Volume 41 | Number 2 | March 2020

Journal of Environmental Biology

p-ISSN: 0254-8704 • e-ISSN: 2394-0379 • CODEN : JEBIDP

Sponsored by :
Dalela Educational Foundation

Triveni Enterprises
1/206, Vikas Nagar
Lucknow, India

Review Article

Journal Home page : www.jeb.co.in ★ E-mail : editor@jeb.co.in

Journal of Environmental Biology

JEB™ p-ISSN: 0254-8704
e-ISSN: 2394-0379
CODEN: JEBIDP

DOI : http://doi.org/10.22438/jeb/41/2/MRN-1275

Role of novel insecticides in crop protection and their selectivity to natural enemies: A review

S. Satpathy*, B.S. Gotyal and V. Ramesh Babu

Division of Crop Protection, ICAR- Central Research Institute for Jute and Allied Fibres, Barrackpore-700 120, India

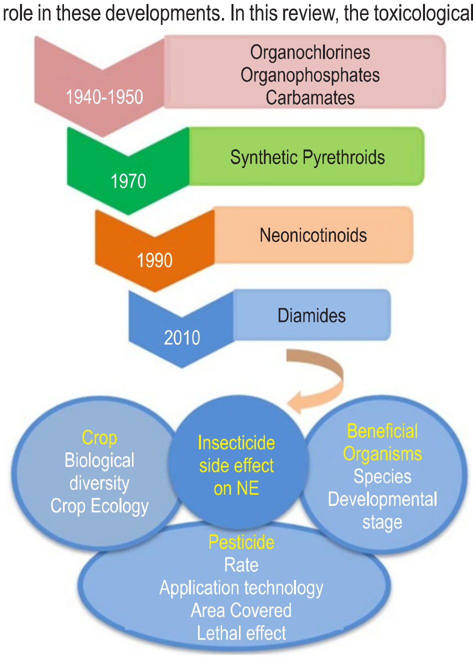
***Corresponding Author Email :** satp1@rediffmail.com

Paper received: 09.09.2019 *Revised received*: 06.01.2020 *Accepted*: 25.01.2020

Abstract

In the present context of pest management in major crops, as the nature of pest pressure evolves, the requirement of new research-based tactics for pest control becomes a continuous process. Insecticide chemistry plays a major, if not dominant role in these developments. In this review, the toxicological aspects of new novel insecticides against crop pests and their selectivity to natural enemies have been discussed.

The progress achieved in toxicological research has introduced new insecticides in crop protection during last two decades which are quite different over the existing groups in terms of chemistry and mode of action. It is evident from their mode of action that these chemicals target alternate physiological and biochemical effect. However, it is important to maintain the diversity in chemistry of insecticides for maximizing flexibility, precision and stability in pest management. In recent years, several new insecticide groups *viz.,* neonicotinoids, butenolides, tetronic and tetramic acid derivatives, oxadiazines, diamides, ketoenols, phenylpyrazoles, pyridines, flonicamid, mitochondrial electron transport inhibitor (METI) acaricides, diafenthiuron, tetrazines, oxazolines, and insecticides from soil microorganisms such as avermectins, milbemycins, spinosyns, pyrrole insecticides and insect growth regulators (IGRs) have been discovered and commercialized for agricultural pest management. The ability of these new groups of insecticides to be effective at low rates or doses, high level of selectivity, greater specificity to target pests along with low toxicity to non-target organisms and the environment, replaced many conventional compounds.



The conservation of beneficial organisms like natural enemies and pollinators is the fundamental principle of integrated pest management (IPM). Majority of new insecticide groups are safer and fit well into IPM. It is perceived that in the process of entry of new chemical insecticides in crop protection there is a gradual shift from traditional chemicals to selective novel groups which have minimal side-effects on natural enemies of the pests. These selective insecticides have less adverse impact on the conservation and multiplication of bio agents which can be used in a compatible manner with other tools of IPM. The new chemistries are emphasizing to account separately for possible non-target effects on predators, parasitoids, and pathogens. These factors are becoming increasingly important as the agricultural sector moves away from highly persistent broad-spectrum insecticides to more selective rapidly decaying products.

Key words: Novel insecticides, Natural enemy, Organophosphates, Pyrethroids

How to cite : Satpathy, S., B.S. Gotyal and V. Ramesh Babu: Role of novel insecticides in crop protection and their selectivity to natural enemies: A review. *J. Environ. Biol.*, **41**, 149-160 (2020).

Introduction

There is hardly any doubt that insecticides play vital role in obtaining higher crop yields by substantially reducing the damage inflicted by insect pests.National agricultural productivity enhancement during the post-sixties was not solely contributed by high yielding crop varieties rather many other farm technologies including the use of fertilizers and pesticides played important role. The problem of insect infestation in newly introduced high yielding and fertilizer–responsive crop varieties gradually builds up because of their susceptibility to biotic stresses. This necessitated greater use of pesticides to prevent 10-30% losses to the potential productivity of different crops. Despite the use of recommended crop protection chemicals, the spectrum of biotic stresses on different crops and the pest status of existing pests have shown increasing trends. This may be due to climatic changes, misuse of chemical insecticides particularly with respect to dose and frequency of application. Pesticides are a vital component and an integral part of modern agriculture which continue to be the major component of crop production technologies.(Narita *et al.,* 2014).

About 2.5 million tonnes of pesticides are used each year. In other words, the most frequent method of managing pests and diseases in most agricultural sectors is through the application of pesticides (Jallow *et al.,* 2017).The top ten pesticide consuming countries in the world are China, the USA, Argentina, Thailand, Brazil, Italy, France, Canada, Japan and India (Worldatlas, 2018). Although, presently, North America, Europe and Japan are the top consumers but countries such as China and India are expected to take the lead in the coming years. The large scale adoption of Bt crops can be attributed to lesser use of chemical pesticides which results in a reduced environmental footprint for agriculture (Koch *et al.,* 2015) Currently, there are about 460 chemical compounds used for controlling insects, mites and other invertebrates worldwide, most of them are used as insecticides (60%). Still the area under crop protection has consolidated a lot. In the developing countries more than 55% of the crop area consumes 26% of the pesticides produced globally. Pesticides have become essential in modern crop protection programmes which protects 45% of total food produced worldwide which saves around 60 billion USD, approximately 6 times the amount spent on it (Oerke, 2006; Popp *et al.,* 2013).

Indiscriminate use of pesticides has many types of fallout including the broad spectrum and persistent toxic effect on natural enemies causing resurgence, insect resistance for prolong use of chemicals having similar chemistry and mode of action, toxic residues on food and the cases of human poisoning. Pest resurgence in many important insect pests like leaf hopper and plant hoppers of rice, whitefly of cotton and red spider mite in vegetables are well evidenced. Since the period of adoption of insecticides there are many reports on insect resistance to insecticides. Globally, 586 species of insect pests have become resistant against 325 insecticides (APRD, 2014). Majority of the cases of insect resistance involve the older groups of insecticides, *i.e.,* organo-phosphates (60 products), carbamates (30 products) and pyrethroids (30 products) (Kodandaram *et al.,* 2016; Sparks and Nauen, 2015) (Table 1).

The development of new active ingredients with softer chemistry and better cross-spectrum activity is a continuous process to phase out the older group of insecticides for improved efficacy, environmental safety and sustainability. Besides, due to requirements for improved environmental and toxicological profiles, changing regulatory requirements, and a shifting spectrum of insect pests, there has been a continuous need to discover and develop new insecticides (Sparks, 2013). Evolving agricultural practices as exemplified by the development and implementation of Integrated Pest Management (IPM) and Good Agricultural Practices (GAP) depend on new insecticides with better chemistries more selective to natural enemies that drives for alternate new insecticidal chemistries (Sparks, 2013). The new insecticides introduced in crop protection are quite different in chemical structure over the existing groups and targets alternate physiological and biochemical effect and diverse mode of action. With the adoption of intensive agriculture by the farmers, there has been significant increase in the pest, disease and weed problems, necessitating use of agro-chemicals. In India, 288 pesticides have been registered for use against different pests, diseases and weeds, among which more than 100 are insecticides alone (http://cibrc.nic.in). The registration of novel pesticides during last two decades has initiated a new era of bio rational pesticides.

Rationalization in development and use of new insecticides

With an attempt to make the use of insecticides sustainable,the focus on insecticide research shifted to search for and development of new green chemistries having novel biochemical targets in the context of pest control and resistance management. The insecticides registered during last 10-15 years are more diverse in terms of their chemistry and mode of action compared to the insecticides in use earlier. Previously, the insecticides registered for use belonged to few conventional chemical groups. Recently, registered insecticides in India belong to new chemistry with less number of insecticides from conventional group (Fig. 1). Prior to 2004, the insecticides had very narrow IRAC mode of action whereas insecticides registered beyond that have more diverse IRAC mode of action group (Fig. 2) (http://www.irac-online.org).

These information reveal that such insecticides will be more sustainable with least probability of triggering insecticide resistance in target insects (Kodandaram *et al.,* 2016). In recent years, several new insecticide groups having new chemistries *viz.,* butenolides, neonicotinoids, oxadiazines, diamides, ketoenols, phenylpyrazoles, pyridines, flonicamid, mitochondrial electron transport inhibitor (METI) acaricides, diafenthiuron, tetrazines, thiazolidinones, oxazolines, and insecticides from soil microorganisms such as avermectins, milbemycins, spinosyns, pyrrole insecticides and insect growth regulators like benzoylureas, triazines, juvenile hormone analogues/mimics have been discovered and commercialized for use in modern crop protection. The ability of these new groups of insecticides to be effective at low rates or doses, high level of selectivity, greater specificity to target pests along with low toxicity to non-target organisms and the environment, replaced many old/conventional compounds (Ishaaya, 2005). Most of the new insecticide groups (pyrroles, pyrazoles, avermectins, diamides, neonicotinoids, spinosins, tetramic/ tetronic acid derivatives) with unique mode of action registered in India during the recent past are safer, highly suitable and fit well into integrated pest management (IPM) or insect resistance management (IRM) programs as these compounds target alternate sites (Das, 2013). The risk of secondary pest out break and resistance development in key pests like whiteflies and aphids is greatly reduced through introduction of these novel groups. These new insecticide classes play an important role in IPM with proven bio-efficacy, high selectivity and low mammalian toxicity that render them attractive replacement for conventional insecticides (Kodandaram *et al.,* 2016; Ishaaya, 2005).

Important novel groups of insecticides

The insecticides introduced in recent past belong to new chemical classes which represent the molecules with superior eco-toxicological profile and diverse mode of action. Some of the major groups are described below.

Diamides: Dimides are recently introduced broad spectrum insecticides which act as rynodyne receptor modulator. Anthranilic dimides are derived from alkaloid isolated from a plant *Ryania speciosa*. Insecticides of this group are particularly significant because of its action at new biochemical targets sites selectively bind to the ryanodine receptors (RyRs) in insect muscle cells, leading to muscle paralysis, cessation of larval feeding and mortality after 1–3 days. Chlorantraniliprole and cyantraniliprole are the recently introduced anthranilic diamides which have proved to be effective against lepidopteran pests as well as against selected species in the order Coleoptera, Diptera and Hemiptera (Lahm *et al.,* 2009). Cessation of larval feeding soon after consumption causes rapid control of the pest. It also has ovicidal and ovo-larvicidal action. Because of translaminar and systemic action, it can be applied as foliar spray and as soil application. It is safe to parasitoids, predators and pollinators. Cyantraniliproleis the second generation ryanodine receptor insecticide with cross spectrum activity against lepidopteran and homopteran pests (Lahm *et al.,* 2009; Kodandaram *et al.,* 2015). It controls whiteflies, dipteran leaf miners, fruit flies, foliage feeding beetles, lepidopteran larvae, aphids, leaf hoppers, thrips, psyllids and weevils. The translaminar activity makes it suitable for soil application (Selby *et al.,* 2013). Flubendiamide belongs to phthalic acid diamide group. It is well suited for controlling a broad range of lepidopteran pests, especially *Helicoverpa armigera* (Jat and Ameta, 2013). The compound is well suited for insect resistance management programmes (pigeon pea pod borers). It is considered as good alternative to indoxacarb and methoxyfenozide.

Butenolides: The insecticidal property of this group is based on the natural product stemsofoline isolated from the leaves and stems of medicinal plant (Fam: Stemonaceae) known as a potent agonist of insect nicotinic acetylcholine receptors (nAChRs). Flupyradifurone is the only insecticide which belongs to this new class of chemistry (Jeschke *et al.,* 2015). Its mode of action differs structurally from known agonists like neonicotinoid insecticides and sulfoxaflor, thus flupyradifurone is assigned to separate chemical group. butenolide group. It shows a fast action on a broad range of sucking pests, as demonstrated in laboratory bioassays, and exhibits excellent field efficacy on a number of crops with different application methods, including foliar, soil, seed treatment and drip irrigation. It is readily taken up by plants and translocated in the xylem, as demonstrated by phosphor imaging analysis. It has high level of efficacy against wide range of sucking insect pests *viz.,* aphids, leafhoppers, psyllids, scales, thrips and whiteflies. Due to adult knockdown effects, it controls nymph and egg stages of sucking pests (Nauen *et al.,* 2015).

Neonicotinoids: The neonicotinoid group of insecticides (imidacloprid, acetamiprid, thiamethoxam, thiachloprid, clothianidin and dinotefuran) are highly active insecticides for foliar application, soil and seed treatment which represents a novel and distinct class with remarkable chemical and biological

Table 1: Some important insects and mites of agricultural crops reported to be resistant to insecticides

Name	Order	No. of compounds/cases
Two-spotted spider mite, *Tetranychus urticae*	Acari	93/414
Diamondback moth, *Plutella xylostella*	Lepidoptera	91/576
Green peach aphid, *Myzus persicae*	Hemiptera	75/402
Sweet potato whitefly, *Bemisia tabaci*	Hemiptera	54/555
Colorado potato beetle, *Leptinotarsa decemlineata*	Coleoptera	54/279
Cotton aphid, *Aphis gossypii*	Hemiptera	48/231
European red mite, *Panonychus ulmi*	Acari	48/197
Cotton bollworm, *Helicoverpa armigera*	Lepidoptera	47/692
Cutworm, *Spodoptera litura*	Lepidoptera	38/457

APRD (2014)

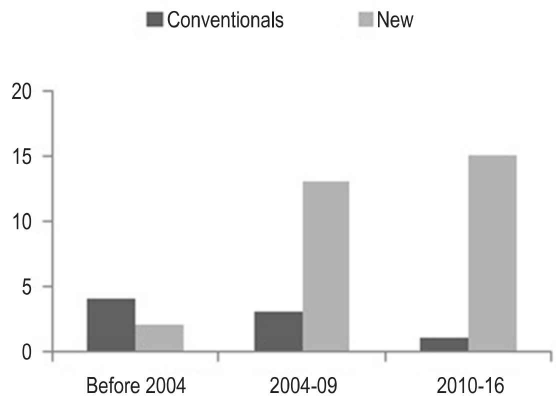


Fig.1: Trends of insecticide chemical groups registered in India.

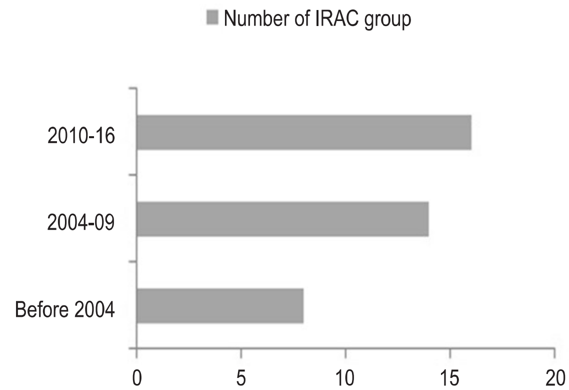


Fig. 2: Trends of insecticides belonging to number of IRAC MoA group.

properties. This group has been the fastest growing class of insecticides in modern crop protection methods (Simon-Delso *et al.,* 2015). Discovery of neonicotinoids is a milestone in the history of insecticide research, development and use because of their broad insecticidal spectrum, exhibiting systemic and translaminar properties and high residual activity with unique mode of action (Elbert *et al.,* 1998). Neonicotinoids are widely used for controlling whiteflies, aphids and leafhoppers, thrips and small lepidopteran and coleopteran pests. Seed treatment in okra with imidacloprid gives prolonged protection against leaf hopper and also significantly increases the photosynthesis activity, substantially replenishing the adverse effect of leaf damage (Satpathy *et al.,* 2004). It acts at synaptic nicotinic acetylcholine receptors in the central nervous system of insects. Specificity for novel type of receptor, found more often in insect nervous system than in non-arthropods makes it very selective. Application of insecticides of this group at very low doses and the flexibility in their application reduces direct exposure to non-target organisms in the environment (Tomizawa and Casida, 2005). Recently, attention is being focused on neonicotinoid pesticides like imidacloprid, which can impair individual and colony fitness of honey bees at even sub lethal doses (Sanchez-Bayo, 2014). It spreads throughout all plant tissues and is found in nectar and pollens. The degradation products of imidacloprid from insect metabolism and environmental decay are also toxic to bees and pollinators causing impaired pollination on prolonged exposure (Goulson, 2013).

Phenylpyrazoles: Being GABA gated chloride channel blocker these insecticides are highly effective against mites and insects (Caboni *et al.,* 2003). Among phenyl pyrazoles, fipronil is a broad spectrum neurotoxin that works as a GABA agonist. It has contact activity on both chewing and sucking insects and controls insects belonging to Coleoptera, Lepidoptera, Diptera, Homoptera, Isoptera and Thysanoptera. It has systemic activity, with long residual effect and shows excellent potential for controling most sucking and chewing insects, thrips, beetles, termites and grasshoppers. The toxicity persists for a variable period of time—depending on the plant, its growth stage, and the amount of pesticides applied (Simon-Delso *et al.,* 2015). It is highly effective against rice pests applied at low rates where residues persist for 45 days (Kumar and Singh, 2013).

Oxadiazines: Oxadiazines are broad-spectrum insecticides those acts as sodium channel blocker, have translaminar movement in to mesophyll of plants. Crucially the mode of action of these insecticides is distinct from other sodium channel targets, due to large and complex structure of sodium channels (Silver *et al.,* 2010). The active metabolites of insecticides exert their effect by blocking the voltage-gated sodium ion channels in insects in distinct sites, which is at least forty times more potent (Dryden *et al.,* 2013). Birds, soil and aquatic organisms are least adversely affected by these insecticides. Indoxacarb is the first commercialized insecticide of oxadiazine group. It is a pro-pesticide with unique mode of action. It inhibits the flow of sodium ions into the nerve cell in insects leading to paralysis and death. It enters into insect body through ingestion of treated foliage and also through penetrating insect cuticle. Once indoxacarb is absorbed or ingested, cessation of feeding occurs immediately within 0-4 hrs. The major use is against chewing insects such as lepidopterous larvae, beetles on pigeon pea, soybean, cotton and other legume crops (pod borer complex), and diamond back moth of cabbage (Satpathy *et al.,* 2007; Shivalingaswamy *et al.,* 2008a). Due to low dermal toxicity, it is safe to beneficial insects (Michaud and Grant, 2003).

Thiourea derivatives: These are pro-insecticides activated by oxidative desulfurization to the insecticidal carbodiamide. Diafenthiuron belongs to this group. It inhibits oxidative phosphorylation, *i.e.,* specially ATP synthase. Besides sucking pest complex like whitefly, aphid, leafhoppers it is also effective against tetranychid and tarsonemid mites and young larvae of lepidopteran pests. It has no cross resistance with any other existing insecticides or acaricides. Because of its unique chemical class, novel mode of action, biological spectrum, translaminar activity, high selectivity towards beneficial insects and lack of cross resistance with other conventional and new insecticide, makes it important for any IPM program (Tomar *et al.,* 2012).

Pyrroles: Pyrroles are derived from natural product, dioxapyrrolomycin, isolated from a strain of *Streptomyces fumanus.* Chlorfenapyr is a commercially developed pyrrole insecticide. It has broad spectrum activity against many species of Lepidoptera, Acarina, Thysanoptera and Coleoptera. It is extremely effective against Diamondback moth of cabbage (Satpathy *et al.,* 2005). Chlorfenapyr acts at mitochondrial level by uncoupling oxidative phosphorylation. They have translaminar activity and are toxic both by contact and ingestion to chewing and sucking arthropods (Hunt and Treacy, 1998). It has been found to be highly effective against two major lepidopteran pests of soybean (Kambrekar, 2018).

Pyridine: This class of insecticides are highly effective against sucking pests mainly aphids, whitefly, hoppers with high translaminar and systemic activity. These insecticides are highly target specific, cause instant feeding cessation by obstructing the stylet movement and penetration in leaf tissues.The sap sucking activity of the insect is severely and instantly impaired causing damage to maximum extent (Deep, 2018).

Pyridine azomethines: Pymetrozine, a novel pyridine azomethine insecticide, is very specific against sucking insect pests. It effects neuro-regulation or nerve-muscle interaction controlling salivary pump and causes immediate and irreversible cessation of feeding due to obstruction of stylet penetration, followed by starvation and insect death. It has rapid knockdown effect on aphids, whiteflies and planthoppers. Pymetrozine has systemic and translaminar activities and can be used as drench or foliar application and is highly specific against sucking insect pests. The compound exhibits low terminal residue and low toxicity against all tested beneficial organisms. Pymetrozine has shown great potential in field application to control paddy planthoppers, because it slowed down the rapid loss of biological function during treatment (Xu *et al.,* 2018).

Pyridine carboxamide: Flonicamid is a novel pyridine carboxamide compound with a unique mode of action. It has contact and upwardly systemic activity. It effectively manages population of aphids, thrips, leaf hoppers and other sucking insects by inhibiting feeding immediately after treatment. The main insecticidal mechanism of this compound is starvation based on the inhibition of stylet penetration in to plant tissues (Morita *et al.,* 2000). It is considered to be safe to natural enemies and pollinators (Chaudhury *et al.,* 2016). In aphids, it inhibits feeding within 30 minutes of treatment (Morita *et al.,* 2007).

Tetramic and Tetronic Acid derivative or Ketoenol group: This group includes spirodiclofen, spiromesifen and spirotetramat which are suitable for foliar and soil application. The mode of action of ketoenols is characterized by inhibition of enzyme in lipid biosynthesis or metabolism (Nauen and Konanz, 2005). Unique mode of action and lack of cross resistance make ketoenols ideal for sucking pest management. Spirotetramat, a novel insecticide belonging to Ketoenois group is a tetramic acid derivative. It is systemic in action, xylem and phloem mobile up to the growing shoots and down to roots. It shows excellent activity against aphids, mealybugs, psyllids, scales, thrips, whiteflies and juvenile stages of sucking pests, even the cryptic stages, and protects new shoots appearing after foliar application. Spiromesifen is a novel insecticide/acaricide introduced recently belonging to new chemical class of spirocyclic phenyl-substituted tetronic acids (Nauen and Konanz, 2005). It is especially effective against whiteflies, tetranychid spider mite and also against all juvenile and nymphal stages. Because of its high selectivity, good residual activity, minimal risk to pollinators and predatory mite species (Nicolaus *et al.,* 2005) combined with a novel mode of action make spiromesifen an excellent substitute for IPM programs. Spirodiclofen is a selective, non-systemic acaricide having excellent efficacy against mites. Due to its high lipophilicity, spirodiclofen has got good residual acaricidal effect up to 14 days. Positive temperature coefficient enables it to be effective at higher temperatures. These acaricides can be used in conjugation with predatory mites (Sarbaz *et al.,* 2017).

Dichloropropenyl ethers: Pyridalyl is the only member of this class which is highly effective against lepidopterous and thysanopterous pests. It controls population of *Helicoverpa armigera* and *Spodoptera litura* as well as against Thysanopteran insects. It also produces unique insecticidal symptoms, so it may have different mode of action from existing insecticides. It is highly selective for its toxicity towards insects and natural enemies (Isayama *et al.,* 2005). Pyridalyl was relatively safer to coccinelids and spider population (Patra *et al.,* 2017). Its safety to beneficial arthropods, makes it an ideal candidate for IPM.

Spinosyns: Spinosyns are class of fermentation derived macro cyclic lactone bioinsecticides, produced from *Saccharopolyspora spinosa.* This class is represented by spinosad and spinetoram. Spinosad is derived from mixture of spinosyn A and D' Whereas spinetoram is a mixture of spinosyn J and L. Spinosyns primarily target the binding sites on nicotinic acetylcholine receptors and also has effects on GABA gated ion channels. (Sparks *et al.,* 2001). These insecticides are highly effective against lepidopterous larvae, dipterous leaf miners and thrips while maintaining the exceptional environmental and toxicological profile. Spinosad acts primarily as stomach poison, but also has some contact action with translaminar activity targeting cryptic stages. This compound has shown exceptional efficacy against diamond back moth in cabbage (Shivalingaswamy *et al.,* 2006). Spinetoram, the second insecticide of this group provides prolong control of a broad spectrum insect pests and exhibits excellent translaminar activity.Spinosyns are highly target specific and ideal for IPM component (Herbert, 2010).

Avermectins: The mectin family are complex macrocyclic lactones with (abamectin and emamectin benzoate) or without (milbemectin) conjugation with sugar residues. Abamectin is a mixture of two naturally occurring avermectins that are derived by fermentation from the soil micro-organism *Streptomyces avermitis* primarily against mites and limited range of insects. Abamectin exhibits very low toxicity against non-target arthropods in agro-ecosystem (Lasota and Dybas, 1990). Emamectin benzoate is a "Semisynthetic" derivative of abamectin. Emamectin affects the nervous system of lepidopterous pests by increasing chloride ion flux at the neuromuscular junction, resulting in cessation of feeding and irreversible paralysis. This insecticide is very much effective against lepidopteran larvae, particularly in vegetables proved to be toxic to the major borers and foliage feeders (Shivalingaswamy *et al.,* 2008b). It has translaminar activity, providing a relatively prolonged residual activity (Fanigliulo and Sacchetti, 2008). Milbemectin is primarily a miticide which causes rapid and prolonged paralysis and death. Milbemectin exerts toxic effect at all life stages of a broad spectrum of phytophagous mites (Sato, 2005).

Benzoyl Phenyl Urea (BPU): BPUs are chitin synthesis inhibitors, disrupt moulting, act by ingestion and contact, cause abnormal endocuticular deposition and abortive moulting (Soltani *et al.,* 2009). Among the BPU group, novaluron, diflubenzuron, teflubenzuron and lufenuron are most important in controlling lepidopteran and coleopteran larvae. Most of these insecticides are effective in the management of diamond back moth of cabbage with no risk of hazardous toxic residues in the product (Satpathy and Rai, 2001). Mostly larval stage of insect are vulnerable, the adult of beneficial species, predators and parasitoids are seldom affected. These compounds are highly selective and affect the larval stage which acts mainly by ingestion, but in some species they suppress fecundity and exhibit ovicidal and contact toxicity. Diflubenzuron is the first commercial compound of this group, highly effective against key lepidopteran insects. Teflubenzuron is non-systemic insect growth regulator which acts on stomach. It affects fertility of female insects after contact or ingestion. It is used for controling Lepidoptera, Coleoptera, Diptera, Aleyrodidae, Hymenoptera, Psyllidae and Hemiptera. Novaluron is a new BPU insecticide having more contact and translaminar activity. Lefenuron was very effective against diamond back moth of cabbage under field condition (Satpathy and Rai, 1999). It has potent insecticidal activity against lepidopteran larvae (by ingestion) and whitefly nymphs (by contact). Abamectin and novaluron are more effective in suppressing developing stages of citrus leaf miners (Patil, 2013).

METI acaricides or insecticides: Pyridaben belongs to pyridazionone group of insecticide having non-systemic acaricidal and insecticidal properties with rapid knockdown and long residual effect. It shows excellent activity against all developing stages of wide range of phytophagous mites and other sucking pests. Biochemically, it inhibits mitocondrial electron transport of complex I (Wood *et al.,* 1996). Fenazaquin is one of several acaricides and insecticides which has a unique chemical configuration consisting of quinazoline moiety. It is widely used as an acaricide for management of mites. Fenpyroximate is mainly an acaricide. It also causes rapid knockdown effect on larvae, nymph and adults. This compound is very much selective towards predatory mite (Lima *et al.,* 2013). Tolfenpyrad is a broad spectrum foliar contact insecticide used for wide range of crops against several economically important insect pests of order hemiptera, thysanoptera, eriophid and tarsonemid mites. It acts on all developmental stages of target insect, particularly mango hopper (Babu and Singh, 2014).

Selectivity and effect of novel insecticides on natural enemies

No doubt the disturbances in biodiversity and ecological impact of these chemicals are unavoidable. Overuse of non-selective pesticides in agriculture has several important adverse effects, of which the harm caused to biological control agents is most relevant (Fernandes *et al.,* 2010). Certainly, IPM has not achieved a reduction in overall pesticide usage, but at least has kept insecticide use static during a period of increasing agricultural intensification (Devine and Furlong, 2007). IPM focuses on long-term prevention of pests using a combination of different techniques such as selective and non-persistent insecticides that do not affect predatory and parasitic organisms (Zalucki *et al.,* 2009).

Thus, it excludes most of the highly toxic, broad-spectrum and persistent insecticides, that cause most damage to the environment. The conservation of beneficial organisms like natural enemies and pollinators is one of the fundamental principles of IPM. It is perceived that in the process of entry of new chemical insecticides in crop protection there is a gradual shift from traditional chemicals to selective novel groups which have minimal side-effects on natural enemies of the pests. Among the new insecticides, there are several groups of novel insecticides which can be used in a compatible manner with the biocontrol agents under the IPM programmes. Pesticide selectivity to beneficial insects should be given top priority in selection of any insecticides in IPM (Gentz, 2010). During the past two decades, research and development programmes have been focused to develop insecticides with selective properties (Ishaaya, 2005). Depending on the mortality of natural enemies in bioassays conducted in laboratory and other studies as specified by International Organization for Biological Control (IOBC), the insecticides are classified for their safety to natural enemies as harmless, slightly harmless, moderately harmful and harmful. The result of majority of the experiments indicate that diamides, tetramic and tetronic acid derivatives and pyridine azomethines are harmless to slightly harmful to natural enemies (Fig. 3) (Singh *et al.,* 2016).

Similarly, new insecticides belonging to diamides, tetramic and tetronic acid derivatives, avermectins and pyridine azomethines were noted to be more selective to major egg parasitoid, *Trichogramma* spp. and the most important predator, *Chrysoperla* spp. which are active in most of the agroecosystem (Fig. 4 and 5). Among one of the new versatile insecticide groups, chlorantraniliprole is compatible with natural enemies (Larson *et*

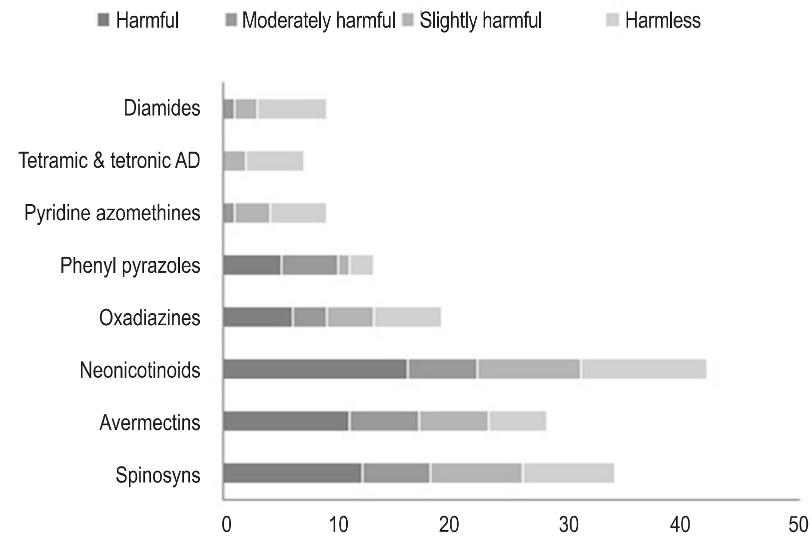


Fig. 3: Number of published reports showing toxicity of new insecticides (IOBC) to natural enemies.

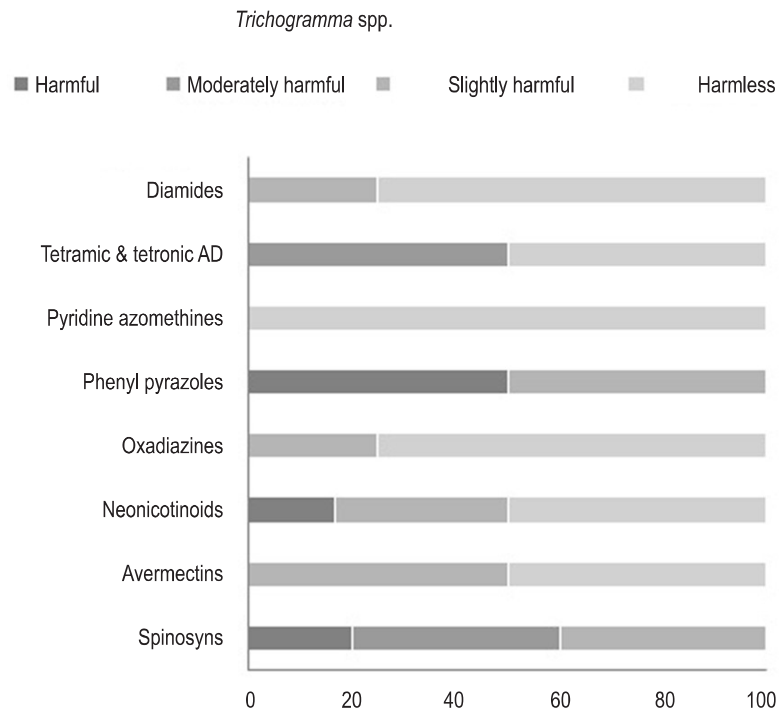


Fig. 4: Percentage of reports categorizing toxicity of new insecticides against *Trichogramma* spp.

al., 2012; Jaafar *et al.,* 2013). The acute contact and oral toxicity to *Cotesia chilonis* and bioagents associated with rice was negligible (Huang *et al.,* 2011; Jaafar *et al.,* 2013). Another diamide insecticide, cyantraniliprole although has cross spectrum activity on chewing (Lepidoptera) and sucking (Hemiptera) pests proved to be safer against the pupal stage of *Trichogramma pretiosum,* an important egg parasitoid of *Helicoverpa armigera* (Mandal, 2012). This insecticide was more selective to the

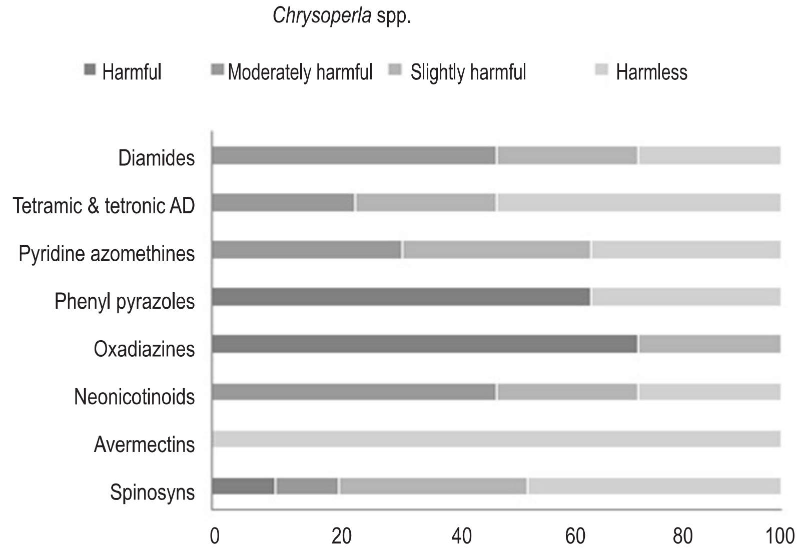


Fig. 5: Percentage of reports categorizing toxicity of new insecticides against *Chrysoperla* spp.

parasitoid (*Tamarixia radiate*) of *Diaphorina citri* making it ideal for IPM in citrus (Tiwari and Stelinski, 2013). The compatibility of flubendiamide with natural enemies may be explored in IPM as it is less toxic to beneficial arthropods, particularly the egg parasitoids of yellow stem borer (Chormule *et al.,* 2014). Most of the reports categorize diamides as 'slightly harmful to harmless' in IOBC category (Singh *et al.,* 2016).

Indoxacarb, a reduced-risk pesticide was ranked very highly for overall safety to beneficial insects. Additionally, field trials using indoxacarb demonstrated suitability for inclusion in pest management through conservation of natural enemies over other insecticides (Hewa-Kapuge *et al.,* 2003), although it has been shown that direct exposure to indoxacarb can decrease field population of natural enemies by as much as 50–90% (Galvan *et al.,* 2005). The beneficials widely used in greenhouse pest management, particularly *Phytoseiulus persimilis* Athias-Henriot (Acari: Phytoseiidae) and *Orius insidiosus* (Say) (Hemiptera: Anthocoridae) have demonstrated no negative effects of indoxacarb (Bostanian *et al.,* 2005). Indoxacarb has been found to be harmless to three species of Trichogrammatids widely used as egg parasitoids in rice, vegetables and sugarcane (Liu and Zhang, 2012; Uma *et al.,* 2014). Several studies have classified indoxacarb as 'slightly harmful to harmless' to different natural enemies and biological control agents. Spinosad derived from soil actinomycete, *Saccharopolyspora spinosa* is relatively harmless to a range of natural enemies. Toxicologically and environmentally it's usually harmful to predators and classified in the reduced risk category (Uma *et al.,* 2014; Liu and Zhang, 2012). Sometimes the toxic effect is recorded on wasp parasitoids. Under laboratory condition, *Trichogramma pretiosum, Telenomus remus* and *Bracon mellitor* exhibited susceptibility to spinosad and was categorized to be slightly harmful to these natural enemies (Williams *et al.,* 2003).

Toxicity studies of pymetrozine, a pyridine azomethines group insecticide on cotton aphid parasitoid, *Aphelinus gossypii* and whitefly predator, *Delphastus pusillus* revealed that parasitoid emergence was not affected while it was safer against whitefly predator complex also (Torres *et al.,* 2003). Pyriproxyfen is another pyridine-based pesticide which is classified as harmful for larvae of *Cryptolaemus montrouzieri* due to its acute effect on pupal mortality. The adults of *C. montrouzieri* when fed with pyriproxyfen-treated prey exhibited increased fecundity but egg hatching was completely restricted. Moreover, the larvae fed on pyriproxyfen-treated prey did not reach the adult stage (Planes *et al.,* 2013). Pymetrozine is classified as 'slightly harmful to harmless' in IOBC. The insecticides and acaricides belonging to tetronic and tetramic acid derivative group have softer effect on natural enemies. Side effects of spiromesifen on the parasitoid, *Eretmocerus mundus* and minute pirate bug, *Orius laevigatus,* the key natural enemies of *Bemisia tabaci* exhibited favourable selectivity to *O. laevigatus* and *E. mundus* and thus its use would complement the biological control of *B. tabaci.* Spiromesifen was found to be the most promising acaricide for managing the two-spotted spider mite, *Tetranychus urticae* when used in combination with the predaceous mite, *Neoseiulus californicus* (Sato *et al.*, 2011). The effect of spirotetramat, another systemic insecticide on adults and larvae of *Cryptolaemus montrouzieri* under laboratory conditions was safe. Direct application on larvae and adults did not affect its survival, longevity, fecundity, egg hatching and offspring survival (Planes *et al.,* 2013). Spirodiclofen, spiromesifen and spirotetramat were found 'harmless' to natural enemies.

The parasitoid, *Oomyzus sokolowskii* was highly susceptible to avermectin, although mixed toxicity was reported on egg parasitoids population, few *Trichogramma* spp. were not affected by avermectins (Prastissoli *et al.,* 2011). Laboratory evaluations have shown that avermectin has many non-target impacts. Under laboratory and greenhouse conditions, avermectin caused up to 97% mortality of *T. brassicae* adults 1 hr after direct application and 23–64% mortality during the first 24 hr in residue assays (Hewa-Kapuge *et al.,* 2003). Despite significant toxicity to a number of non-target species, avermectin was once considered suitable for many beneficial insects due to its short environmental persistence (Zhang and Sanderson, 1990) which made avermectin a historically important component of greenhouse and orchard IPM (Lasota and Dybas,1991). Surface residues of insecticide decompose rapidly in sunlight, hence this compound is considered an important component in IPM programmes. The wide-ranging non-target impacts make the use of avermectins a step to be carefully considered, in particular if conservation biological control is a desired component of the pest management program.

Though fipronil is more toxic to various natural enemies than other new insecticides, it has little or no risk to beneficials when applied as a granule or seed treatment. The toxicity of fipronil used against the larvae of diamondback moth, *Plutella xylostella* caused mortality to two major parasitoids, *Cotesia plutellae* and *Oomyzus sokolowskii* within 24 hr (Shi *et al.,* 2004). High insecticidal effect of fipronil to population of *Cotesia chilonis* was also observed (Huang *et al.,* 2011). The study conducted to investigate the effects of fipronil against spider and insect abundance in a rice ecosystem showed a significant reduction of natural enemy population in fipronil treatments (Jaafar *et al.,* 2013). *Trichogramma pretiosum* Riley is an important egg parasitoid and biological control agent. Seven insecticides (buprofezin, chlorantraniliprole, spirotetramat, flonicamid, flubendiamide) and miticides (spiromesifen, cyflumetofen) were found to cause no significant mortality to immature stages or pre-emergent adult parasitoids (Khan and Ruberson, 2017).

Because of high translaminar and systemic activity of neonicotinoids, the translocated chemicals may increase the chances of contact toxicity of the insecticide with natural enemies on the plants and cause high mortality to nectar feeding beneficials as it contaminates the nectar and pollens. Ecotoxicology studies with imidacloprid have shown that direct mortality of bees is only a part of the colony collapse problem, which includes behavioral changes such as disorientation, feeding problems and communication disturbance (Yang *et al.,* 2008). Acetamiprid, thiamethoxam and imidacloprid were selective to spiders and other natural enemies belonging to family Tachinidae under field conditions (Fonseca *et al.,* 2008). Thiamethoxam was also selective to Arachnida although initial toxicity to the members of Formicidae and Tachinidae was high. Application of acetamiprid and imidacloprid affected the parasitization capacity and development of *Trichogramma pretiosum* (Carvalho *et al.,* 2010). In addition to the effect on hymenopteran parasitoids, imidacloprid has been found to be toxic to coccinellids and neuropteran species when applied as a foliar spray. Imidacloprid should be used with caution by growers desiring long-term control of pests through IPM and preservation of natural enemies. The studies on selectivity of neonicotinoids to natural enemies categorised this group to be harmful to moderately harmful.

The effect of insecticides on natural enemies depends on multiple factors. Non-target toxicity must consider differences in the ecology and behavior of natural enemies. The toxicity of any insecticide at particular concentration may range from harmless to harmful, depending on the developmental stage of the natural enemy (Souza *et al.,* 2014). For example, it has been reported that pupae of a diamond back moth parasitoid, *Diadegma semiclausum* (Hellen) (Hymenoptera: Ichneumonidae) were less susceptible to several pesticides than adults at field application rates (Haseeb *et al.,* 2000). Parasitoid pupae showed higher tolerance to pesticides in comparison with adults might be linked to the location of the parasitoid inside the host egg, which is protected against insecticide contact by the chorion (Stecca *et al.,* 2016). Besides, the action of a pesticide may vary between species of beneficial arthropods. Imidacloprid had harmful effect on *Chrysoperla externa* adults but was harmless to *C. cubana* (Godoy *et al.,* 2015). In addition to being species-specific, pesticide selectivity may also depend on insect strains. Efforts have been made during the past three decades to develop insecticides with selective properties that act specifically on biochemical sites present in particular insect groups (Ishaaya, 2005). The new chemistries are emphasizing to account separately for possible non-target effects in predators and parasitoids. These factors are important as the dependency of agricultural sector on insecticides is gradually shifting from highly persistent broad-spectrum insecticides to more selective rapidly decaying products. Many of these new insecticides exhibit a great deal of selectivity, possessing increasingly favorable environmental and toxicological profiles (Sparks, 2013).

Conclusion

There has been a gradual change in the approaches to pest management for last past 50 years and no doubt will continue to witness such changes to overcome the new challenges in crop protection in future. Insecticide-centric approach mostly dominated which is characterised by continued evolution of chemicals against key insects of important crops. Recent improvements in the selectivity and efficacy of synthetic chemicals and isolated bioactive compounds provide greater opportunity for adopting the integrated management practices. Pest management now requires more knowledgeable users for production of agricultural commodities in an economically successful manner. A component of these more sophisticated approaches is the prescription use of pesticides for the control of specific pests in geographically defined areas. As the nature of pest pressures evolves, accompanied by societal concerns over pest control and the economic realities of agriculture and pest management change over time, there will be continuing needs for new research-based tactics to pest control. Insecticide chemistry will play a major, if not dominant, role in these developments. However, it is important to maintain the diversity in chemistry of insecticides for maximizing flexibility, precision and stability in pest management. The potential benefits of a particular insecticide with respect to IPM program should be carefully considered in light of the dominant insect pests and predators in the application area. Formulation, application schedule and timing and delivery methods can all play a role in determining the safety of insecticide in a particular agro-ecosystem. Better understanding and knowledge of the diversity of natural enemy species in agroecosystems and of different ways pesticides can affect their efficacy are essential to overcome the challenges and constraints for research on pesticide selectivity to natural enemies and resulting field recommendation.

References

APRD: Arthropod Pesticide Resistance Database, Michigan State University, <*htttp://www.pesticideresistance.org*> (2014).

Babu, S.R. and V. Singh: Bioefficacy of tolfenpyrad 15 EC against hopper complex in mango. *Pest Manag. Hort. Ecosys.,* **20**, 22-25 (2014).

Bostanian, N.J., M. Akalach and H. Chiasson: Effects of a chenopodium-based botanical insecticide/acaricide on *Orius insidiosus,* Hemiptera: Anthocoridae and *Aphidius colemani,* Hymenoptera: Braconidae. *Pest Manag. Sci.,* **61**, 979–984 (2005).

Caboni, P., R.E. Sammelson and J.E. Casida: Phenylpyrazole insecticide photochemistry, metabolism, and gabaergic action: Ethiprole compared with fipronil. *J. Agric. Food Chem.,* **51**, 7055-7061 (2003).

Carvalho, G.A., M.S. Godoy, D.S. Parreira and D.T. Rezende: Effect of chemical insecticides used in tomato crops on immature *Trichogramma pretiosum* (Hymenoptera: Trichogrammatidae). *Rev. Colomb. Entomol.,* **36**,10-15 (2010).

Chormule, A.J., S.B. Kharbade, S.C. Patil and N.D. Tamboli: Bioefficacy of new insecticide molecules against rice yellow stem borer, *Scirpophaga incertulas* (Walker). *The Ecoscan,* **6**, 63-67 (2014).

Chaudhary, R.I., M.B. Zala, R.K. Thumar and M.U. Dindor: Effect of some insecticides against natural enemies on mustard, *Brassica juncea* in field condition. *Int. J. Agril. Sci. Res.,* **6**, 219-226 (2016).

Das, S.K.: Mode of action of pesticides and the novel trends – A critical review. *Int. Res. J. Agric. Sci. Soil Sci.,* **3**, 393-401(2013).

Deep, G., J. Patil, S. Yadav, B. Kumer and R. Nath: Novel insecticides: A potential tool for the management of insect pest. *J. Entomol. Zool. Stud.,* **6**, 277-281 (2018).

Devine, G.J. and M.J. Furlong: Insecticide use: contexts and ecological consequences. *Agric. Hum. Values,* **24**, 281–306 (2007).

Dryden, M.W., P.A. Payne, V. Smith, K. Heaney and F. Sun: Efficacy of indoxacarb applied to cats against the adult cat flea, *Ctenocephalides felis*, flea eggs and adult flea emergence. *Parasit. Vectors,* **6**, 126 (2013).

Elbert. A., R. Nauen and W. Leicht: Imidacloprid, a novel chloronicotinyl insecticide: Biological activity and agricultural importance. In: Insecticides with Novel Mode of Action: Mechanism and Application (Eds.: I. Ishaaya and D. Degheele). Springer, Berlin Heidelberg, New York., pp. 50-73 (1998).

Fanigliulo, A. and M. Sacchetti:Emamectin benzoate: New insecticide against *Helicoverpa armigera.* Commun. *Agric. Appl. Biol. Sci.,* **73**, 651-653 (2008).

Fernandes, F.L., L. Bacci and M. S. Fernandes: Impact and selectivity of insecticides to predators and parasitoids. *Entomo. Brasilis.,* **3**, 1-10 (2010).

Fonseca, P.R.B., T.F. Bertoncello, J.F. Ribeiro, M.G. Fernandes and P.E. Degrande: Selectivity of insecticides to natural enemies on soil cultivated with cotton. *Pesqui. Agropecu. Trop.,* **38**, 304-309 (2008).

Galvan, T.L., R.L. Koch and W.D. Hutchison: Effects of spinosad and indoxacarb on survival, development and reproduction of the multi-coloured ladybeetle. *Biol. Con.,* **34**, 108–114 (2005).

Gentz, M.C., G. Murdoch and G.F. King: Tandem use of selective insecticides and natural enemies for effective, reduced-risk pest management. *Biol. Control.,* **52**, 208- 215 (2010).

Godoy, C.V., De F. Bueno and D.L.P. Gazziero: Brazilian soybean pest management and threats to its sustainability. *Outlooks Pest Manag.,* **26**, 113-117 (2015).

Goulson, D.: Review: An overview of environmental risk posed by neonicotinoid insecticides. *J. Appl. Ecol.*, **50**, 977-987 (2013).

Haseeb, M., H. Amano and H. Nemoto:.Pesticidal effects on mortality and parasitism rates of *Diadegma semiclausum,* a parasitoid of the diamondback moth. *Bio Control,* **45**, 165-178 (2000).

Herbert, A. Kirst: The spinosyn family of insecticides: realizing the potential of natural products research. *J. Antibiot.,* **63**, 101–111 (2010).

Hewa-Kapuge, S., S. Mcdougall and A.A. Hoffman: Effects of methoxyfenozide, indoxacarb, and other insecticides on the beneficial egg parasitoid, *Trichogramma* nr. brassicae (Hymenoptera: Trichogrammatidae) under laboratory and field conditions. *J. Econ. Entomol.,* **96**, 1083-1090 (2003).

Huang, J., S.F. Wu and G.Y. Ye: Evaluation of lethal effects of Chlorantraniliprole on *Chilo suppressalis* and its larval parasitoid, *Cotesia chilonis. J. Integra. Agric.,* **10**, 1134-1138 (2011).

Hunt, D.A. and M.F. Treacy: Pyrrole insecticides: A new class of agriculturally important insecticides functioning as uncouplers of oxidative phosporylation. In: Incecticides with novel modes of action, mechanism and application (Eds.: I. Ishaaya and D. Degheele). Springer, Berlin Heidelberg New York, pp. 138-151 (1998).

Isayama, S., S. Saito, K. Kuroda, K. Umeda and K. Kasamatsu: Pyridalyl, a novel insecticide: Potency and insecticidal selectivity. *Arch. Insect Biochem. Phys.,* **58**, 226-233 (2005).

Ishaaya, I.: Novel Insecticides: Modes of Action and Resistance Mechanism. *Arch. Insect Biochem. Physiol.,* **58**,191 (2005).

Jaafar, W.N.W., N. Mazlan, N.A. Adam and D. Omar: Evaluation on the effects of insecticides on biodiversity of arthropod in rice ecosystem. *Acta Biol. Malays.,* **2**,115-123 (2013).

Jallow, M., D. Awadh, M. Albaho, V. Devi and B. Thomas: Pesticide risk behaviours and factors influencing pesticide use among farmers in Kuwait. *Sci. Total Environ.,* **574**, 490–498 (2017).

Jat, S. K. and O.P. Ameta: Relative efficacy of biopesticides and newer insecticides against *Helicoverpa armigera* (Hub.) in tomato. *The Bioscan,* **8**, 579-582 (2013).

Jeschke, P., R. Nauen, O. Gutbrod, E.M. Beck, S. Matthiesen, M. Haas and R. Velten: Flupyradifurone (Sivanto™) and its novel butenolide pharmacophore: Structural considerations. *Pestic. Biochem. Physiol.,* **121**, 31–38 (2015).

Kambrekar, D.N.: Pyrrole (Chlorfenapyr) insecticide potential to manage *Spodoptera litura* (Fabricius) and *Helicoverpa armigera* (Hubner) in soybean. *J. Entomol. Zool. Stud.,* **6**, 947-951(2018).

Khan, M.A. and John R. Ruberson: Lethal effects of selected novel pesticides on immature stages of *Trichogramma pretiosum* (Hymenoptera: Trichogrammatidae). *Pest Manag. Sci.,* **73**, 2465-2472 (2017).

Koch, M. S., J.M. Ward, S.L. Levine, J.A. Baum, J.L. Vicini and G.B. Hammond: The food and environmental safety of Bt crops. *Front. Plant Sci.,* (2015). https://doi.org/10.3389/fpls.2015.00283

Kodandaram, M.H., A.B. Rai and J. Halder: Novel insecticides for management of insect pests in vegetable crops: A review. *Veg. Sci.,* **37**, 109-123 (2010).

Kodandaram, M.H., A.B. Rai, K. Sireesha and J. Halder: Efficacy of cyantraniliprole, a new anthranilic diamide insecticide against fruit and shoot borer, *Leucinodes orbonalis* (Lepidoptera: Crambidae) on brinjal. *J. Environ. Biol.,* **36**,1415–1420 (2015).

Kodandaram, M.H., Y.B. Kumar, A.B. Rai and B. Singh: An overview of insecticides and acaricides with new chemistries for the management of sucking pests in vegetable crops. *Veg. Sci.,* **43**, 1-12 (2016).

Kumar, R. and B. Singh: Persistence and metabolism of Fipronil in rice (*Oryza sativa* Linnaeus) field. *B. Environ. Contam. Tox.,* **90**, 482–488 (2013).

Lahm, G.P., D. Cordova and D. Barry James: New and selective ryanodine receptor activators for insect control. *Bioorg. Med. Chem.,* **17**, 4127–4133 (2009).

Larson, J.L., C.T. Redmond and D.A. Potter: Comparative impact of an anthranilic diamide and other insecticidal chemistries on beneficial invertebrates and ecosystem services in turf grass. *Pest Manag. Sci.,* **68**, 740-748 (2012).

Lasota, J.A. and R.A. Dybas: Abamectin as a pesticide for agricultural use. *Acta Leiden.,* **59**, 217-222 (1990).

Lasota, J.A. and R.A. Dybas: Avermectins, a novel class of compounds: Implications for use in arthropod pest control. *Annu. Rev. Entomol.,* **36**, 91-117 (1991).

Lima, D.B., V. B Monteiro, R.N.C. Guedes, H.A.A. Siqueira, A. Pallini and M.G.C. Gondim Jr.: Acaricide toxicity and synergism of fenpyroximate to the coconut mite predator, *Neoseiulus barak. BioControl.,* **58**, 595-605 (2013).

Liu, T.X. and Y. Zhang: Side effects of two reduced-risk insecticides, indoxacarb and spinosad, on two species of *Trichogramma* (Hymenoptera: Trichogrammatidae) on cabbage. *Ecotoxicol.,* **21**, 2254-2263 (2012).

Mandal, S.K.: Bio-efficacy of Cyazypyr 10% OD, a new anthranilic diamide insecticide, against the insect pests of tomato and its impact on natural enemies and crop health. *Acta Phytopathol. Entomol. Hung.,* **47**, 233-249 (2012).

Michaud, J.P. and A.K. Grant:IPM-compatibility of foliar insecticides for citrus: Indices derived from toxicity to beneficial insects from four orders. *J. Insect Sci.,* **3**, 1-10 (2003).

Morita, M., T. Ueda, T. Yoneda, T. Koyanagi, S. Murai and N. Matsuo: IKI-220–a novel systemic aphicide. Proceedings of Brighton Crop Protection Conference-Pests and Diseases, BCPC, Farnham, Surrey, UK, pp. 59–65 (2000).

Morita, M., T. Ueda, T. Yoneda, T. Koyanagi and T. Haga: Flonicamid, a novel insecticide with a rapid inhibitory effect on aphid feeding. *Pest Manag. Sci.,* **3**, 969-973 (2007).

Narita, K., Y. Matsui, L. Iwao, M. Kamata, T. Matsushita and N. Shirasaki: Selecting pesticides for inclusion in drinking water quality guidelines on the basis of detection probability and ranking. *Environ. Int.,* **63**, 114–120 (2014).

Nauen, R. and S. Konanz: Spiromesifen as a new chemical option for resistance management in whiteflies and spider mites. *Pflanzenschutz-Nachr. Bayer,* **58**, 485–502 (2005).

Nauen, R., P. Jeschke, R. Velten, M. E Beck, U. Ebbinghaus-Kintscher, W. Thielert, K. Wölfel, M. Haas, K. Kunz and G. Raupach: Flupyradifurone: A brief profile of a new butenolide insecticide. *Pest Manag. Sci.,* **71**, 850-862 (2015).

Nicolaus, B., C. Romijn and L. Bowers. Eco-toxicological profile of the insecticide Oberon. *Pflanzenschutz-Nachr. Bayer,* **58**, 353–370 (2005).

Oerke, E.C.: Crop losses to pests. *J. Agric. Sci.,* **144**, 31-43 (2006).

Patra, S., V. Dhote, S. Sarkar, A. Samanta: Evaluation of novel insecticides against diamondback moth and natural enemies in cabbage ecosystem. *J. Environ. Biol.,* **38**,1383-1389 (2017).

Planes, L., J. Catalan and A. Tena: Lethal and sub lethal effects of spirotetramat on the mealybug destroyer, *Cryptolaemus montrouzieri. J. Pestic. Sci.,* **86**, 321-327 (2013).

Popp, J. K., Peto and J. Nagy: Pesticide productivity and food security. A review. *Agron. Sustain. Dev.,* **33**, 243- 255 (2013).

Pratissoli, D., A.M. Milanez and N.F. Celestino: Selectivity of pesticides used in cucurbits to *Trichogramma atopovirilia* Oatman & Platner (Hymenoptera: Trichogrammatidae). *Rev. Ceres,* **58**, 661-664 (2011).

Patil, S.K.: Evaluation of insecticides against citrus leaf miner, *Phyllocnistis citrella* Stainton in acid lime. *Pest Manag. Hort. Ecosys.,* **19**, 237-239 (2013).

Sarbaz, S., S. Goldasteh, A. A. Zamani, E. Solymannejadiyan and R. V. Shoushtari: Side effects of spiromesifen and spirodiclofen on life table parameters of the predatory mite, *Neoseiulus californicus* McGregor (Acari: Phytoseiidae). *Int. J. Acarol.,* **43**, 380-386 (2017).

Sato, M. E., M. Da Silva, a. Raga and M. F. De Souza Filho: Abamectin resistance in *Tetranychus urticae* Koch (Acari: Tetranychidae): Selection, cross-resistance and stability of resistance. *Neotrop. Entomol.,* **34**, 991-998 (2005).

Sato, M.E., Z.S. Marcos and A. Raga: Spiromesifen toxicity to the spider mite *Tetranychus urticae* and selectivity to the predator, *Neoseiulus californicus. Phytoparasitica,* **39**, 437- 445 (2011).

Satpathy, S. and S. Rai: Bioefficay of new insecticides against diamondback moth (*Plutella xylostella*) of cabbage. *Progre. Hortic.,* **31**,176-180 (1999).

Satpathy, S. and S. Rai: Toxicity of insect growth regulator against diamondback moth, *Plutella xylostella* (L.). *Pestology,* **25**, 2-3 (2001).

Satpathy, S., A. Kumar, A.K. Singh and P.K. Pandey: Chlorfenapyr: A new molecule for diamondback moth (*Plutella xylostella* L.) management in cabbage. *Ann. Pl. Protec. Sci.,* **13**, 88-90 (2005).

Satpathy, S., A. Kumar, T.M. Shivalingaswamy and M. Rai: Evaluation of new molecules for diamondback moth (*Plutella xylostella* L.) management in cabbage. *Indian J. Hortic.,* **64**, 175-177 (2007).

Satpathy, S., S. Rai, N. De and A.P. Singh: Effect of insecticides on leaf net carbon assimilation rate and pest incidence in okra. *Indian J. Pl. Prot.,* **32**, 22-25 (2004).

Sattelle, D.B., D. Cordova and T. Cheek: Insect ryanodine receptors: Molecular targets for novel control chemicals. *Invert. Neurosci.,* **8**, 107-119 (2008).

Sanchez-Bayo, F.: The trouble with neonicotinoids. *Sci.,* **346**, 806-807 (2014).

Selby, P.T., P.L. George, T.M. Stevenson, A.H. Kenneth, D. Cordova, I.B. Annan, B.D. James, A.B. Eric, J.C. Martin and F.P. Thomas: Discovery of cyantraniliprole, a potent and selective anthranilic diamide ryanodine receptor activator with cross spectrum insecticidal activity. *Bioorg. Med. Chem. Lett.,* **23**, 6341–6345 (2013).

Shi Z., S. Guo, W. Lin and S. Liu: Evaluation of selective toxicity of five pesticides against *Plutella xylostella* (Lep: Plutellidae) and their side-effects against *Cotesia plutellae* (Hym: Braconidae) and *Oomyzus sokolowskii* (Hym: Eulophidae). *Pest Manag. Sci.,* **60**, 1213-1219 (2004).

Shivalingaswamy T.M., A. Kumar, S. Satpathy and A.B. Rai: Efficacy of emamectin benzoate in the management of vegetable pests. *Progre. Hortic.,* **40**,193-197 (2008b).

Shivalingaswamy, T.M., A. Kumar, S. Satpathy and A.B. Rai: Efficacy of indoxacarb against tomato fruit borer, *Helicoverpa armigera* Hubner. *Pestology,* **32**, 39-41(2008a).

Shivalingaswamy, T.M., A. Kumar, S. Satpathy, A.B. Rai and M. Rai: Spinosad: a new molecule for management of diamondback moth (*Plutella xylostella* L.) in cauliflower. *Veg. Sci.,* **33**, 55-57 (2006).

Silver, K.S., W. Song, Y. Nomura, V.L. Salgado and K. Dong: Mechanism of action of sodium channel blocker insecticides (SCBIs) on insect sodium channels. *Pestic. Biochem. Physiol.,* **97**, 87–92 (2010).

Simon-Delso, N., V. Amaral-Rogers, L.P. Belzunces, J. M. Bonmatin, M. Chagnon, C. Downs, L. Furlan, D.W. Gibbons, C. Giorio, V. Girolami, D. Goulson, D.P. Kreutzweiser, C.H. Krupke, M. Liess, E. Long, M. McField, P. Mineau, E.A.D. Mitchell, C.A. Morrissey, D.A. Noome, L. Pisa, J. Settele, J.D. Stark, A. Tapparo, H.V. Dyck, J.V. Praagh, J.P. Van der Sluijs, P.R. Whitehorn and M. Wiemers: Systemic insecticides (neonicotinoids and fipronil): Trends, uses, mode of action and metabolites. *Environ. Sci. Pollut. Res.,* **22**, 5-34 (2015).

Singh, V., N. Sharma and S. K. Sharma: A review on effects of new chemistry insecticides on natural enemies of crop pests. *Int. J. Sci. Environ. Technol.,* **5**, 4339-436 (2016).

Soltani, N., H. Lechekhab and G. Smagghe: Impact of the insect growth regulator diflubenzuron on biochemical composition of cuticle of the shrimp *Penaeus kerathurus.* Commun. *Agric. Appl. Biol. Sci.,* **74**, 137-141 (2009).

Souza, J.R., G.A. Carvalho, A.P. de Moura and M.H.G. Couto: Toxicity of some insecticides used in maize crop on *Trichogramma pretiosum* (Hymenoptera, Trichogrammatidae) immature stages. *Chil. J. Agr. Res.,* **74**, 234-239 (2014).

Sparks, T.C. and R. Nauen: IRAC: Mode of action classification and insecticide resistance management. *Pestic. Biochem. Phys.,* **121**, 122–128 (2015).

Sparks, T.C., G.D. Course and G. Durst: Natural products as insecticides: The biology, biochemistry and quantitative structure-activity relationship of spinosyns and spinosoids. *Pest Manag. Sci.,* **57**, 896-905 (2001).

Sparks, T.C.: Insecticide discovery: An evaluation and analysis. *Pestic. Biochem. Phys.,* **107**, 08-17 (2013).

Stecca, C.S., A. De F. Bueno, A. Pasini, D.M., Silva, K. Andrade and D.M.Z. Filho: Side-effects of glyphosate to the parasitoid, *Telenomus remus* Nixon (Hymenoptera: Platygastridae). *Neotrop. Entomol.,* **45**, 192-200 (2016).

Tiwari, S. and L.L. Stelinski: Effects of cyantraniliprole, a novel anthranilic diamide insecticide, against Asian citrus psyllid under laboratory and field conditions. *Pest Manag. Sci.,* **69**, 1066-1072 (2013).

Tomar, S., S. Sharma and K. Malik: Diafenthiuron (a novel insecticide) for management of whitefly, *Bemisia tabaci* Indian *J. Sci. Res.,* **16**, 120-122 (2017).

Tomizawa, M. and J.E. Casida: Neonicotinoid insecticide toxicology: Mechanisms of selective action. *Ann. Rev. Pharmacol. Toxicol.,* **45**, 247-268 (2005).

Torres, J.B., C.S.A. Silva-Torres and J.V. Oliveira: Toxicity of pymetrozine and thiamethoxam to *Aphelinus gossypii* and *Delphastus pusillus. Pesqui. Agropecu. Bras.,* **38**, 459-466 (2003).

Uma, S., S. Jacob and K.R. Lyla: Acute contact toxicity of selected conventional and novel insecticides to *Trichogramma japonicum* Ashmead (Hymenoptera: Trichogrammatidae). *J. Biopest.,* **7** (Supp.), 133-136 (2014).

Williams, T., J. Valle and E. Vinuela: Is the naturally derived insecticide spinosad compatible with insect natural enemies? *Biocontrol Sci. Technol.,* **13**, 459-475 (2003).

Wood, E., B. Latli and J.E. Casida: Fenazaquin acaricide specific binding sites in NADH: Ubiquinone oxidoreductase and apparently the ATP synthase stalk. *Pestic. Biochem. Phys.,* **54**, 135-145(1996).

Worldatlas: https://www.worldatlas.com/articles/top-pesticide-consuming-countries-of-the-world. html (2018).

Xu, W., M. Zhang, K. Wei, Y. Chen, Q. Liu, W. Xue, L. Jin, M. He, Z. Chen and S. Zeng: Development and evaluation of pymetrozine controlled-release formulation to control paddy planthopper. *RSC Adv,* **8**, 22687-22693 (2018).

Yang, E.C., Y.C. Chuang, Y.L. Chen and L.H. Chang: Abnormal foraging behaviour induced by sub lethal dosage of imidacloprid in the honey bee (Hymenoptera: Apidae). *J. Econ. Entomol.,* **101**, 1743–1748 (2008).

Zalucki, M.P., D. Adamson and M.J. Furlong: The future of IPM: Whither or wither? *Aust. J. Entomol.,* **48**, 85-96 (2009).

Zhang, Z.Q. and J.P. Sanderson: Relative toxicity of abamectin to the predatory mite, *Phytoseiulus persimilis* (Acari: Phytoseiidae) and two spotted spider mite (Acari: Tetranychidae). *J. Econ. Entomol.,* **83**, 1783–1790 (1990).

Registered with the Registrar of Newspaper for India   Registration No. 35574/1979

JEB

Website : www.jeb.co.in
E-mail : editor@jeb.co.in

Journal of Environmental Biology

Covered / Abstracted / Indexed by

J. Environ. Biol. *is covered by the following Abstracting and Indexing services:*

- Medline®
- Scopus®
- Embase®
- Geo Abstracts
- Paryavaran Abstracts
- Toxicology Abstracts
- Zoological Record®
- Biological Abstracts®
- Chemical Abstracts™
- Indian Science Abstracts
- EBSCO Discovery Service
- Elsevier Bibliographic Databases
- Forest Science Database (CABI)
- Current Contents® (Agriculture, Biology and Environ. Sci.)
- Essential Science Indicators
- PubMed®
- Aqualine
- Science Direct
- Web of Science
- Global Health
- BIOSIS Previews
- Excerpta Medica
- Pollution Abstracts
- Science Citation Index
- Environment Complete™
- Environmental Abstracts
- Cambridge Scientific Abstracts
- Veterinary Science Database
- Environmental Science Database
- Aquatic Sciences and Fisheries Abstracts (ASFA)

Editor-in-Chief : Professor R. C. Dalela
Publisher & Printer : Kiran Dalela
Triveni Enterprises,
1/206, Vikas Nagar, Lucknow-226 022
Sponsored by : Dalela Educational Foundation
2/503, Vikas Nagar, Lucknow-226 022
Telephone : +91-522-4017359; +91-522-3556509
Website : www.jeb.co.in
E-mail : editor@jeb.co.in; rnd@jeb.co.in