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INSECTIGATION AS AN APPROACH TO INSECTICIDE APPLICATION

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ABSTRACT

The burgeoning human population requires raising food production and in order to meet the requirements, factors affecting yields *viz*. insects, pathogens, nematodes are necessary to be managed. Though the conventional methods of crop protection chemicals application is the major practice, the knowledge and awareness of novel methods play a major role in combating the target pest effectively and one such method is application of insecticides through drip irrigation system, termed as insectigation. This method predominantly used to control the sucking pests, soil residing insects and different stages of insects viz, egg, larvae, pupae and adult that requires soil for development. The approach seems to be more advantageous over traditional spraying enabling plants to absorb water and insecticide at same period of time along with drift reduction, decrease in residues and in curbing the human exposure to insecticides. The existing drip irrigation system needs certain extra paraphernalia viz. chemical mix tank, an injection system and most importantly, a back-flow prevention device to check the ground water pollution. In a nutshell, insectigation offers a wide range of benefits over other pesticide application methods to mitigate the insect pest population below threshold levels.

Key words: Insectigation, subsurface drip irrigation, neonicotinoids, diamides, oxadiazines, sucking pests, soil insects, absorption, drift reduction, chemical mix tank, injection system, back flow prevention device

Plants are constantly exposed to biotic stress caused by insects and pathogens, causing changes in plant metabolism involving physiological damages that lead to reduction in productivity. The ever-growing pest population needs a continuous intervention with either chemicals or botanicals or microbial insecticides. This is not to say that more of these products usage results in higher yield, though use of such chemicals to control the insect pests shows quick and promising results but may lead to many disastrous environmental effects, especially in case with chemical insecticides. The plant protection chemicals and application has turned to be costlier these days, pushing the researchers to think towards a more economical approach. Despite the success achieved by foliar applications to suppress insect pests, there are several drawbacks *viz*. risk to humans, environment and spray drift being the foremost. The soil/ broadcast application of pesticides has even more drastic effects leading to chemical runoff, leaching and contamination of ground water. On the other side of agriculture, the recurring drought conditions, lead to judicious use of water and further coinciding with shortage of agriculture labor, forced Indian farmers to gradually adopt to drip system of irrigation. In this context, a different pesticide application approach to tackle the insect pests arises termed as "insectigation" (Owens 1981; Ghidiu 2012). The application of insecticides through irrigation water had been cited even in the early literatures (Phene et al., 1979; Young, 1980; Potter, 1981). The era of modern drip irrigation system began with plastic emitters (Blass and Blass, 1969) and though it started late, more advances and improvements in drip system constantly, facilitated to immensely expand its wide scope in farming sector. The first agriculture input to use through drip was fertilizers in 1979. In 1980, insecticides were first injected into drip irrigation for the control of European corn borer *Ostrinia nubilalis* Hubner, on bell peppers in New Jersey. This used pressurized carbon dioxide to inject oxamyl into drip lines (Ghidiu, 1980). In 1981, it was again studied on Mexican bean beetle (*Epilachna varivestis* Mulsant) (Ghidiu, 1981) and these two initial trials were not effective against the pests targeted. The positive results of insectigation started in 1985, when asparagus aphid (*Brachycorynella asparagi* (Mordvilko)) was controlled using disulfuton (Wildman and Cone, 1986) and surprisingly Reed et al., (1986) reported entomopathogenic nematodes applied through drip system controlled spotted cucumber beetle

Diabroctica undecimpunctata howardi Barber. Later on, numerous studies were carried out on insectigation, with positive results on pest control (Kerns and Palumbo, 1995; Palumbo, 1997; Kuhar and Speese, 2002; Ghidiu et al., 2009; Kuhar et al., 2009; Schuster et al., 2009).

Though insecticides can also be applied by surface irrigation (furrow system), but the drawback is it gets diluted resulting in less uptake at rootzone leading to higher environment contamination (Danne et al., 2006) and ultimately making the pesticide less effective (Mansour, 2008). The introduction of drip irrigation in India started in mid-1980's and in many parts of India, especially in arid zones, farmers shifted their predominant mode of irrigation to drip. A total of 18,97,282 ha of agricultural land is under drip irrigation in India with Maharashtra and Andhra Pradesh growers being the top adopters (Chand, 2012). Even though developed countries have crop specific insectigation labels for many approved pesticides, India is yet to frame guidelines for use of registered insecticides based on scientific studies and till now only a single insecticide combination (chlorantraniliprole 08.80%+ thiamethoxam 17.50% SC w/w) is registered in India for soil-drenching (MUPI, 2020), and this if translated, can be utilized for insectigation. In the current scenario, migration of agricultural labour to other occupations leading to labour scarcity and increase in cost of foliar applications, forcing the farmers shift to different methods of pesticide application and insectigation being a better alternative.

Insecticides suitable for insectigation

Only xylem mobile insecticides with high solubility and specific toxicity can be used for insectigation (Ghidiu et al., 1992). In the early years of 1980 to late 1990's, there were no such insecticides used to be apt for insectigation with good water solubility, selectivity and systemic activity properties. It was only during late 1990's, the discovery of two novel group of insecticides, neonicotinoids (especially effective against sucking pests and beetles) and anthranilic diamides (effective against lepidopterans) (Lahm et al., 2007) paved the way for use of these molecules in insectigation. Some insectigation studies conducted are given in Table 1. Insecticides of neonicotinoid group mainly imidacloprid, acetamiprid and thiamethoxam are best suitable through drip application as they are water soluble (potential to some amount of leaching), systemic in nature and highly effective at low application rates.

Table 1. Insectigation studies carried out against insect pests

Insecticide group	Insecticide	a.i	Pest	Crop	Reference
Neonicotinoids	Imidacloprid 350SC	0.75g ai/ plant	Mealybug (*Pseudococcus viburni*)	Grape	Larrain, 1999
Neonicotinoids	Imidacloprid 21.4FL	0.67ml ai/ tree	White grub	*Cornus kousa*	Reding et al., 2008
Mixture	Imidacloprid 21.4FL + EPN	0.11 ml ai + 23000 IJs/ plant	White grub	*Cornus kousa*	Reding et al., 2008
Anthranilic diamides	Chlorantraniliprole1.6SC	4.1 to 8.998 ml ai/ ha	*Trichoplusia ni* *Spodoptera exigua* *Liriomyza sp*	Lettuce	Palumbo, 2008
Neonicotinoids	Imidacloprid 20SL	0.2 or 0.4 ml ai/ vine	*Planococcus citri* Risso *Planococcus ficus* Signoret	Grape	Mansour et al., 2010
Anthranilic diamides	Chlorantraniliprole 1.67SC	1-application @ 0.099 kg ai/ha 2- applications @ 0.074 kg ai/ ha each	*Helicoverpa zea*	Tomato	Kuhar et al., 2010
Anthranilic diamides	Chlorantraniliprole 20SC	74 g ai/ ha	European corn borer	Bell peppers	Ghidiu et al., 2012
Pyrethroid	Dinetofuron 70SG	428.52 ml ai/ ha	Stink bug (*Euschistus servus)*	Tomato	Walgenbach and Schoof, 2015
Carbamates	Carbofuran 3G	1 kg ai/ ha	Rice root nematode	Rice	Thiyagarajan et al., 2019
Sulfoximines	Sulfoxaflor 50WDG	700g ai/ ha	Aphids	Cotton	Jiang et al., 2019
Pyridines	Flonicamid 50SG	700g ai/ ha	Aphids	Cotton	Jiang et al., 2020a

Table 2. Water solubility of some insecticides

Insecticide	Water solubility (mg/ l)	Solubility type	Source
Dinotefuran	39,830	High	Cloyd, 2018
Cyantraniliprole	14,200	High	
Flonicamid	5200	High	
Thiamethoxam	4100	High	
Acetamiprid	2950	High	
Imidacloprid	610	Moderate	
Pymetrozine	290	Moderate	
Spirotetramat	29	Moderate	
Sulfoxaflor	670	Moderate	Corteva, 2019
Chlorantraniliprole	0.88	Low	IUPAC, 2019

Low (< 10 ppm or 10 mg/ l), moderate (10 to 1,000 ppm or 10 to 1,000 mg/ l), or high (> 1,000 ppm or 1,000 mg/ l)

The effect of imidacloprid will be rapid enough, when incorporated in Integrated Pest Management (IPM), to allow time for performing other methods of pest control (Felsot et al., 2000) but has the potential to leach to a depth of 150cm, if scheduling is not done properly (Felsot et al., 1998). The systemic insecticides with high solubility in water will easily get translocated, kills the pest more rapidly, but does not persist its action for long time and this problem can be overcome by using higher label rates. Water solubility of frequently used chemicals for insectigation are given in Table 2.

Mealybugs have a natural protection from contact insecticides due to wax coating on their body and to overcome this problem, imidacloprid @ 1-2 ml/ vine (Spector) applied through drip in grape vine yards proved to be more effective in controlling mealybugs than traditionally registered pesticide, methidathion (Mansour et al., 2010). Hop (*Humulus lupulus* L.) a climbing perennial crop about to extinct in India (Manta, 2019) is attacked by aphids (*Phorodon humuli* (Schrank)) and the protection of this crop plays a key role in keeping the cultivation alive, thereby fetching hops a better market price. Wright and Cone (1999) with their experiments in Poland found rapid uptake of imidacloprid and disulfuton by the plants when applied through subsurface drip irrigation. Similarly, imidacloprid 21.4FL @ 0.6ml/ tree (Marathon II) can be applied to control white grubs in ornamental nurseries (Reding et al., 2008). The diamide group of insecticides is also most suitable for insectigation. A single injection of chlorantraniliprole @ 0.099 kg ai/ ha or two injections @ 0.074 kg ai/ha each at 14 days interval fairly controlled *Helicoverpa zea* all round the crop season and even showed a systemic activity upto 66 days after insectigation in leaves, and 22 days in flowers (Kuhar et al., 2010). Schuster et al., 2009 reported the efficacy of drip applied chlorantraniliprole in tomato against *Liriomyza trifolii* (Burgess) and *Spodoptera* sp. No chlorantraniliprole phytotoxicity was noticed in leafy vegetables, lettuce @ 4.1 to 8.9 ml ai/ha, applied via subsurface drip and in turn showed remarkable control of pests viz. beet army worm, cabbage looper and leaf miners (Palumbo, 2008).

Other than these two major groups, sulfoxaflor belonging to novel insecticide group, sulfoximines are also been reported to be successful through insectigation (Sanchez-Bayo and Goka, 2014, Jiang et al., 2019). Sulfoxaflor applied @ 700 g ai/ha, against cotton pests could achieve 5% additional yield and was not traced in any plant part at harvest stage (Jiang et al., 2019). A carbamate insecticide, carbofuran had been proved to be effective in controlling root knot nematode *Meloidogyne graminicola* Golden & Birchfield in rice, to sustain the water resources, the cultivation of paddy through drip system is now a days a viable option and carbofuran @ 33 kg/ha in two splits through drip irrigation at 10 and 30 DAS was found effective for control of root knot nematodes (Thiyagarajan et al., 2019). Similarly, the novel pesticide, Flonicamid 50SG, a pyridine organic group insecticide was also proved to control cotton aphid after application through drip @ 700 g ai/ha (Jiang et al., 2020a). The trial of applying fumigants through drip to control weeds, soil pests and diseases was also proved to be successful and was more economical and environment friendly compared to conventional shank injection in the raised beds of strawberry in California (Ajwa et al., 2002). Emulsifiable concentrate formulations of fumigants possessing low vapour pressure are more advantageous for application through drip (Lembright, 1990). The insecticides registered for insectigation in different countries are given in Table 3.

Impact on environment and non-target organisms

The neonicotinoids insecticide group has a share of 24% of world insecticide market (Jeschke et al., 2011) and among them, imidacloprid and thiamethoxam stands top in terms of use by the growers. The positive attributes (solubility, systemic activity) of these insecticides though make them most suitable for insectigation but to certain extent show negative effect on pollinators, honey bees, bumble bees. The quantity of imidacloprid (358g ai/ha) present in plant system and flower bases applied through drip was 218 and 31ppb, respectively and that of thiamethoxam (140g ai/ha) was 362 and 22ppb, respectively. The traces of these compounds were detected from every part of the

Table 3. Pesticides approved for insectigation

Insecticide	Formulation	Crop	Pest	Dose	Source
USA					
Flonicamid	50WG	cotton, cucurbits, brassicas, leafy greens	aphids, plant bugs, thrips whiteflies,	0.088-0.133 lbs ai/ ac	USEPA, 2020
Chlorantraniliprole	18.5SC	Brassicas, Cucurbits	beet army worm, DBM, corn ear worm, cross stripped cabbage worm, Hawaiian beet worm, imported cabbage worm, western yellow stripped army worm	0.045-0.065 lb ai/ ac	Coragen, 2017
		brassicas, cucurbits, fruiting vegetables, leafy greens	leafminer larvae, silver leaf whitefly nymphs	0.065-0.098 lb ai/ ac	
		Fruiting and leafy vegetables	Fall army worm, Colorado beetle, European corn borer, loopers, Southern army worm, Horn worm, Tomato fruit worm, Tomato pin worm	0.045-0.065 lb ai/ ac	
Sulfoxaflor	21.8SC	Potatoes	green peach aphid and potato aphid	5.7-8.7 oz/ ac	USEPA, 2019
CANADA					
Flonicamid (Only for emergency use in Ontario and Alberta, from July 2015 to May 2016)	Beleaf50 WG	Peppers in greenhouses	Lygus bugs	15 mg ai/ m^2	UAPCA, 2015
INDIA					
Chlorantraniliprole+ Thiamethoxam	08.80% +17.50% SC	Tomato	leafminer, whitefly, fruitborer	50-100 ml/ plant (Single application)	MUPI, 2020

experimented plant, squash when used according to the label recommendations and the concentration of imidacloprid in pollen and nectar was 14 and 10 ppb, while thiamethoxam was 12 and 11 ppb, respectively (Stoner and Eitzer, 2012). Similarly, sulfoxaflor applied @ 450 or 700 g ai/ ha at 30, 20 and 10 days before flowering, no residues in nectar and a very negligible amount in cotton pollens was noticed, but in contrast, insectigation during flowering, the residues were as high as 17 and 39.2 µg/ kg pollen @450 and 700 g ai/ ha, respectively on 5th day after application. The maximum contact LD_{50} of sulfoxaflor being 0.585 µg ai/bee and oral LD_{50} is 0.187 µg ai/ bee in its life span, indicating that it is not advisable to practice insectigation during crop flowering stage. The contact flower hazard coefficient (FHQ_{do}) was highest on 5th day after insectigation, posing a danger to pollinators (Jiang et al., 2020b). Flonicamid's safety to natural enemies was proved by Jiang et al. (2020a), as it showed comparatively less effect on two natural enemies, seven spotted beetle, *Coccinella septumpunctata* L. and green lacewing, *Chrysoperla carnea* T. in cotton ecosystem.

Impact on soil

Soil is a major sink for pesticides (Das et al., 2017) and no such direct investigations over the effect of insecticides on soil ecosystem is studied, but certain evidences from researches prove that insecticides directly affect the soil life via disturbing the ecosystem, influence biochemical processes and finally impact bio-transformations. (Demanou et al., 2004, Mahia et al., 2008). Though pesticides *viz*. carbofuran, thiamethoxam, imidacloprid, chlorpyrifos, monocrotophos does not have any effect on few soil bacteria (Sarnaik et al., 2006), but in contrast, imidacloprid inhibited the growth of a urease-producing bacterium *Proteus vulgaris* Hauser, but not bacterial urease from *Bacillus pasteuri* Miquel (Ingram et al., 2005). Similarly, the same pesticide (imidacloprid) inhibited nitrification and denitrification in soil but stimulated sulfur oxidation (Tu, 1995) and in addition, it showed an increasing effect of arginine deaminase activity in soil (Singh and Singh, 2005).

Equipment needs to be attached to pre-existing drip system

The existing drip system can be well utilized for chemigation with few modifications (Ghidiu, 2012) as shown in Fig. 1 and given below:

i. Chemical mix tank/ supply reservoir: made of polyethylene or fiberglass materials, to make it resistant to corrosion and tank capacity should be enough in size to contain at least the chemical solution required for one application.

ii. Containment tray- to catch the spillage or leakage from the chemical tank.

iii. Injection system: Use of efficient injection devices is necessary for uniform application of chemical from each emitter. The device should be on down flow side from the main pump to avoid backflow contaminations. There are three types of pumps used in injecting various types of chemical solutions into main line *i.e.*, centrifugal pump, positive displacement pumps (PDP's) and pressure differential methods including venturi meters or water driven pumps. In the positive displacement pumps, an expanding cavity on suction side of the pump sucks the solution from chemical tank and the decreasing cavity on outlet side of pump forces out the chemical into irrigation and in each cycle, equal quantity of chemical is drawn and released. There are two types of PDP's being explored, one is piston pump used for nitrogen application and other is diaphragm pump adopted in insectigation.

iv. Back flow prevention devices (Fares et al., 2009):
   - A main line check valve has to be installed upstream from the injection point, to prevent water flow back into source after the pump is shut off.
   - Injection line check valve that prevents water from flowing back to the chemical tank.
   - Vacuum relief valve to prevent vacuum development inside the pipeline and has to be installed between check valve and pump.
   - Low pressure drains to drain water leaking post the check valve.
   - Interlocking circuits to turn off the chemigation unit, if the injection pump is shut off accidentally.

v. Low pressure shutoff valve to shut the injection system off.

All the components that are in contact with pesticides should be of plastic or steel and water quality also plays an important role in designing the system as higher pH causes more precipitation in the system leading to clogging (Anon, 1994). Over watering during or after insectigation creates unnecessary percolation of chemicals deep into soil layers, finally leaching into ground water but at the same time, lower watering does not allow the uniform spread of insecticide at the root zone, so after every insectigation, it is necessary to flush the entire system with fresh water to minimize clogging

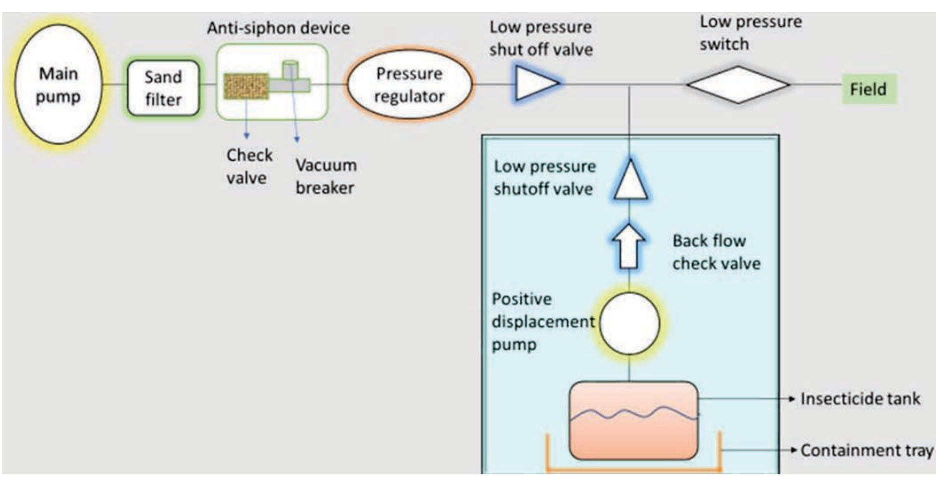

Fig. 1. Parts of insectigation equipment for the pre-existing drip system (Source: Ghidiu, 2012)

issue. At any point of time, if two different pesticides are to be applied simultaneously, two different injection pumps have to be used as each pesticide has varied injection rate. In the case of insecticides applied through drip, the major concern is about uniformity and a uniform water distribution distributes the insecticide uniformly that again depends on capacity of pump used to inject the chemical. To quote, a 179.1 metric feet lbs positive displacement pump used to apply chlorantraniliprole @ 74g ai/ ha, particularly on row crops (bell pepper), the recoveries from emitters at beginning, middle and end of the drip system was 89, 92 and 81% (Ghidiu et al., 2012). To assess the uniform distribution of chemicals, distribution uniformity (DU) is the ratio which indicates uniformity in application and a DU value of 1 indicates more uniformity (Burt, 2003).

$$DU = \frac{\text{Average of low quarter depths of irrigation water received by plants}}{\text{Average depth of irrigation water received by plants}}$$

Drip manifold for research experiments on insectigation

It was specially designed for conducting research experiments on insectigation. Ghidiu et al., (2012) created a design of drip chemigation system as described in Fig. 2, through which up to 10 different insecticides as treatments to 10 different rows of a single experimental field can be injected. A total of 10 sub main lines are to be attached to the insecticide main line with 1.27cm ball valves (5 on each side of design) at 10.16 cm apart. Again, a total of 10 submain lines are to be joined to main line from water source 8.9 cm apart, using 1.27 cm ball valves. The 10 submains from insecticide main line and 10 submains from water source are joined using a T connection. Thus, enabling the operation of each water valve and insecticide valve separately, allowing the injection of each insecticide or its dose in to a single sub main, and application of single treatment to a particular row. A valve should be placed in the center to rinse the injection system after each treatment to prevent contamination. This can create ease in doing insectigation experiments with very small quantities of insecticides in small plots.

Determining injection rate and calibration of the injection pump

A simplified method of calibration is given by Granberry et al. (2017) where injection rate is required to calibrate the injection pump with the following procedure.

i. The area (ha) to be insectigated is to be determined first.

ii. The volume of chemical solution (gallons/ l) required/ ha is multiplied with the area (acres) to get total quantity of chemical solution needed to treat the entire field.

iii. The time for which we want to run the system is determined and the injection rate is determined by dividing the total chemical solution (gallons/ l) by time (hr). A minimum injection time is obtained by using approximately 4 l of water mixed with 3 to 4 drops of detergent. By recording the time of injection of this detergent to appearance of soap bubbles in the last emitter, minimum injection time

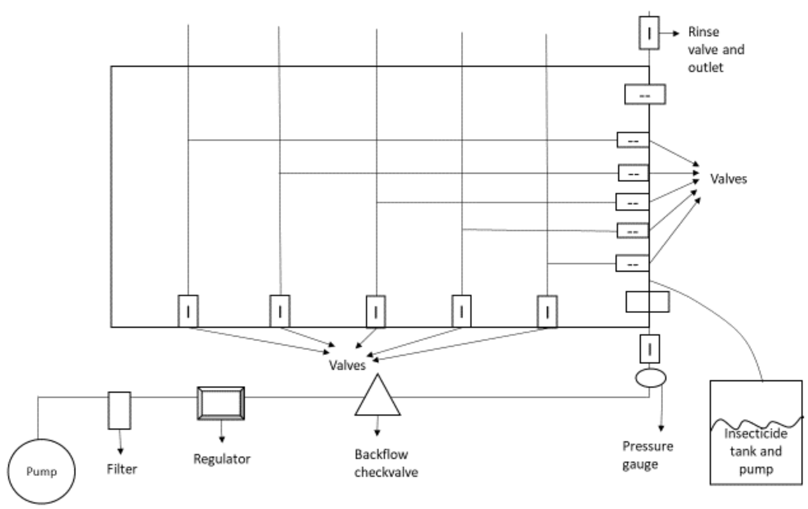

Fig. 2. Schematic design of 5 injection manifold (half of the design) and pump to deliver different treatments to individual plots

can be calculated. If the injection time is less than the determined minimum injection rate, it will result in non-uniform application of insecticide.

iv. If conversion is required, ml/ min = 63.09x gallons or l/ hr.

v. The injection rate of pump is calibrated and adjusted to the above rate by using any pre-measured solution and a graduated cylinder.

Injection rate should be modified according to the crop stage *i.e*., if the plants are at seedling stage or establishment stage, less water should be used to reduce the wetting area and loss of insecticide, however injection rate can also vary with the type of root system and irrigation requirements. High organic matter content also hinders insecticide uptake by plants. (Ghidiu et al., 2012). In drip chemigations, the system should run for certain time with clean water, then chemical injection should be carried out and again it is to be flushed with clean water for 2 hr. The next irrigation has to be provided only after 4 days of insectigation (Palumbo, 2008). Insecticides namely imidacloprid, clothianidin and chlorantraniliprole possess low water solubility and low partition coefficient, which makes them less mobile in soil and the solution for this problem is, these insecticides should be injected at early stage of irrigation cycle, so that the normal irrigation after injection pushes the insecticide to the root zone (Dupont, 2008)., but at the same, few insecticides viz. thiamethoxam is highly soluble and mobile in the soil, for which insecticide injection should be planned only in the 2/3rd part of irrigation cycle i.e., if the system is operated for 120 min, injection should start 40 min after motor start. (Dupont, 2008; Ghidiu, 2012).

Advantages and disadvantages

Compared to non-systemic insecticides that act by contact action, systemic insecticides tend to be more selective to the targeted insects, show less toxicity to non-target pests and humans, eliminates spray drift, less quantity lands on the plant surface enhancing safety to the farm labour and chemical input is comparatively low. Only one third to half of the insecticide quantity used in aerial and conventional applications is required for insectigation (Johnson et al., 1986) and often reduces the total amount of insecticide that enters the field (Kuhar et al., 2009). The pesticide is present near the root system, so runoff and leaching into ground water is greatly reduced. The method can be economically feasible due to low input and fuel costs thereby improving the net profit. There is also feasibility to apply insecticide at any time, under different weather and environmental conditions. The regularity of insecticide application can be made more accurate and even though the insecticides are activated within few days of application; they act quickly and efficient post application is done that is enough to keep the pest under threshold limits (Timmeren et al., 2012). The application of pesticide through drip is very useful for urban growers as spray drift is completely absent and labour cost can be reduced to the maximum extent.

A few disadvantages are noticed to every progressive invention. The capital for establishing drip system is high, but once established, the costs of each application are minimal with lesser cost of operation per hour. Not all the insecticides for particular pest/crop are suitable for insectigation, where selection of insecticide and dosage requires scientific support unless mentioned in the recommendation label. Some insecticides cannot be applied to wet or saturated soils, for which soil conditions should also be considered, otherwise higher runoff of chemicals into water systems occurs. The extent of leaching can also be confined to safety limit by proper application and it is showed that 70% imidacloprid remained in the root zone even after 40 days of application without leaching (Leib and Jarrett, 2003). The crops *viz*., transplanted rice, millets and other low land crops, cannot be insectigated where drip irrigation is not adopted. Similarly insectigation can be a limiting application method for migratory pests (locusts, armyworm etc.) management. All the commercially available insecticides are not suitable for insectigation limiting their choices (Larrain and Quiroz, 2007). The combined use of incompatible chemicals may lead to formation of insoluble compounds or precipitate clogging the drip system and if backflow is not properly prevented, water pollution occurs. The chemical accumulation in nectar and pollen is likely to occur, in turn reaching the honey and other products (Bilbo et al., 2019).

Conclusions

Insectigation can be fairly utilized to reduce the number of insecticide applications and total insecticide input and the cost of insecticide application in a preexisted drip system is far lower than any kind of application. The future research investigations may be made on three objectives, efficacy of systemic insecticides via drip application, migration of pesticides into different parts of environment and translocation of insecticides to harvesting parts during growing season and ways to mitigate them. There arises a risky situation of pesticide residues, if insectigation comes into normal method of application, for which strict guidelines, training programs, and awareness among growers is needed. The suitable formulated pesticides need to be innovated specially for drip application, by the research institutions in collaboration with the chemical industries. An integrated software system developed for monitoring and automation, if utilized can make more sense of drip chemigation with maximum output completely thereby reducing the labour cost and generates the programmed reports of the chemigated products.

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