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NOVEL INSECTICIDES FOR MANAGEMENT OF INSECT PESTS IN VEGETABLE CROPS : A REVIEW

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Summary

During the last five decades conventional insecticides, all neuroactive chemicals have played major role in management of insect pests in vegetables, their indiscriminate uses led to several problems like resistance, residue, resurgence and safety to environment. 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. Now it is in a renaissance of integrating chemicals and biologicals for sustainable pest control with human safety. In recent years, several new insecticide groups having new chemistries *viz*., neonicotinoids, oxadiazines, diamides, ketoenols, phenylpyrazoles, pyridines, flonicamid, METI (Mitochondrial Electron Transport Inhibitor) acaricides, diafentiuron, tetrazines, thiazolidinones, oxazolines, and insecticides from soil microorganisms such as avermectins, milbemycins, spinosyns, pyrrole nsecticides and insect growth regulators like benzoylureas, triazines, diacylhydrazines, juvenile hormone analogues/mimcs have been discovered and commercialized for uses in modern crop protection. Because of the relatively low risk to non-target organisms and environment, high target specificity and their versatility in application methods, these important classes of new insecticides will certainly play a greater role in the present context of environmental safety and their consequent uses in integrated pest management and insect resistance management programmes. This review pertains to the to the most promising compounds along with unique characteristics in the light of their uses in agriculture in general and vegetables in particular.

Introduction

The extensive use of conventional insecticides (oraganochlorines, organophosphates, carbamates and synthetic pyretrhroids) has resulted in the development of severe pest resistance to insecticides, out-break of secondary pests, objectionable pesticide residues, direct hazard to the users and adverse effect on environment and non-target organisms. This has led to the search for and development of new compounds or newer bio-rationals or "low risk" insecticides viz., neonicotinoids, oxadiazines, diamides, tetramic/ tetronic acid derivatives, phenylpyrazoles, pyridine, avermectins, spinosyns, pyrroles, insect growth regulators (IGRs), etc. which has now-a-days, because of their good controlling properties of insect pests 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 (Hara, 2000). Besides, they are also less likely to cause outbreaks of secondary pests, extremely helpful for delaying resistance in key pests such as whiteflies and aphids and have no cross-resistance with the old and already established insecticides. These new insecticide groups with unique mode of action have been registered from late 1990s to early 2009 for insect control in vegetables. These characteristics render many of these new insecticides as safer, highly suitable and fit well into integrated pest management (IPM) or insect resistance management (IRM) programs (Casida and Quistad, 1998). An effort has been made in this paper to critically review the information related to different groups of novel insecticide molecules (Table 1.) in the light of their use in agriculture in general and vegetables in particular.

I. Insecticides of synthetic origin

Neonicotinoids or Chloronicotinyl insecticides (CNIs)

Neonicotinoids represent a novel and distinct chemical class of insecticide with remarkable chemical and biological properties. This group has expanded most rapidly in last two decades because of their broad insecticidal spectrum, exhibiting systemic and translaminar properties, and high residual activity with unique mode of action (Elbert *et al*., 1998). CNIs mimic nicotine in their mode of action and the biochemical target site is the nicotinic acetylcholine receptor (nAChR) of insect nervous system (Bai *et al*., 1991). An excellent overview on neonicotinoid chemistry, mode of action and biological activity is given by Jeschke and Nauen, 2007; Jeschke and Moriya 2007). Imidacloprid is the first compound to be launched in 1991 (Elbert *et al*., 1990 and 2007) and in a span of one decade six additional nicotinoids were

developed and commercialized (Table 2). Neonicotinoid group includes Imidacloprid, Acetamiprid, Nitenpyram, Thiamethoxam, Thiacloprid, Clothiamidin, Dinotefuran.

Neonicotinoids are widely used for controlling whiteflies, aphids and leafhoppers, thrips and small lepidopteran and coleopteran pests in most of the vegetable crops like tomato, chilli, okra, capsicum, cucurbits, melons, leaf vegetables etc. Additional biological profile of all neonicotinoid insecticides is presented in table 3. Neonicotinoids are flexible insecticides that can be used as foliar, drench or seed dressing treatments (Elbert and Nauen, 2004). As a foliar treatment, these insecticides would have an adverse impact on predatory hemipterans, honeybees and other pollinators. As seed treatment, imidacloprid and thiamethaxam can provide protection for a period of 30-35 days after sowing against sucking pests. Their versatile uses render them as an important component in IPM and IRM programs.

Imidacloprid : It is the first neonicotinoid to be commercialized and being used over 140 crops in more than 120 countries. Its versatility allows worldwide application against sucking and chewing pests of many vegetable crops (Mandal *et al*., 2007, Rana *et al.,* 2006). It is also, reported to be effective against soil insects (termites and white grubs) and no effect on spider mites and nematodes. It is available in different formulations *viz*., WG, FS, WS and SL. Imidacloprid @ 3 g/kg of seed when mixed with

Table 1. Classification of novel insecticides with new chemistries and their target sites

Sl. No	Insecticide Group	IRAC MOA*class	Active Ingredient	Primary Target Sites/Mode of Action
I.	Insecticide of synthetic origin			
1	Neonicotinoids	4A	Imidacloprid, Acetamiprid, Thiamethoxam, Thiacloprid, Clothiamidin, Dinotefuran, Nintenpyram.	Agonists of nicotinic acetylcholine receptor (nAChR)
2	Oxadiazines	22A	Indoxacarb	Blockers of voltage-gated sodium channels
3	Diamides	28A	Chlorantraniliprole, Flubendamide, Cyantranniliprole (Cyazypyr)	Ryanodine receptor modulators
4	Ketoenols	23A	Spirodiclofen, Spiromesifen, Spirotetramat	Inhibitors of acetyl CoA carboxylase
5	Phenylpyrazoles	2B	Fipronil, Ethiprole	GABA gated chloride channels antagonists
6	Pyridine	9B	Pymetrozine	Selective homopteran feeding blockers
7	Flonicamid	9C	Flonicamid	
8	METI	21A	Fenpyroximate, Fenzaquin, Pyridaben, Tebufenpyrad, Tolfenpyrad, Pyrimidifen, Flufenerim	Mitochondrial complex I electron transport inhibitors.
9	Diafentiuron	12A	Diafentiuron	Inhibitors of mitochondrial ATP synthase
10	Tetrazines	10A	Clofentezine	Mite growth inhibitors
11	Thiazolidinones	10A	Hexthiazox	
12	Nereistoxin	14	Cartap hydrochloride, Bensultap, Thiocyclam, Thiosultap sodium	Nicotinic acetylcholine receptor channel blockers
13	Formamidines	19A	Chlordimeform and Amitraz	Octopamine receptor agonists
II. Insecticides derived from soil microorganisms / Macrocyclic lactones				
1	Avermectins	6A	Abamectin, Emamectin Benzoate/vermectin	Activate glutamate-gated chloride channels
2	Milbemycins	6A	Milbemectin, Milbemycin D	
3	Spinosyns	5A	Spinosad, Spinetoram	Allosteric activators of nAChRs
4	Pyrrole Insecticides	13A	Chlorfenapyr	Uncoupers of oxidative phosphorylation via disruption of proton gradient
III. Insect Growth Regulators				
1	Benzylphenylureas	15	Diflubenzuron, Chlorofluazuron, Teflubenzuron, Hexaflumuron, Novaluron, Lufenuron, and Flufenoxuron	Chitin biosynthesis Inhibitors type 0, for lepidopterans.
2	Buprofezin	16	Buprofezin	Chitin biosynthesis Inhibitors type I, for Homoptera
3	Triazine	17	Cryomazine	Moulting disruptors for dipterans
4	Diacylhydrazines	18	Methoxyfenozide, Tebufenozide, Halofenozide, Methofenozide.	Ecdysone receptor agonists
5	Juvenile Hormone analogues/mimcs	7A	Hydroprene, Methoprene and Kinoprene.	Juvenile Hormone Mimics
		7B	Fenoxycarb,	
		7C	Pyriproxifen,	

*IRAC MOA: Insecticide Resistance Action Committee Mode of Action (IRAC 2010)

polymer @ 40 ml/kg provided good control against okra jassids and fruit borer (Satpathy *et al*., 2010). As foliar spray the recommended dose is 20-25 g a.i/ha, for seed treatment the dose is @ 3.5-7 gm/kg seed and as seedling root dip the dose is 0.02-0.03 % solution in okra (Satpathy and Kumar, 2010) chilli, brinjal and tomato.

Thiamethaxam: It is second neonicotinoid insecticide in use and marketed as actara for foliar spray and as cruiser for seed treatment use (Maienfisch *et al.,* 2001). This is highly systemic and broad spectrum insecticide used against sucking pests and some chewing and soil living insects. It is used on wide range of vegetable crops. It is highly toxic to honeybees. The usage rates as foliar spray is 25-50 g ai/ha and as seed treatment is 200 g a.i/kg of seed.

Acetamiprid: It is another new CNI having abroad spectrum activity with some ovicidal and larvicidal action against wide range of sucking insects (aphids, leafhoppers, thrips, whiteflies, psylla, leafminers, beetles and termites) on vegetables (Kiriyama *et al*., 1993). It has good translaminar, long lasting systemic activity with contact and stomach action and moderately active against lepidopteran pests such as diamond back moth. It can be applied to soil as well as foliage and as seed treatment. It exhibits high activity on insects resistant to organophosphates and synthetic pyrethroids. It is toxic to honey bees, so it should not be applied when bees are present in the area being treated. It is available in 20 SP and the recommended dose is 20-50 g a.i/ha.

Thiacloprid : It is systemic insecticide with broad spectrum having long lasting effect against sucking pests such as aphids, leafhoppers, thrips, whiteflies, psylla, leafminers and weevils on vegetables (Erdelen, 2001*)* and has been developed especially for foliar spray application. Another outstanding advantage is that it has no effect on pollinating insects such as honeybees and bumble bees and parasitic wasp which allows its application not only before and after but also during the flowering period of the crops and available in the trade of Calypso/Alanto and the recommended dose is 54-72 g a.i/ha.

Dinotefuran: This neonicotinoid is granted as alternative to organophosphate insecticides. Effective against leafminers, beetles and weevils on vegetables. It is available as 1-2 G, 20 SC and 0.5% D, but not registered in India.

Clothianidin: It is a broad spectrum insecticide having contact, stomach and high systemic action and relatively used at very low usage rates as foliar spray, soil application and as seed treatment (Altmann 2003). It is active against sucking insects such as aphids, leafhoppers, whiteflies and thrips. Because of its excellent root systemicity, clothianidin is very active against a broad spectrum of root, stem and leaf feeding pests as well as soil inhabiting pests that dwell in and around the seed. It is available in 50 % WDG and the recommended dose is 15-25 g a.i/ha.

Nitenpyram: It has good translaminar and translocation action, because of its high water solubility nitenpyram shows good systemic activity. (Minamida *et al.,* 1993). Therefore it can control pests by special soil treatment methods such as hole placement, plant root treatment before and after transplanting and as soil incorporation. It controls homopterous insects pests (leafhoppers, planthoppers, whiteflies and aphids) on vegetables and against thrips of vegetable grown under greenhouse conditions. It inhibits feeding in addition it also has ovicidal activity. It is applied at the rate of 75 g a.i./ha as dust formulation. Soil application of granular formulation has good potential for the control of leafminers in tomato and other crops grown in greenhouse condition. It is not registered in India.

Oxadiazines

Indoxacarb : It is the first commercialized insecticide of the oxadiazine group (McCann *et al.,* 2001). It acts on voltage gated sodium channels by inhibiting sodium

Table 2. Development of neonicotinoids insecticides

Sl. No.	Neonicotinoids	Year	Developed by	Source
1	Imidacloprid	1991	Bayer Crop Science	Elbert *et al*., 1990 and 2007
2	Acetamiprid	1995	Nippon Soda	Matsuda *et al.,* 1996
3	Nitenpyram	1995	Sumitomo chemical Takeda Agro company	Minamida *et al.,* 1993
4	Thiamethoxam	1998	Syngenta	Maienfisch *et al* 2001
5	Thiacloprid	2000	Bayer Crop Science	Erdelen *et al*., 2001; Elbert *et al*., 2001
6	Clothianidin	2001	Bayer Crop Science and Sumitomo Agro chemical company	Altmann *et al*., 2003
7	Dianotefuron	2002	Mitsui Chemicals	Kodaka *et al*., 1998

ion entry into nerve cells (Lapied *et al*., 2001) resulting in paralysis and death of target pest species. No cross-resistance has yet been reported between indoxacarb and other insecticide groups (Holloway and Forrester, 1998). Furthermore, negative cross-resistance has been observed between indoxacarb and pyrethroids in *Helicoverpa armigera* (Gunning and Devonshire, 2002). The ingested toxicant causes very rapid cessation of feeding (within a few hours in lepidopterans) and death within 48 hours. This insecticide is effective against lepidopteran pests (*Helicoverpa* sp., *Spodoptera* sp., *Plutella* sp.) (Rai *et al.,* 2007, Shivalingaswamy *et al*., 2008) as well as certain homopteran (*Lygus* sp., *Empoasca* sp.) and coleopteran pests in vegetables crops (Pluschkell *et al*., 1998; Tong-Xian *et al*., 2002). Indoxacarb ranked very high in overall ranking of insecticides for their safety to beneficial insects, largely because of its low dermal toxicity (Michaud and Grant, 2003). It is available as 14.5 and 15.8 SC and recommended dose is 30-75g ai/ha.

Diamides

Two classes have been developed in this group are flubendiamide and chlorantraniliprole belonging to phthalic acid diamide and anthranilic diamide class, respectively. The recent introduction of flubendiamide and chlorantraniliprole (Rynaxypyr) is significant in the field of crop protection, particularly important in light of the ability of insects to rapidly develop resistance and the need for safe and effective pesticides that act at new biochemical targets sites. Insecticides in this class selectively bind to the ryanodine receptors (RyRs) in insect muscle cells, resulting in activation of RyRs and causing an uncontrolled release of Ca^{+2} ions from internal stores in the sarcoplasmic reticulum (Lahm *et al.,* 2007) leading to muscle paralysis and death. These insecticides provide rapid plant protection through the cessation of larval feeding and mortality after 1–3 days. Translaminar activity has been demonstrated for both against *Plutella xylostella* in cabbage and Barry. To date, neither flubendiamide nor chlorantraniliprole has been found to exhibit cross-resistance with other commercial insecticides and are good candidates for consideration in IPM programs (Koppenhofer and Fuzy, 2008).

Table 3. Biological profiles of neonicotinoid insecticides

Neonicotinoids	Additional spectrum	Foliar spray	Soil use	Seed Treatment
Imidacloprid	Thrips, mealybugs, leafminers, termites	+ + (+)	+ + +	+ + (+)
Acetamiprid	Diamond back moth	+ + +	+	-
Nitenpyram	-	+ +	+	-
Thiamethoxam	Mealybugs, plant bugs, leafminers, termites	+ + +	+ + +	+ +
Thiacloprid	Thrips, Minor lepidopterans and small beetles	+ + +	-	-
Clothianidin	Wooly aphid, fruit moths, rootworms	+ + (+)	+ +	+ + +
Dianotefuron	Soft scales, thrips, mealybugs	+ + +	+ +	-

+ + + broad, + + good, + limited, - not relevant.
Source: Elbert *et al*., 2007

Chlorantraniliprole (Rynaxypyr) : It is recently released anthranilic diamide insecticides having excellent activity on Lepidopteran insects with field application rate of 25– 75 g ai/ha (Lahm *et al*., 2007) and can be as low as 15-20 g ai/ha against *Earias vitella* and *Leucinodes orbonalis* (Kodandaram *et al*., 2010a and 2010b). It provides rapid plant protection through the cessation of larval feeding soon after consumption. It also has ovicidal and ovo-larvicidal action. It is also effective against leafminers, beetles, weevils and white grubs. Because of its translaminar and systemic action, rynaxpyr can be applied as foliar spray and as soil application. It is found to be safe to parasitods, predators and pollinators. It is available in 18.5 SC and used at 10 g a.i /ha against *Plutella xylostella* in cabbage and cauliflower.

Flubendamide: It was discovered in 1998 as a result of the synthesis and screening of two thousand derivatives based on a pyrazine dicarboxamide derivative (Kodama *et al*., 2007). It has high activity against lepidopterans insect of many cucubitaceous, cole and solanaceous vegetables pests but there is no evidence of activity in other insect orders. It is applied

Table 4. List of new insecticides registered under/section 9 (3) of the Insecticide Act, 1968.

1 Acetamiprid	11 Ethiprole	21 Lufenuron
2 Bifenazate	12 Fenazaquin	22 Milbemectin
3 Buprofezin	13 Fenpyroximate	23 Novaluron
4 Cartap Hydrochloride	14 Fipronil	24 Pyridalyl
5 Chlorantraniliprole	15 Flubendiamide	25 Pyriproxyfen
6 Chlorfenapyr	16 Flufenoxuron	26 Spinosad
7 Chlothianidin	17 Flufenzine	27 Spiromesifen
8 Difenthiuron	18 Hexythiazox	28 Thiacloprid
9 Diflubenzuron	19 Imidacloprid	29 Thiodicarb
10 Emamectin Benzoate	20 Indoxacarb	30 Thiamethoxain

as foliar spray and also through chemigation. It is considered as good alternative to indoxacarb and methoxyfenozide. It is available in 24 WG and 240 SC and the recommended dose is 48-60 g a.i/ha.

Cyantraniliprole (Cyazypyr) : It is the second generation ryanodine receptor insecticide with cross spectrum activity against lepidopteran and homopteran pests (Selby *et al.,* 2008),. The target crops are fruiting vegetables and cucurbits. It controls whiteflies, dipteran leafminers, fruitflies, foliage feeding beetles and lepidopteran larvae. Also, controls aphids, leaf hoppers, thrips, psyllids and weevils.The translaminar activity makes it suitable for soil application. The dosage for chewing and sucking insects is 10-100 g a.i./ha.

Ketoenol group or tetramic and tetronic acid deravatives

This group includes spirodiclofen, spiromesifen and spirotetramat insecticides (Nauen *et al.,* 2005). The mode of action of ketoenols has been characterized by the inhibition of enzyme (Acetyl Co A carboxylase enzyme) in lipid biosynthesis or metabolism (Bretschneider *et al*., 2003). The biological activity correlates with inhibition of lipogenesis especially triglycerides and free fatty acids. This new mode of action and lack of cross resistance to other commercial products make ketoenols as a valuable tool for mite, whitefly and other sucking pests management in many vegetable crops.

Spirodiclofen : It is a selective, non-systemic acaricide having broad-spectrum activity with excellent efficacy against mites such as *Panonychus*, *Tetranychus*, *Phyllocoptruta*, *Brevipalpus* and *Aculus* (Wachendorff *et al.,* 2000). Due to its high lipophilicity spirodiclofen has got good residual efficacy against the spider mite species and the acaricidal effect remains stable for up to 14 days. Spirodiclofen is more active at higher temperatures indicating a positive temperature coefficient. Under greenhouse conditions it dose not have any phytotoxicity on tomato and cucumber even at the highest concentration of 1000 ppm. It showed no cross-resistance to organophosphates, METIs (mitochondrial electron transport inhibitors), hexythiazox and abamectin in strains of spider mites with high resistance (Rauch and Nauen, 2003). It is but not registred in India.

Spiromesifen : It is second tetronic acid derivative new insecticide and acaricide introduced recently (Bretschneider *et al*. 2003; Nauen *et al.,* 2005). It provides good efficacy against whiteflies *Bemisia tabaci*, *Trialeurodes* spp. (Palumbo 2004, Elbert *et al*., 2005). In addition to whiteflies, it is highly effective against mites including spider mites such as *Tetranychus* spp., red spider mites (*Panonychus* spp.) and *Oligonychus sp.*, Tarsonemid mites *(Polyphagotarsonemus latus)* and Eriophyd mites *(Aculops lycopersici)* (Elbert *et al.,* 2005). It is also reported to suppress some species of thrips such as *Scirtothrips dorsali, Thrips palmi* and *Thrips tabaci* in

Table 5. New insecticides recommended for insect control in different vegetable crops

Common name	Formulation	Dosage /ha			Common name	Formulation	Dosage /ha		
		a.i (gm)	Formulation (gm/ml)	Dilution in water (Litre)			a.i (gm)	Formulation (gm/ml)	Dilution in water (Litre)
Buprofezin	25 % SC	75-150	300-600	500-750	Imidacloprid	17.8 % SL	25-20	125-250	500-700
Chlorantranilprole	18.5% SC	10	50	500	Indoxacarb	14.5% SC	30-75	200-500	400-750
Chlorfenpyre	10 % SC	75-100	750-1000	500	Indoxacarb	15.8 % SC	40	266	500-1000
Difenthiuron	50 % WP	300	600	500-750	Lufenuron	5.4% EC	30	600	500
Emamectin benzoate	5 % SG	6.75-10	135-200	500	Metaflumizone	22 % SC	165-220	150-1000	500
Fenazaquin	10 % EC	125	1250	400-600	Milibectin	1 % EC	3.25	325	500
Fenpyroximate	5 % EC	15-30	300-600	300-500	Novaluron	10% EC	33.5-75	750-375	500-1000
Fipronil	5 % SC	40-50	800-100	500	Pyridalyl	10%EC	50-75	500-750	500-750
Flufenoxuron	10 % DC	40	400	500-1000	Spinosad	2.5% SC	15.0-17.5	600-700	500
Flumite/ Flufenzine	20 % SC	80-100	400-500	500-1000	Spinosad	45% SC	73	160	500
Hexythiazox	5.45 % EC	15-25	300-500	625	Spiromesifen	22.9% SC	96	400	500
Imidacloprid	70 % WG	21-24.5	30-35	375-500	Thiacloprid	21.7% SC	54-72	225-300	500
Imidacloprid	48 % FS	300-540 (per 100 kg seed)	500-900	-	Thiamethoxam	25% WG	25	100	500-1000
Imidacloprid	70 % WS	350-700 (per 100 kg seed)	500-1000	-	Thiamethoxam	70% WS	200	286	

Source: Anonymous 2009.

vegetables. It is highly effective against all juvenile and nymphal stages of mite and whitefly, with a significant effect on pupal stage.

Because of its high selectivity, good residual activity, minimal risk to pollinators (Nauen *et al*., 2002; Nicolaus *et al*., 2005) and to other many beneficial insect and predatory mite species (Nicolaus *et al*. 2005) combined with a novel mode of action make spiromesifen as an excellent new tool for many Integrated Pest Management programs. It is also found to be effective against whiteflies resistant to pyrethroids, organophosphates, carbamates, cyclodienes and neonicotinoids. Some field studies have also revealed that spiromesifen is effective against whiteflies resistant to pyriproxifen (Nauen and Konanz, 2005). Therefore, spiromesifen is expected to become an excellent resistance management tool in combination or rotation strategies for managing whitefly resistance to insecticides (Nauen and Konanz, 2005). It can be applied or used as foliar spray or through chemigation (application by several irrigation systems except drip irrigation). It is available in 22.9 SC and recommended dose is 96 gm a.i/ha.

Spirotetramat : It is third new insecticide of tetramic acid derivatives that shows excellent activity against aphids, mealybugs, psyllids, scales, thrips and whiteflies in cabbage, brinjal, pepper, tomato, cucurbits, melons, potato and other tuberous and corm vegetables. Juvenile stages of sucking pests are particularly more susceptible, thereby; it provides even control of hidden pests (such as root aphids) and protects new shoots appearing after foliar application. It is considered as alternative to the neonicotinoids and IGRS. It has good systemic action, translocates upward and downward within plants (2-way systemic action). Its potential impact on different ecosystems is favourable with less eco-toxicological profile (Van Waetermeulen *et al*., 2007). It is available in 2 SC formulation (Not yet registered in India).The overall profile of this insecticide will make it highly effective tool for the management of sucking pests in vegetables.

Phenylpyrazoles

Fipronil: The phenylpyrazoles represents a new class of pesticides which exhibit insecticidal activities. Fipronil has contact action on both chewing and sucking insects. Its mode of action is the neuroinhibition of GABA -gated chloride channels (Bloomquist, 2001). Fipronil exhibits broad activity against various insect pests such as soil insects, foliar feeding pests such as diamondback moth, *Plutella*. *Xylostella*, *Spodoptera* sp., the sucking pests such as thrips and *Lygus* sp. (but not aphids or whiteflies), and on various non crop and household pests. It can be used as foliar spray and seed treatment . 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. It is available as 5 % SC used @ 40-50 g a.i /ha as foliar spray against vegetable pests and 0.3% as granules @ 50-75 g a.i .ha against soil pests.

Pyridine

Pymetrozine: Pymetrozine, a novel azomethine pyridine insecticide, having systemic and translaminar activities and is highly specific against sucking insect pests. It affects the nerves controlling the salivary pump and causes immediate and irreversible cessation of feeding due to an obstruction of stylet penetration, followed by starvation and insect death. It has rapid knockdown effect on aphids such as *Aphis gossypii* and *Myzus persicae* and is a powerful toxicant to whiteflies *B. tabaci* and *Trialeurodes vaporariorum* and planthoppers and also effective in reducing aphid-transmitted diseases caused by persistent viruses. It has shown effectiveness against different strains of resistant aphids with no evidence of cross-resistance and can play an important role in IRM strategies for aphids. It can be applied as soil drench or foliar spray. It has very low mammalian toxicity and no appreciable effect on non targets and beneficial insects, thus it can be a potential IPM component in controlling sucking insect pests. It is used @ 100-300 g a.i/ha and not registered in India for its usage.

Flonicamid

Flonicamid is a novel selective aphicide belongs to the pyridinecarboxamide group. It shows moderate insecticidal activity on major sap sucking insects like whitefly, jassids, scales, thrips and mealy bugs on vegetables and potatoes. Flonicamid is active against both adults and nymphs. It is found effective in controlling aphids resistant to various conventional insecticides (Morita *et al*., 2000, Hancock, 2003). Flonicamid specifically inhibits feeding immediately after treatment in aphids and this antifeeding activity was not recoverable until death. The main insecticidal

mechanism of this compound is starvation based on the inhibition of stylet penetration to plant tissues (Morita *et al.*, 2000). Although the insecticidal properties of flonicamid seem to resemble those of pymetrozine different aspects exist between the two insecticides. Thus, the mode of action of flonicamid is different from that of pymetrozine. Most treated aphids display uncoordinated locomotion, and some aphids walked staggeringly with their legs stretched immediately after treatment (Morita *et al.*, 2000). It is considered to be safe to natural enemies and pollinators. Beside foliar application it can also be applied in soil. One single spray can control the pests for 2-3 weeks. Its usage rate is 50-100 g ai/ha. This is not yet registered in India.

Diafenthiuron

It is a proinsecticide activated by oxidative desulfurization to the insecticidal carbodiamide. It not only controls sucking pest complex like whitefly, aphid, leafhoppers but also tetranychid and tarsonemid mites and young larvae of lepidopteran pests especially DBM (Ishaaya *et al.,* 1995). Though it has no systemic action yet it displays translaminar activity. It is known to disrupt oxidative phosphorylation by direct inhibition of mitocontrial ATP synthase (complex V) involved in energy metabolism. Because of its unique mode of action, it has no cross resistance with any other existing insecticides or acaricides being used against *Bemisia tabici*, *Aphis* gossypi (*Denholm et al.,* 1998) and Diamond back moth *Plutella xylostella*. Because of its unique chemical class, novel mode of action, biological spectrum, translaminar activity, high selectivity towards beneficial insects and lack off cross resistance with other conventional and new insecticide, it can be a an important active ingredient in protection of many vegetable crops and also can be an important component of rotational spray regimes, in any IPM programs. It is available in trade name Pegasus and Polo and the recommended dose is 300-400 gm a.i/ha.

METI acaricides or insecticides

Pyridaben: Pyridaben belongs to pyridazionone group of insecticide having non systemic acaricide and insecticide properties with rapid knockdown and long residual effect. It shows excellent activity against all developing stages of wide range of phytophagus mites and also effective against whiteflies, aphids, mealybugs, leafhoppers, psyllids and thrips of vegetable crops. Biochemically, it inhibits mitocondrial electron transport of complex I. It also found to be compatible with many entomopathogenic fungi like *Beauveria bassiana* when applied for the management of red mite, *Panonychus citri*. Thus, this new class of insecticide offering long term residual control and is good to fit in IPM. It is available in EC, SC and WP formulations and the recommended dose is 5-20 g a.i /ha. It is not yet registered in India.

Fenazaquin : Fenazaquin is one of several acaricides and insecticides and has an unique chemical configuration consisting of quinazoline moiety. Among vegetables, it is widely used as an acaricides for management of chilli mite, *Hemitarsonemus latus*, okra and brinjal mite (*Tetranychus urticae*) (Walnuj and Pawar, 2000). It is known to act by inhibiting NADH ubiquinone oxidoreductase (Complex I) of the nervous system (Wood *et al.*, 1996) and also inhibits the mitochondrial electron transport at site I of the mitochondrial respiratory chain (Hollingworth *et al.*, 1994). It is available mainly in 10 % EC formulation and the recommended dose is 125 g a.i/ha.

Fenpyroximate: It is effective against mites of family, tetranychidae, Tarsonemidae, Tenuipalpidae and Eriophyidae in vegetables. It also causes rapid knockdown effect against larvae, nymphs and adults, mainly by contact and ingestion. Beside this, it also has some moulting inhibitory activity on nymphs. Fenpyroximate serve as an inhibitor of mitochondrial electron transport at complex I. No phytotoxicity effect is observed in vegetables crops. It is available mainly in 5 % EC formulation and the recommended dose is 15-30 g a.i/ha.

Tetrazines

Clofentezine: It is a specific acaricide having contact action with long residual activity. It Inhibits embryogenesis and can be used for control of mainly eggs and young motile stages of *Panonychus ulmi* and *Tetranychus spp* (Herron *et al.*, 1993). It has no adverse effect on predatory mites or beneficial insect species. It is formulated in SC and WP available under the trade name of Apollo, Acaristop, Cara, etc. It is not yet registered in India.

Thiazolidinones

Hexythiazox: It is a broad spectrum acaricide having

ovicidal, larvicidal and nymphicidal activity against mites, thrips and leafhoppers and is applied at any stage of plant growth from budding to fruiting. It is widely used in controlling many phytophagous mites in vegetables crops and it has special affinity towards tetranychid and teneuipalpidae mites (Campos and Omoto, 2002).It is highly persistent and toxic to fish and other aquatic invertebrates. The recommended dose is 15-25 g a.i/ha.

Nereis toxin

Cartap hydrochloride: It is a broad spectrum insecticides and mainly used for control of chewing and sucking insects (particularly Lepidoptera and Coleoptera), at almost all stages of development, on many crops, including rice (*Scirpophaga incertulus, Cnaphalocrocis medinalis*) potatoes, cabbage (*Plutella xylostella)* (Reddy and Guerrero, 2001), brinjal (*Leucinodes orbonalis*) (Anonymous, 2007; Sinha *et al.,* 2009). It is available in the market in DP, G and SP formulations and it is not compatible with pesticides which are alkaline.

Formamidines

Amitraz: Amitraz, a member of the amidine class, is an insecticide and acaricide used to control red spider mites, two spotted spider mite (Bynum *et al*, 1997) leaf miners, scale insects, and aphids in which the mechanism of action is similar to other á2-adrenoreceptors agonists as well as by the inhibition of the enzyme monoamine oxidase.

II. Insecticides derived from soil microorganisms/ macrocyclic lactones

In past there have been various attempts to exploit insecticides from natural or biological sources. Some important classes of insecticides are derived mostly from soil microorganisms by fermentation procedures. Among these are avermectins, spinosyns and pyrrole insecticides. Another important insecticide in this group is *Bacillus thuringiensis* (*Bt*) which is not discussed in this paper.

Avermectins

This group includes abamectin, emamectin benzoate and milibemectin, which have been commercialized for use in crop protection. Several reviews (Strong and Brown, 1987; Lasota and Dybas, 1991; Jansson and Dybas, 1996) cover this family, which has gained importance in recent past. Avermectins are a group of macrocyclic lactones (macrolides) isolated from fermentation of the soil actinomycete microorganism, *Streptomyces avermitilis* Burg (Strong and Brown, 1987). The avermectins consist primarly of four major (A1a, A2a, B1a, B2) components and four homologus minor (A1b, A2b, B1b, B2b) components. The B series has more biological activity than A series.They are relatively broad-spectrum pesticides having both insecticide and acaricidal properties (Strong and Brown, 1987) as well as nematodes (Campbell et al., 1983) and mites and effective by either contact or stomach action.

The biochemical mode of action of avermectins and milibemycins has been thoroughly discussed in several reviews (Lasota and Dybas, 1991; Jansson and Dybas, 1996).The main target sites for avermectins is the GABA -gated chloride channels receptor in the insect nervous system (Fisher 1993; Bloomquist 2001). They stimulate GABA gated chloride channels which results in an increased flow of chloride ions into the cell and causing rapid activation, inactivation and inhibition of neurotransmission (Jansson and Dybas, 1996). Despite significant toxicity to a number of non-target species, avermectin are considered suitable for use with many beneficial insects due to its short environmental persistence which made avermectins a historically important component of greenhouse and orchard IPM (Lasota and Dybas, 1991).

Abamectin : It is a mixture of two molecules, (not less than 80 % avermectin B1a and not more than 20% avermectin B1b) (Fisher and Mrozik 1989) isolated from a set of eight molecules produced by the original soil microorganism. It is a broad spectrum insecticide with contact and translaminar action. Highly toxic to many arthropods, including spider mites, leafminers, thrips, psylla and also the diamond back moth and selected lepidopteran pest species (Lasota and Dybas 1991). Despite its rapid photodecomposition following application, abamectin provides residual activity in the field due to its translaminar action. The use of mineral oil or surfactants in combination with abamectin extends its foliar residual toxicity, especially aganist phytophagous mites, under greenhouse and field conditions (Rai *et al.,* 2009; Mizell *et al.,* 1986). It is considered as a leading compound for controlling mites in various agricultural systems. Abamectin binds tightly to soil, with rapid degradation by soil

microorganisms, and consequently there is no bioaccumulation (Lankas and Gordon, 1995). Abamectin is available in the trade name of Vertimec 1.9 EC used @ 4.5 to 22.05 g a.i/ha for mite control and 11–22 g a.i./ ha for control of leafminers.

Emamectin Benzoate: It is second-generation avermectins derived by chemical synthesis from abamectin. It has good contact and stomach action with broad spectrum of insecticidal activity than abamectin with limited plant systemic activity, but exhibits good translaminar movement providing a relatively prolonged residual effect. While abamectin acts specifically on mites, with low efficacy on lepidopterans, emamectin benzoate exhibits excellent activity particularly against caterpillar pests (Lepidopterans) and is also found to be highly effective for controlling leaf miners and thrips and has suppressive activity against mites (Dunbar *et al*., 1998). The extreme potency of this compound against Lepidoptera was discovered by Merck scientist. The compound acts on various lepidopteran pests such as *P. xylostella, Trichoplusia ni*, *Heliothis spp* and *Spodoptera litura* infesting vegetable crops (Shivalingaswamy *et al.,* 2010). Emamectin benzoate is very active against beneficial insects such as honey bees and as such should not be sprayed during flowering (Fisher, 1993). It is available as 5% SG formulation under the trade name Proclaim and the recommended dose is 7.5-10 g a.i a/ha.

Milbemycins

Milbemectin: It is derived from the soil bacterium *Streptomyces hygroscopicus* subsp. *aureolacrimosus*, and used for control of mites (Mishima, 1983). The predominant components of commercial product is a mixture of milbemycins containing milbemcin A4 and milbemycin A3 in the ratio of 7:3. It is an acaricide with contact and stomach action, with limited plant systemic activity, but it does exhibit translaminar movement. Milbemycin is used for the control of red mites, pink rust mites, spider and other mites, and is also recommended for control of leaf miners in vegetables protected ornamentals (Mishima, 1983). It does not persist in the environment and is considered to be relatively non-toxic to nontarget organisms, although some beneficial insects are susceptible. Milbemycin is available as EC and WP formulations and the recommended dose is 25 g a.i./ha for mite control.

Spinosyns

The spinosyns are a class of fermentation bioinsecticides derived from macrocyclic lactones produced by soil actinomycete, *Saccharopolyspora spinosa* (Mertz and Yao, 1990; Crouse and Sparks 1998). This group includes two insecticides, spinosad and spinetoram. They are effective against various insect pests, especially lepidopteran, thysanopterans and dipterans (Sparks *et al.,* 2001). Spinosyns primarily target the binding sites on nicotinic acetylcholine receptors and also has secondary effects on GABA gated ion channels leading to disruption of acetylcholine neurotransmission (Sparks *et al.,* 2001). However, the site of interaction of spinosyns on the acetylcholine receptors differs from that of neoicotinoids, fiproles, and avermectins (Salgado, 1998). As a result of this novel mode of action this group causes spontaneous muscle contractions, tremors by exciting neurons and disruption in the central nervous system of insects (Salgado, 1998 and Sparks *et al*., 2001).

Spinosad: Spinosad is a mixture of the two most abundant spinosyns, A and D (Sparks *et al*. 2001). It acts primarily as stomach poison, but also has some contact action with translaminar activity thus, affecting hidden insect pests that are not targeted by the spray solution. It has broad spectrum of activity against a range of agricultural insect pests, *Helicoverpa armigera*, *Pieris rapae*, *Plutella xylostella* and *T. ni* (Hines and Hutchison, 2001; Shivalingaswamy *et al*., 2006; Satpathy *et al*., 2007). It is the most potential and powerful insecticide for controlling the selective insects in vegetables cultivated in greenhouses (Schoonejans and van der Staaij, 2001). Spinosad may also be used on row crops, vegetables, and ornamentals (Copping and Duke, 2007). Spinosad is rapidly degraded on soil surfaces by photolysis and, below the soil surface, by soil microorganisms (Saunders and Bret 1997). It is available in market in the with trade name of Tracer 45 % SC, used @ 75-100 g a.i/ha against bollworm complex and as Success 2.5 % SC @15-17.5 g a.i/ha on vegetables (cabbage, cauliflower).

Spinetoram: It is a second generation insecticide of the spinosyn class, derived from fermentation of *Saccharopolyspora spinosa*, but fermentation is followed by chemical modification to create this unique active ingredient (Sparks *et al*., 2007; Lewer *et al*.,

2007) . Spinetoram will provide long-lasting control of a broad spectrum of insect pests in a variety of crops and exhibits excellent translaminar activity. Spinetoram has good potential in desert grown leafy vegetables and melons. It is used as foliar spray or soil application with residual impact for 10-15 days. Field application rates range from approximately 30 - 120 g a.i /ha, depending on crop and pest. It is available in 1% SC but not yet registered in India.

Pyrrole insecticides

Chlorfenapyr : Pyrrole insecticides are derived from a natural product, dioxapyrrolomycin, isolated from a strain of *Streptomyces fumanus*. Using dioxapyrrolomycin as a template, several pyrroles have been synthesized, chlorfenapyr is a commercially developed pyrrole insecticide. Chlorfenapyr is mainly a stomach toxicant, but has some contact action (French *et al*., 1996). It has broad spectrum activity against many species of Lepidoptera, Acarina, Thysanoptera and Coleoptera, (Hunt and Treacy, 1998, Satpathy *et al*., 2005) in vegetables. Chlorfenapyr acts at the mitochondrial level by uncoupling oxidative phosphorylation. The activated compound disrupts the proton gradient across mitochondrial membranes and impairs the ability of the mitochondria to produce ATP, which leads to cell destruction and death of the affected pest arthropod (Hunt and Treacy 1998). It's available as 10% SC formulation in the trade name of Pirate and recommended dose is 75-100 g a.i/ha.

III. Insect Growth Regulators

One of the new approaches in the management of insect pest management is the use of analogs and antagonists of insect growth regulators (IGR) such as chitin synthesis inhibitors, ecdysones, juvenile hormones (JH) and related compounds. Because of their high selective toxicity towards insect species, low toxicity to mammals and their safety to the environment, they can assume a prominent role in the integrated pest management program. In addition, there is so far no report on resistance and resurgence problems aganist this group of insecticides.

Benzyl phenyl ureas (BPUs)

Moulting is one of the important physiological process of arthropods. Chitin synthesis inhibitors interfere during chitin biosynthesis by exerting their toxic effects at the time of molting thereby causing abnormal endocuticular deposition and abortive molting (Mulder and Gijswijt, 1973). These compounds are highly selective and affect the larval stage and acts mainly by ingestion, but in some species they suppress fecundity and exhibit ovicidal and contact toxicity (Ishaaya and Horowitz, 1998). CSI elicit symptoms of poisoning a few days after treatment, unlike the conventional neurotoxic insecticides which are fast-acting. Death typically occurs within 3 to 10 days, depending on the molecule, the insect, its life stage, when the product is applied. Some of the important chitin synthesis inhibitors are the benzoylphenyl ureas (BPUs), such as diflubenzuron, chlorfluazuron, lufenuron, novaluron, etc. These BPUs have been developed as commercial compounds for controlling agricultural pests, especially against lepidopterans.

Diflubenzuron: This is first commercial compound in this group and very effective in controlling insect pests such as *Spodoptera* spp., and *Heliothis* spp of vegetable crops. It is slow-acting, and effective against all molting stages. Diflubenzuron is primarily active through ingestion, it is less toxic to a number of natural enemies, especially parasitic wasps. The eggs and immature stages of predatory beetles, as well as lacewings, are sensitive to diflubenzuron. Resistance to diflubenzuron in codling moth populations is reported in France (Sauphanor *et al*., 2000), indicating the need for the careful rotation of this insecticides with insecticides that have different modes of action. It is available in 25 %WP and the recommended dose is 75-100 g a.i/ha.

Teflubenzuron: It is non-systemic insect growth regulator with stomach action. It affects fertility of female insects after contact or ingestion. It is used in control of Lepidoptera, Coleoptera, Diptera, Aleyrodidae, Hymenoptera, Psyllidae, and Hemiptera larvaes on cabbage, cauliflower, potato vegetables. It is not registered in India.

Flufenoxuron: Flufenoxuron is another IGR insecticide that has insecticidal and acaricidal properties. It has contact and stomach action. Widely used in controlling insects and mites of vegetables. Beside these it can also be applied control the pest that has got resistance to resistance to conventional insecticides. It is available as 10% DC and the recommended dose is 40 g a.i./ha.

Novaluron: A new BPU insecticide having more

contact and translaminar activity as compared with other CSI. It is very effective in controlling Diamond back moth, bollworms and caterpillars, *Spodoptera litura* and *S. exigua*. In addition it is effective against coleopteran larvae and a powerful toxicant against developing stages of whiteflies, (*B. tabaci* and *Trialeurodes vaporariorum*) and leafminers (Ishaaya *et al.,* 1996). Its translaminar activity enables in controlling the leaf miners of vegetables. The compound has no cross-resistance with other leading compounds for controlling whiteflies such as buprofezin and pyriproxyfen. It has no appreciable effect on parasitoids and predators. It is persistent up to 10-30 days under field conditions. It is available in 10 % EC and the recommended dose is 33.5-75 g a.i/ ha.

Buprofezin

It is a thiadizine-like compound with long residual activity that acts as a chitin synthesis inhibitor. It has contact and stomach action with some vapor activity. It acts on nymphal stages of sucking insects such as leafhoppers, planthoppers, whitefly, scale insects and mealybugs (Ishaaya *et al*., 1988). Similar to the other BPUs, buprofezin is effective on immature stages and not on adults. It has a mild effect on natural enemies and is considered an important component in IPM programs for controlling whiteflies and mealybugs in vegetables. It is available in 25% SC and the recommended dose is 75-150 g a.i/ha.

Triazine

Cyromazine: It is another new IGR compound belonging to the chemical class of triazines. This new chemistry is currently used for controlling dipteran leafminers, *Liriomyza* in cole crops, lettuce, peppers, spinach, celery, tomatoes and cucurbits. It is very effective at low dosages. Young larval stages are more susceptible to this chemical which interferes with their development and with pupation, the adult insects are not affected. It has translaminar activity and quickly penetrates into leaves. Because of its high level of specificity, cyromazine is much less toxic to natural enemies, compared with other IGRs such as diflubenzuron, making it highly compatible with integrated pest management (IPM) programs (Schuster, 1994). As a number of leafminer species have developed resistance to the conventional groups of insecticides around the world thus, cyromazine will be important tool in rotational sprays with other insecticide chemistries to combat insecticide resistance in leafminers. This is not registered in India.

Diacylhydrazines

Various physiological and biochemical processes in insects are regulated by juvenile hormones, insecticides which target ecdysteroid and juvenile hormone (JH) receptor sites have been developed during the past two decades (Dhadialla *et al*., 1998). Among various ecdysone agonists developed two compounds, tebufenozide and methoxyfenozide, have been commercialized for controlling lepidopteran pests in vegetables (Dhadialla *et al.,* 1998; Smagghe and Degheele, 1998). These compounds disrupt insect hormonal systems, and bind to the ecdysteroid receptors, thereby accelerating the molting process (Palli *et al.,* 1996).

Tebufenozide: It is first ecdysone agonist having stomach poison and if very effective against lepidopteran pests such as *Spodoptera sp*., *Helicoverpa* in vegetables (Smagghe and Degheele 1992; Ishaaya *et al*., 1995). It mimics moulting hormone and blocks completion of normal molting process (Retnakaran *et al.,* 2001). The insect stops feeding within a few hours and undergoes a premature lethal molt within 3 to 7 days, becoming trapped within the shedding head capsule. It is slow-acting having residual activity for 14 to 21 days. Application timing is critical, because it is more active on early larval stages (Waldstein and Reissig 2001). It is non-toxic to honeybees and doses not affect most of the natural enemies (Dhadialla *et al*., 1998). There is likely to be cross-resistance between tebufenozide and methoxyfenozide, because they have the same mode of action, thus this insecticide need to be used infrequently, alternated with other insecticide chemistries, and coupled with alternative methods of control, such as mating disruption, to delay resistance in key pests. It is not registered in India.

Methoxyfenozide: It is a second generation moult accelerating compound, similar to tebufenozide in its mode of action (Carlson *et al*., 2001). Methoxyfenozide is five to tenfold more potent than tebufenozide (Ishaaya *et al*., 1995), due to its better binding with lepidopteran receptors and have longer residual efficacy as compared to tebufenozide. It has much lower ability to bind with receptors in non

lepidopteran species, making it a highly selective insecticide. It controls lepidopteran larvae, but with more activity against bollworm and diamondback moth (Dhadialla *et al*., 1998; Smagghe and Degheele, 1998). Larvae die of dehydration and starvation. It is recommended at 25-300 g a.i./ha. It is not registered in India.

Tebufenozide and methoxyfenozide are considered highly selective for lepidopteran pest with no harm to other orders of arthropods and natural enemies, make them fit well into IPM and IRM programs (Dhadialla *et al*., 1998; Smagghe and Degheele, 1998). Neither of the compounds have an appreciable cross-resistance with conventional insecticides (Ishaaya *et al.,* 1995), but the risk for development of resistance to both compounds is apparent (Moulton *et al.,* 2002).

Juvenile Hormone Mimics

Among the JH mimics, fenoxycarb and pyriproxyfen are two important compounds effective in controling agricultural pests. Fenoxycarb is the first commercial JH compound for controlling agricultural pests (Masner *et al*., 1987). Pyriproxyfen is most potent JH mimic currently used in pest management.

Pyriproxyfen: Is a pyridine compound that acts as JH mimic affecting the hormonal balance in insects, thereby resulting in strong suppression of embryogenesis, metamorphosis and adult formation (Ishaaya *et al*., 1994). It is most effective on late larval instars, nymphs and early pupal stages when juvenile hormone is normally low. It is considered as a leading insecticide for controlling whiteflies (Ishaaya and Horowitz, 1995; Ishaaya *et al.,* 1994). Because of its persistence and efficacy, pyriproxyfen has been extremely effective in controlling insects that have developed resistance to organophosphate insecticides. It is safer for hymenopterous parasites than OP insecticides. Pyriproxyfen is toxic to crustaceans, limiting its use around water bodies. Although high resistance to pyriproxyfen in *B. tabaci* has evolved in some areas (Horowitz *et al*., 2002), but it remains as an important component for controlling whiteflies (Denholm *et al.,* 1998).

Hydroprene : It is a growth regulator that inhibits the maturity and growth of certain insect pests in their immature stages. Hydroprene is photolabile and there by used for indoor only for controlling mainly house hold and domestic pests. It is very popular for controlling the young cockroaches (nymphs) that are exposed to this are unable to reach maturity and will never reproduce. Hydroprene makes this maturing process very difficult, stopping or slowing the growth of the cockroach. Besides, this compound can also be used for managing many store grain pests including cigarette beetle. It is compatible with many convetional insecticides like Cypermethrin, Acephate or Deltamethrin and there by increases its sscope. It is available in liquid concentrate, aerosol and in solid dispensers.

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