigeonpea or sesame (Devi et al., 2020). Fernandes et al. (2018) reported that cotton–cowpea intercropping increased the parasitism of aphids due to the strong attractiveness of predaceous beetles towards cowpea crop (Coleoptera: Coccinellidae). Intercropping of cotton with buckweheat reduced *Apolygus lucoru* population (Tillman et al., 2015; Li X. et al., 2019). Study conducted by Tonhasca (1993) revealed that most foliage-inhabiting natural enemies were significantly more abundant in intercropping than in monoculture plots, whereas soil-inhabiting natural enemies had higher numbers in no-tillage plots than conventional tillage plots (Tonhasca, 1993). Another study found that relay intercropping winter and spring strip crops with cotton conserved and enhanced the numbers of predators of the cotton aphid (*Aphis gossypii*) and predators appeared in higher numbers earlier in the summer in relay intercropped cotton than in isolated cotton (Parajulee et al., 1997).

The impact of various conservation agriculture practices on natural enemies of crop insect-pests has been tabulated in Table 2.

5. Conclusions and future perspectives

Conservation agriculture (CA) packages a set of practices that reduce soil disturbance, increase crop residue retention on the soil surface, and promotes crop diversification. Growing concerns over the consequences of conventional agricultural practices (soil carbon lost, deteriorated soil structure etc.) especially deep tilling of soils, led to the promotion of soil conservation practices under the name of *CA*. These practices can improve soil quality as a significant amount of organic residue left on the soil surface slowly decomposes to add soil carbon, and cover crops protect soil from erosion alongside providing many agronomic as well as environmental benefits. Since the crop residue in CA is retained on the surface of soil rather than incorporated into the soil, its decomposition will vary, temporarily as well as spacially from the coventional soil-incorporation based organic matter application. Conservation agriculture promotes residue load on the soil surface and reduced/no tillage helps in slowing down its assimilation into the soil. Such conditions can lead to the creation of niches and ecosystems that can help in the development of more insect pests on the soil surface because of more hide-out space, increased humidity and less soil disturbance, the conditions that favor high biological activity. Therefore, less disturbed soil structure due to reduced/ no tillage would have both positive and negative influences. The primary purpose of tillage is to break the soil surface for crusts, weed removal, soil pulverization for seed sowing, and exposing soil-dwelling insect pests to sunlight, in addition to many crop-specific and landscape-specific benefits. Tillage help in controlling the insect pest population by physically damaging the insect niches and exposing them to the predators such as birds. Even before CA was conceptualized, mulching and cover crops was also part of conventional agriculture for specific conditions, especially for erosion control on rolling agricultural landscapes as observed in many countries, worldwide. These practices packaged together in CA can therefore be expected to have combined effects on the insect pests dwelling within the agroecosystems. Recent reports of pest outbreaks in the CA systems in the Indo-Gangetic Plain for both rice [mealybug (*Brevennia rehi*)] and wheat crops [oriental armyworm (*Mythinma separata*)] are on-ground evidence of these changes (Kumar et al., 2022).

The abundance of crop residue matter on the soil surface would have a direct impact on the microclimate in the agricultural field. The most influenced factors include changes in temperature and surface reflectance. The surface residue also acts as a hide-out place for insect pests (as well as beneficial insects). Inside the soil, below the surface, a less disturbed soil structure provides permanent hideouts for insects to complete their life cycles, which otherwise are destroyed by tillage. The permanent cover combined with reduced tillage can provide an advantage to the insect pests that complete their life cycle below the soil surface due to lesser exposure to UV radiations. The surface reflectance due to residue retention on the soil surface reduces the soil temperatures and increased humidity, making conditions conducive for insect pest survival and growth. A higher weed population associated with the reduced tillage can provide an opportunity to the insects that need alternative hosts though the increased complexity of the systems due to diversification of crops can also create an environment that is less conducive to the outbreak of insect pests.

Though it is difficult to reach a consensus on the effect of each practice (no-till, reduced tillage, residue retention) as there are plenty of studies contradicting effects on insect pest dynamics, it is clear that the adoption of CA-based management techniques in crop production alters the diversity of some pests due to temporal and spatial distrubtion of organic matter (crop residues), humidity/soil moisture, and nutrient regimes. It seems that the insect pests with major activity on the crop canopy may get a disadvantage by adoption of CA practices while the insect pests with dominant activity at the soil surface and beneath the soil surface may have increased activity due to it. Similar to the effect on insect pests, their natural predators are also favored by the CA based practices. Less disturbed habitats are better for arthropod predators. The systems that are subject to mechanical operations kill predators and force them to leave their habitats. Their endurance is aided by the presence of more organic matter on soil surface (such as crop leftovers) and structural components. Many reports indicated that mechanical disruption is not as important driver for these changes as residue/organic matter retention on the surface. The predators that dwell in the crop canopy and like crop vigor would be benefitted more than those which dwell outside the crop-field area (e.g., coccinelids, wasps). Increase in the natural enemies may balance the favors received by the insect pests but the natural biological control may not suffice as evident from the reported outbreaks.

Keeping in view the changes that are brought in by the CA practices, the insect pest management strategies also need to be revised. The conventional pest control practices are limited to the application of pesticides on the crop canopy and at the time of reaching the threshold levels. It may not suffice for the agroecosystems where the CA practices are adopted as the major advantage for the insect pests is provided by the hideouts in the residue load as well as the undisturbed soil depths. Better and long-term solutions to insect pest management need to be developed through the integration of chemical, cultural, biological, and physical methods. Reports of direct linkages of grassy weeds, which prevail more in CA-based systems (than conventional), to increase in insect pests (e.g., mealy bugs in rice) also hint that improvements in CA itself such as better weed control may help taking of some of the insect pests. Better weed control methodologies would help in getting enough insect pest control in such cases. In general, insect pest control must go beneath the surface of mulch/soil, and therefore insecticide drenching/fumigation could be more beneficial but that also brings in other associated by-effects on the soil-dwelling ecological communities. Devising new insect pest control strategies including CA specific insecticides and modes of application is imminent in adoption of CA for sustainable crop production under conservation agriculture based production systems.

Author contributions

PJ, PK, and AB compiled the literature and wrote the article. KM, PLK, SK, and GS critically reviewed the manuscript and corrected the manuscript. All authors contributed to the article and approved the submitted version.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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