



Chemigation for insect pest management: An established but under-utilised insecticide application technology

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Abstract

Insecticides play a key role in managing pests in agricultural and horticultural crops worldwide. Although several pest management approaches, including biological control agents, resistant varieties and behavioural manipulation, are widely adopted, insecticides remain indispensable when pest populations exceed economic threshold levels. The method of insecticide application is equally as important as the choice of the chemical itself. Although conventional foliar spraying has been widely practiced, it is frequently associated with limitations such as exposure of non-target organisms, operator risk and reduced application efficiency, depending on the insecticide and target pest. Chemigation, the application of insecticides through irrigation systems, has emerged as a promising alternative that minimises exposure of non-target organisms while improving the delivery of insecticides to the target zone. The availability of systemic and root-systemic insecticides has further enhanced the potential of chemigation as an effective, economical and environmentally safer approach for pest management in a wide range of crops. In addition to improving insecticide use efficiency, chemigation reduces labour requirements, spray volume and application costs while ensuring uniform distribution of insecticides through irrigation networks. Despite these advantages, its adoption is influenced by factors such as irrigation infrastructure, formulation compatibility, application technology and regulatory guidelines. This article comprehensively reviews the role of chemigation in pest management across different cropping systems, highlighting recent technological developments, specialised formulations, adoption trends in developed and developing countries, advantages and limitations for sustainable insecticide application. The review also identifies key knowledge gaps and research priorities, including the need for optimised chemigation strategies, improved pesticide formulations, standardised application protocols and a better understanding of environmental impacts and long-term sustainability.

Keywords: drip-chemigation; insecticide application; pest management; sprinkler-chemigation

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1. Introduction

Insect pests continue to be a global challenge, significantly reducing crop productivity and threatening food security. Over the past three decades, pesticide use has nearly doubled worldwide, reflecting an increasing dependence on chemical control strategies (1). Pesticides play an important role in integrated crop protection strategies by helping to reduce pest-related losses alongside other management approaches. Therefore, pesticides remain essential for ensuring stable crop production and meeting the rising global food demand. However, the effectiveness of insecticides depends not only on the molecule itself, but also on the method of application, timing and pest ecology (2, 3). The pest control practices have been utilised since early

civilisation developed simple methods to protect crops from insects and other pests. The Sumerians used elemental sulphur as early as 2500 BC to control mites and insects (4). Subsequent technological advancements, such as the development of synthetic pesticides, established chemical control as the dominant plant protection strategy. By the mid-20th century, chemical insecticides enabled rapid and effective pest management. However, their intensive use has raised concerns related to environmental contamination, ecological imbalance, insecticide resistance and long-term sustainability (4). To achieve effective pest control, insecticides are applied using conventional methods such as spraying, dusting and granular application. Based on spray volume, spraying is classified into high-volume (300–500 L ha⁻¹), low-volume (50–150 L ha⁻¹)

and ultra-low-volume ($< 5 \text{ L ha}^{-1}$) applications. Sprayers, particularly knapsack sprayers, are widely used for insecticide delivery. Dust and granular formulations are applied using suitable applicators or by manual broadcasting.

Despite their widespread use, these conventional application methods suffer from several limitations. Inefficient pesticide application continues to limit the effectiveness of pest management strategies, as only a very small fraction of the applied pesticide, often less than 0.1 %, actually reaches the target pest, while the majority is lost to the surrounding environment (5). Compared with other precision application technologies, such as electrostatic spraying, unmanned aerial vehicle (UAV)-based spraying and sensor-guided precision spraying, chemigation offers distinct advantages where irrigation infrastructure is already available. It enables the simultaneous delivery of water and insecticides through existing irrigation systems, reducing the need for additional field operations, labour and specialised application equipment. Chemigation can also facilitate targeted placement of insecticides within the crop canopy through sprinkler systems or directly in the root zone through drip systems. However, its suitability depends on the availability of appropriate irrigation infrastructure, insecticide properties, target pest biology and environmental conditions. Therefore, chemigation should be considered a complementary precision application technology rather than a universal replacement for other advanced pesticide application methods.

To overcome these limitations, advanced insecticide application technologies such as chemigation have emerged as promising alternatives. Chemigation involves applying insecticides through irrigation systems, enabling precise chemical delivery. This method improves insecticide use efficiency, reduces water consumption, minimises off-target losses and lowers operator exposure (6). Once the chemigation system is installed, it can reduce application costs while enhancing pest control efficiency and crop yield (7–9). This review provides a comprehensive overview of insecticide chemigation, with particular emphasis on its principles, application methods, factors influencing uptake efficiency, environmental fate and role in integrated pest management. It also discusses the physicochemical properties of insecticides that influence their suitability for chemigation, along with the advantages, limitations and prospects of this application technique. The review aims to summarize the current state of knowledge, identify major knowledge gaps and research priorities and highlight key considerations for the effective and sustainable use of insecticides through chemigation in agricultural production systems.

2. Methodology

This study was conducted as a narrative review and was not designed as a formal systematic review or quantitative meta-analysis. The literature was searched

primarily through major scientific databases, including Scopus, Web of Science, PubMed, Google Scholar and ScienceDirect. Publications available up to 2026 were considered, with greater emphasis placed on recent studies while landmark publications were included where necessary to provide historical context.

The search was performed using combinations of keywords and Boolean operators. Representative search strings included “chemigation AND insecticide*”, “drip chemigation AND insecticide*”, “drip irrigation AND insecticide*”, “sprinkler chemigation AND pest management”, “chemigation AND pest management”, “insecticide application AND irrigation systems” and combinations of related terms such as “chemigation”, “drip irrigation”, “sprinkler irrigation”, “insecticide application” and “integrated pest management”. Relevant publications were identified based on their scientific relevance to chemigation technologies, insecticide application methods, irrigation systems, application efficiency, environmental implications and integrated pest management.

As this was a narrative review, no predefined systematic search protocol, formal inclusion and exclusion criteria, or preferred reporting items for systematic reviews and meta-analyse (PRISMA)-based screening procedure was applied. Rather, the literature was critically selected and synthesised to provide a comprehensive overview of the current state of knowledge, recent developments, challenges, knowledge gaps and future research priorities related to the use of chemigation for insect pest management in agricultural production systems.

Evolution and development of drip chemigation systems

Drip irrigation technology has undergone significant advancements over the past four decades, building upon a much longer history of development and application. Symcha Blass developed the first modern, practical drip irrigation system. He also pioneered the use of micro-tubing with low-volume, clog-resistant emitters (10). In 1959, he patented plastic emitters in collaboration with Kibbutz Hatzerim in Israel, leading to the establishment of Netafim and the commercialisation of drip irrigation systems. The integration of drip irrigation with plastic row covers, known as plasticulture, was first demonstrated in 1963 in New York (11). Later, improvements in drip tape and emitter design enabled the development of cost-effective and uniform water delivery systems. Hence, drip irrigation rapidly expanded in the United States, reached over 54000 hectares by 1975 and increased by approximately 650 % between 1982 and the late 1990s (12).

With the increasing adoption of drip irrigation, research on chemigation was also initiated. Fertilisers were first applied through drip systems in 1979 (13). Later, the first attempts to apply insecticides through drip irrigation began in 1980 against the European corn borer and Mexican bean beetle in bell pepper and lima bean (14). These early applications were not successful



due to the poor systemic performance of orthene. A significant advancement occurred in 1985 when using drip irrigation to apply disulfoton effectively decreased asparagus aphid populations (15). Subsequent studies identified limitations, noting that carbofuran and methomyl exhibited phytotoxicity and poor pest control in some cases (16), emphasising the need for selecting suitable insecticides and safer formulations. Further advancements included the use of entomopathogenic nematodes for pest control (17), demonstrating the potential of biological agents in chemigation systems. In the 1990s and 2000s, systemic insecticides such as imidacloprid and thiamethoxam showed improved effectiveness against various pests in vegetable crops (18). More recently, chlorantraniliprole has demonstrated high efficacy against major pests such as European corn borer, armyworms and fruit worms when applied through drip irrigation (19, 20). These developments highlight the importance of selecting insecticides with appropriate physicochemical properties and systemic activity for successful chemigation. A summary of the historical development is presented in Table 1.

Principles and mechanisms behind drip chemigation

Drip chemigation operates by a combination of hydraulic, physical and chemical principles that ensure the efficient and precise delivery of agrochemicals through irrigation. The system operates on pressure

differentials where water and dissolved chemicals flow from regions of higher to lower pressure through pipelines and emitters to ensure uniform distribution (23). A key concept is fluid dynamics, which regulates flow rate, turbulence and mixing behaviour within the drip. Systems employing Venturi injectors operate on Bernoulli's principle, in which increase in water velocity at a narrow section creates a pressure drop that facilitates the suction and injection of agrochemical solutions into the irrigation stream (24). The effectiveness of chemigation also depends on the solubility and compatibility of the applied chemicals, as only highly soluble formulations can remain uniformly dispersed without causing precipitation or emitter clogging (25). Upon reaching the soil, the movement of chemicals follows the principles of mass flow and diffusion, where solutes are transported along with water toward the root zone and transported from higher to lower concentration (26). However, their transport and availability are also influenced by sorption-desorption processes, chemical degradation, soil moisture conditions, preferential flow pathways and plant uptake. These factors interact with the physicochemical properties of the applied chemical and soil characteristics to determine its persistence, mobility and availability within the root zone. The principle of uniform distribution is also crucial, it ensures that each emitter delivers an equal concentration of the chemical solution, thereby optimising application efficiency and minimising environmental losses (27).

Table 1. Key milestones in the development of drip chemigation

Year	Development	Crop	Insecticide	Outcome/ findings	Reference
Pre-1950s	Early drip irrigation concepts	-	-	Experimental stage	(10)
1959	Plastic emitters patented	-	-	Commercial drip systems were developed in Israel	(10)
1963	Plasticulture introduced	Cucurbits	-	Improved irrigation efficiency in the United States	(11)
1979	First fertiliser chemigation	Tomato, eggplant	-	Successful nutrient delivery in the United States	(13)
1980	First insecticide chemigation	Bell pepper	Orthene	Ineffective pest control	(14)
1980	Second insecticide trial	Lima bean	Orthene	Ineffective pest control	(14)
1985	First successful insectigation	Asparagus	Disulfoton	Effective aphid control	(15)
1986	Biological chemigation	Vegetables	Entomopathogenic nematodes	Successful pest control	(17)
1992	Carbamate trials	Bell pepper	Carbofuran, Methomyl	Phytotoxicity observed	(16)
1995	Systemic insecticides	Vegetables	Imidacloprid	Effective pest control	(21)
2002	Neonicotinoids	Melons	Imidacloprid, Thiamethoxam	Effective beetle control	(18)
2004–09	Diamide insecticides	Bell pepper, tomato	Chlorantraniliprole	Highly effective control	(22)

The drip mediated delivery involves a systematic and controlled process through which agrochemicals are introduced, transported and delivered to the plant root zone through an irrigation system. Initially, the chemical is prepared as a homogeneous solution or suspension in a mixing tank. This solution is then injected into the irrigation stream using devices such as Venturi injectors or positive displacement injection pumps, where the entry of chemicals is regulated either by pressure differentials or mechanical force. Once injected, the chemical-water mixture is delivered through the drip-irrigation network, including mainlines, sub-mains and lateral pipes. The mixture is subsequently discharged through drip emitters at a predetermined rate, allowing precise placement of chemicals directly into the root zone. Once it reaches soil, water movement in soil creates a wetted bulb pattern, within which the dissolved chemicals are transported through mass flow and diffusion processes (21). Systemic chemicals are then absorbed by plant roots and translocated to various plant parts by ensuring effective pest management. To ensure system efficiency and prevent clogging or residue build-up, flushing the system with clean water has to take place. Overall, the mechanism of drip chemigation ensures accurate, efficient and targeted application of agrochemicals while minimising losses and environmental contamination.

Design and components of the chemigation system for safer application

A chemigation system requires several key components to function effectively. These include a stock solution tank to hold the chemical mixture, hoses or pipes to transport the agrochemical solution, an injector or pump to introduce the chemical into the irrigation water, along with the backflow prevention devices. Emitters are also essential for the uniform distribution of water and chemicals to the crop. There are four main types of injection systems used in chemigation: centrifugal pumps, positive displacement pumps (such as piston, diaphragm, gear, lobe and peristaltic pumps), pressure differential injectors and venturi injectors. In some cases, a single injector may combine features from more than one of these types. Pressure differential systems are usually the cheapest option, but they are also the least accurate. Venturi injectors and water-driven systems generally have lower basic costs compared to other systems. However, when they are equipped with feedback and control systems, their cost becomes similar to that of positive displacement pumps. Positive displacement pumps are commonly preferred in chemigation because they provide accurate chemical dosing and help prevent backflow.

Many companies produce liquid injection pumps for chemigation. These pumps are used to apply water-soluble fertilisers, pesticides, plant growth regulators, wetting agents, soil amendments, mineral acids and other chemicals. Injector selection plays a vital role; thus, injection systems should be capable of

handling different types of formulations, including emulsifiable concentrates, suspension concentrates, soluble liquids, soluble powders, soluble granules, wettable granules, water dispersible granules, wettable powders, among others, even at low concentrations (about 1–100 mg L⁻¹) (28). Accurate calculation of insecticide quantity is critical, as the compound is injected directly into the irrigation line and precise dosing ensures both efficacy and environmental safety. Injection pumps must be properly calibrated and the insecticide should be mixed with water according to recommended ratios (29).

The chemical solutions vary widely in pH and may be corrosive and hence, injectors made from different materials may be needed. In addition, separate injectors may be used for fertilisers and insecticides due to differences in chemical compatibility, dosing requirements, contamination concerns and formulation characteristics (29). Injecting multiple chemicals at the same time requires careful planning to ensure they are compatible, properly spaced and can be applied under different operating conditions. Since some insecticides are not compatible with each other, separate injection arrangements are necessary. Some positive displacement pumps are designed with multiple separate heads, allowing different chemicals to be injected simultaneously while keeping them separate within a single pump system.

All insecticide formulations must be filtered prior to injection to prevent clogging and ensure uniform delivery. In general, the injection rate should not exceed 0.1 % of the total system water flow rate (30). However, the required concentrations of insecticides are usually much lower, as specified by recommended limits and product label instructions. Among all-injector systems, Venturi injectors are the most reliable and commonly used systems by farmers because they have low maintenance costs and they do not require any external power to operate and have no moving parts, which increases their lifespan and reduces the chances of failure.

After the Venturi injector, the emitter is one of the most important components in the drip chemigation system. Emitters should provide uniform water distribution and be suitable for the field conditions, crop type and water quality. It is important to consider the flow characteristics and durability of the emitters. The manufacturer's coefficient of variation (CV) should be less than 0.05 and ideally around 0.03 for better uniformity. Testing the emitter flow rates at both the beginning and end of the irrigation zone helps to ensure that the uniformity is within acceptable limits. The system should also ensure correct injector type, injection duration and a post injection flush period to thoroughly clean the laterals from insecticides (31).

Backflow prevention devices

Backflow in a chemigation system can occur in two ways: either by back-siphonage or backpressure (28). Back-siphonage occurs when there is a drop in



pressure in the water supply line, which causes water to flow backwards into the system. This can occur for several reasons. These include failure of the mainline check valve to close when the pump stops or during a power failure and the development of a strong pressure difference caused by undersized supply pipes. It may also result from a break in the main water pipeline, particularly when the pipeline is located below the user's connection point. In addition, a reduction in mainline pressure due to high water demand, such as firefighting or pipeline flushing, or a decrease in supply pressure resulting from pump or power failure can contribute to this problem.

Backpressure occurs when the pressure in the user's system becomes higher than the pressure in the main water supply, causing water to flow backward. This can happen due to several factors, such as the use of booster pumps to increase flow and meet pressure requirements, connections with other pipelines operating at higher pressures, the use of electric or gas-driven injector systems, linkage to pressurised systems like boilers and differences in elevation between the irrigation system and the water source. Backflow prevention devices such as an air gap, atmospheric or pressure vacuum breaker, check valve with low-pressure drain and vacuum relief valve, double check valve assembly and reduced-pressure device should be installed between the pump discharge and the point of chemical injection to ensure safe operation and prevent contamination of the water source (31).

Additional safety equipment to avoid environmental risk

A chemigation system should also include additional anti-pollution and safety devices on both the irrigation system and the chemical injection system (32). These devices help to minimise risks to the environment and protect the operator during chemigation operations. Injection-line equipment and injector pump interlocks should be installed to reduce environmental risks. A check valve in the injection line helps prevent water from flowing back into the chemical tank, which could cause it to overflow. It also stops chemicals from flowing into the irrigation system by gravity when the system is not running. Injector pump interlocks help ensure safe operation. They connect the power supply of the injector, irrigation pump and irrigation system so that they work together. This prevents chemicals from being injected when the irrigation system is not operating properly.

Uniformity of chemical distribution in drip chemigation

Uniformity in drip chemigation refers to how evenly the insecticide is delivered through the irrigation system to all plants in the field. Application uniformity helps ensure that insecticides are distributed as consistently as possible across the treated area, thereby reducing the risks associated with under-application and over-application. Poor uniformity may result in inadequate pest control in areas receiving insufficient doses,

whereas excessive application may increase the risk of crop injury depending on the insecticide, formulation, crop tolerance and applied dose. One of the major factors affecting uniformity is the amount of irrigation water delivered (33). If the water delivered is too low, the insecticide may not move appropriately in the soil and may fail to reach the entire root zone. This limits its availability to plant roots. On the other hand, if too much water is delivered, the insecticide may move below the root zone through leaching (34), making it unavailable to plant roots and reducing its effectiveness. Hence, applying the right amount of water is essential for maintaining uniform distribution. Another important factor is the balance between the chemical injection rate and the irrigation water flow rate. If the insecticide is injected too quickly or too slowly compared to the water flow, it can lead to uneven mixing and distribution across the field. Maintaining a proper ratio between these two ensures that the insecticide is carried evenly with the irrigation water to all emitters (31).

The design and condition of the drip irrigation system also play a major role. Variations in pressure along the pipes can cause some emitters to release more water and others less, leading to uneven delivery of insecticide. Similarly, clogging of emitters due to sediments, algae, or chemical deposits can disturb the uniformity. Using pressure-compensating emitters, installing proper filtration units and carrying out regular maintenance can help maintain consistent flow and improve uniformity. Drip systems can achieve very good uniformity for both soluble insecticides and suspendible biopesticides when the system is clean and hydraulically balanced (35). However, formulations containing particles need extra care. Proper filtration and continuous stirring of the chemical solution are necessary to prevent particles from settling, which can otherwise block emitters and disturb uniform distribution. It is also important to note that the overall field effectiveness of chemigation depends largely on how uniformly the insecticide is distributed. Even if a highly effective insecticide is used, poor uniformity can reduce its field performance. Compared to conventional foliar spraying, drip chemigation can reduce the total amount of insecticide usage, improve delivery to the target zone and reduce labour requirements. However, these advantages are achieved only when irrigation scheduling, system maintenance and chemical application are properly managed (36).

Uptake efficiency in drip chemigation

Uptake efficiency in drip chemigation refers to how effectively the applied insecticide is absorbed by plant roots and utilised for pest control. This depends on the persistence of insecticide in the root zone for a sufficient period of time without leaching or soil binding. The movement of insecticides in the soil during chemigation is strongly influenced by soil texture and organic matter content (37). In sandy soils, insecticides tend to move quickly with water, which may lead to leaching losses. In contrast, clay soils can slow down the movement of insecticides and limit their availability. Similarly, soils



with high organic matter can bind insecticides, reducing their availability for root uptake (38).

Systemic insecticides are most suitable for drip chemigation. These include neonicotinoids and diamides such as imidacloprid, dinotefuran and chlorantraniliprole (36). Once absorbed by the roots, these chemicals are transported through the plant's vascular system (xylem and phloem) to different plant parts. This allows effective control of sap-feeding insects that feed on xylem or phloem sap. The systemic organophosphates (OPs and carbamates, viz., dimethoate, oxydemeton-methyl and oxamyl are also applied through drip chemigation. In contrast, contact insecticides are generally not suitable for chemigation or may have label restrictions, as they are not efficiently taken up by roots (39). Though insecticides like chlorpyrifos are contact in their action, they are still being applied through drip irrigation for managing subterranean pests like termites and white grubs in sugarcane.

Solubility of insecticide in water and its mobility in soil play a major role in determining uptake efficiency. Insecticides with low solubility and low mobility (e.g., imidacloprid, chlorantraniliprole) should be injected early during irrigation, followed by sufficient irrigation time to move them into the root zone (40). On the other hand, highly soluble and mobile insecticides (e.g., dinotefuran) should be injected later in the irrigation cycle to reduce the risk of leaching beyond the root zone (39). Overall, uptake efficiency depends on matching the insecticide properties with soil conditions and irrigation management. When properly managed, chemigation allows insecticides to be absorbed through roots rather than applied on leaves, shifting pest exposure from surface contact to ingestion through plant tissues. This makes drip chemigation particularly effective against sap-feeding insects that rely on xylem and phloem for nutrition.

Formulations used in chemigation

Pesticide formulation plays a vital role in determining the efficiency of chemigation systems, because it influences solubility, dispersion, stability and interactions with soil and plant surfaces. Formulations such as soluble powders (SP) and soluble liquids or concentrates (SL) dissolve quickly in water, allowing insecticide to move evenly within the soil profile. Excessive solubility may result in rapid movement with irrigation water, leading to dilution, reduced retention and inconsistent pest control (41). Emulsifiable concentrates (EC) and similar oil-based formulations spread easily, stick better on plant surfaces and penetrate tissues more effectively, making them more effective against foliar-feeding insects. Oil carriers further enhance performance by reducing wash-off, improving deposition and reduce insecticide movement in the soil.

Excessive solubility along with high irrigation volumes can lead to leaching beyond the root zone and reduce efficacy (41). Water-dispersible granules (WDG/WG) are commonly used because they can form stable suspensions in water. Sulfoxaflor 50 % WDG has been reported to be effective against *Aphis gossypii* in cotton and similarly flonicamid 50 % WG shows high efficacy against *Thrips tabaci* in onion (42, 43). Environmental Protection Agency (EPA)-approved formulations commonly used in chemigation are given in Table 2. Irrigation practices also interact with formulation type and higher water volumes may dilute pesticide concentration and reduce efficiency, whereas optimised irrigation provides uniform distribution within the root zone. Overall, formulations that are fully soluble or capable of forming stable dispersions are most suitable for chemigation, as they ensure effective delivery and minimise operational issues. Insecticides with high systemic activity are generally preferred, as they can be absorbed through roots and translocated within the plant, ensuring effective pest management under drip chemigation.

Table 2. Environmental Protection Agency (EPA)-approved insecticides and formulations for chemigation in the United States

IRAC-Group	Active ingredient	Trade name, as in the United States	Formulation
4A - Neonicotinoids	Thiamethoxam	Platinum	75 SG
	Thiamethoxam + Chlorantraniliprole	Durivo	17.5 SC
	Imidacloprid	Admire PRO	42.8 SC
	Dinotefuran	Venom	70 SG
	Clothianidin	Arena	50 WDG
28 - Diamides	Chlorantraniliprole	Belay	16 WSG
		Coragen	18.4 SC
1B - Organophosphates	Dimethoate	Dimethoate 400	43.5 EC
	Diazinon	Diazinon AG500	48 EC
	Malathion	Malathion 8 Aquamul	81.8 EC
1A - Carbamates	Methomyl	Lannate	90 SP
	Oxamyl	Vydate	24 SL
Group UNE	Rosemary + Peppermint oils	Ecotec	-
Group UN	Azadirachtin	Aza-direct	1.2 EC

SG: soluble granules; SC: suspension concentrate; WDG: water-dispersible granules; WSG: water-soluble granules; EC: emulsifiable concentrate; SP: soluble powder; SL: soluble concentrate.



Suitability of insecticide for drip chemigation

The suitability of insecticide for drip chemigation depends on the physicochemical characteristics, environmental behaviour and systemic nature, as shown in Table 3. Insecticides, largely belonging to neonicotinoid groups, exhibit high water solubility, favourable partition coefficients, moderate soil adsorption and strong systemic activity. These features enhance the effectiveness of neonicotinoids and make them suitable for drip chemigation systems. High water solubility ensures that these molecules readily dissolve in irrigation water, allowing uniform distribution within the wetted soil zone. Poorly soluble compounds result in uneven dispersion and reduced availability to plant roots. Also, low to moderate octanol-water partition coefficient

(Log Kow) values indicate a hydrophilic nature, facilitating movement with soil water while enabling penetration into plant tissues. In addition, low to moderate soil organic carbon adsorption coefficient (Koc) values suggest limited adsorption to soil organic matter, keeping the insecticides available in the soil solution for root uptake. This balance between mobility and retention is essential, as excessively mobile compounds may leach beyond the root zone, while highly adsorptive compounds may remain localised near emitters. Highly leachable insecticides like flupyradifurone, clothianidin, chlorantraniliprole, dinotefuran, imidacloprid and thiamethoxam, should be injected during later stages of irrigation to minimise leaching losses.

Table 3. Physicochemical properties, environmental fate and suitability of insecticides for drip chemigation delivery

IRAC-group	Active ingredient	Water solubility (mg/L) at 20 °C	Log P (Log Kow) /Octane water partition coefficient	Koc (mL/g)	DT ₅₀ (days)	Systemicity	Leachability	Common Formulation	Country/region of practice	Ref.
4A - Neonicotinoids	Thiamethoxam	4100	-0.13	56.2	39	highly	High	WG and SC	United States and Ukraine	(44–46)
	Imidacloprid	610	0.57	225	174	highly	High	SL and F	United States and Ukraine	(44, 45, 47, 48)
	Dinotefuran	39830	-0.549	26	75	highly	High	SG and WG	United States and Egypt	(42, 44, 49)
	Acetamiprid	2950	0.8	200	3	highly	Low	SP	Ukraine	(44, 45)
	Thiacloprid	184	1.26	-	8.1	highly	Low	SC	Ukraine	(44, 45)
	Clothianidin	327	0.905	123	121.2	highly	High	WSG	United States	(44, 48)
28 - Diamides	Chlorantraniliprole	0.88	2.86	362	204	highly	High	SC and FC	United States and Ukraine	(20, 44, 45)
1A - Carbamates	Oxamyl	148100	-0.43	14.91	6	highly	Transition state	SL	United States	(44, 50)
	Dimethoate	25900	0.75	-	7.2	highly	Transition state	-	China	(37, 44)
1B - Organophosphates	Diclotophos	25	3.95	1345	-	highly	Low	EC	United States	(15, 44)
	Oxydemeton-methyl	1200000	-0.74	10	5	highly	Low	EC	United States	(44, 50)
29-Flonicamid	Flonicamid	5300	0.1	5.4	3.1	highly	Low	SG and WG	Egypt and the United States	(42, 44, 51)
4C - Sulfoximines	Sulfoxaflor	568	0.802	40.8	3.54	highly	Low	WDG	China	(43, 44)
4D - Butenolides	Flupyradifurone	3200	1.2	98.4	130	highly	High	SL	United States	(44, 49)
17-Moulting	Cyromazine	13000	0.069	-	9.7	highly	Low	SC and WP	United	(44, 50)

disruptors -
insect growth
regulators

States

34-Flometoquin Flometoquin - 6.25 - 3.3 - - SC Egypt (42, 44)

IRAC: Insecticide Resistance Action Committee; Log P (Log K_{ow}): octanol-water partition coefficient; Koc: soil organic carbon adsorption coefficient; DT50: dissipation half-life; WG: water-dispersible granules; SC: suspension concentrate; SL: soluble concentrate; F: flowable; SG: soluble granules; SP: soluble powder; WSG: water-soluble granules; FC: flowable concentrate; EC: emulsifiable concentrate; WP: wettable powder.

The environmental fate of these molecules, particularly soil persistence, further supports their suitability. Moderate persistence ensures prolonged availability within the root zone, providing sustained pest control without frequent application, while controlled leachability minimises groundwater contamination under proper irrigation management. Most importantly, the selected molecules should exhibit high systemicity, enabling absorption by roots and translocation throughout the plant. This property is essential in drip chemigation, as insecticides must move from the root zone to aerial plant parts to control pests, particularly sucking insects. In contrast, insecticides lacking these characteristics are unsuitable for drip chemigation. Molecules with low water solubility show poor distribution, while high Log Kow and Koc values lead to strong adsorption to soil, reducing mobility and availability. Non-systemic insecticides are ineffective, as they cannot be translocated within the plant after root uptake. Additionally, unsuitable formulations may cause emitter clogging, uneven application and increased environmental risks. The selection of insecticides for drip chemigation must be based on a balanced combination of physicochemical and environmental properties, particularly water solubility, Log Kow, Koc, persistence and systemicity. Molecules meeting these criteria ensure efficient delivery, optimal distribution, effective uptake and sustained pest control, whereas any deviations from these can compromise system performance and its safety. Non-systemic and contact insecticides are generally less suitable for drip chemigation when pest control depends on plant-mediated systemic activity. However, they may be effective against soil-dwelling pests when delivered directly to the target zone through irrigation. Such insecticides can also be effectively applied through alternative methods, including sprinkler chemigation.

Modern use of drip-irrigation to deliver insecticides in crop protection

Neonicotinoids as suitable candidates for drip-chemigation

Since their introduction in the early 1990s, neonicotinoids have become one of the most important groups of insecticides in vegetable crop protection, with imidacloprid being the first widely adopted compound (52). Later, molecules such as thiamethoxam, dinotefuran and clothianidin expanded their use against a wide range of sap-feeding and leaf-feeding pests (18, 19, 53). Their success in drip-chemigation systems is attributed to favourable physicochemical properties, strong systemic activity and consistent field performance. High water solubility facilitates uniform movement within the wetted soil zone thereby offers efficient delivery to the roots. Field studies that demonstrated the effectiveness of neonicotinoids applied through drip chemigation are given in Table 4. For example, imidacloprid (Confidor 200 SL) applied at 0.6 kg a.i. ha⁻¹ effectively controlled *Ostrinia nubilalis* in corn (45). Similarly, thiamethoxam at 150 g a.i. ha⁻¹ showed effective control of *Monolepta hieroglyphica* in maize (8), while imidacloprid (Admire 2F) applied through drip chemigation at 30 mL (label rate) and 15 mL (half-label rate) per 100 m of crop row effectively controlled striped cucumber beetle *Acalymma vittatum* in muskmelon (54). This is because of systemic translocation, where insecticides are absorbed by roots and transported to aerial plant parts, helping control of pests feeding on leaves, stems and hidden tissues. Uniform distribution in the root zone further provides consistent uptake and pest management.

Table 4. Pest management through drip chemigation in economically important crops

IRAC-group	Active ingredient	Rate (kg a.i. ha ⁻¹)	Formulation	Target pest	Crop	Reference
4A- Neonicotinoids	Thiamethoxam	0.6 kg a.i. ha ⁻¹	Actara 25 WG	<i>Ostrinia nubilalis</i>	Corn	(45)
		0.15 kg a.i. ha ⁻¹	-	<i>Monolepta hieroglyphica</i>	Corn	(8)
	Imidacloprid	0.23 kg a.i. ha ⁻¹	Durivo SC	<i>Macrosiphum euphorbiae</i>	Tomato	(46)
		0.6 kg a.i. ha ⁻¹	Confidor 200 SL	<i>Ostrinia nubilalis</i>	Corn	(45)
		0.28 kg a.i. ha ⁻¹	Provado 1.6 SL	-	Hop	(47)
		2 lb/gal of a.i. per	Admire 2 F	Cucumber beetle	Muskmelon	(54)



		100 m row				
		0.000134 kg a.i. tree ⁻¹	Marathon II SL	White grubs	Kousa dogwood	(48)
		0.403 kg a.i. ha ⁻¹	Admire Pro 4.6 SC	<i>Macrosiphum euphorbiae</i>	Tomato	(46)
	Dinotefuran	0.286 kg a.i. ha ⁻¹	Raptor 20 % SG	<i>Thrips tabaci</i>	Onion	(42)
		0.294 kg a.i. ha ⁻¹	Venom 70 WG	<i>Bemisia tabaci</i>	Cantaloupes	(49)
	Acetamiprid	0.1 kg a.i. ha ⁻¹	Mospilan 20 SP	<i>Ostrinia nubilalis</i>	Corn	(45)
	Thiacloprid	0.5 kg a.i. ha ⁻¹	Calypso 480 SC	<i>Ostrinia nubilalis</i>	Corn	
	Clothianidin	0.0000208 kg a.i. tree ⁻¹	Celero 16 WSG	White grubs	Kousa dogwood	(48)
		0.6 kg a.i. ha ⁻¹	Coragen 20 SC	<i>Ostrinia nubilalis</i>	Corn	(45)
28 - Diamides	Chlorantraniliprole	0.05 and 0.07 kg a.i. ha ⁻¹	rynaxypyr 20 FC	<i>Ostrinia nubilalis</i>	Bell pepper	(20)
		0.099 kg a.i. ha ⁻¹	Coragen20 SC	<i>Helicoverpa zea</i>	Tomato	(55)
		2.25 kg a.i. ha ⁻¹	DuPont SL	Green peach aphid	Bell pepper	
1A - Carbamates	Oxamyl	2.25 kg a.i. ha ⁻¹	DuPont SL	Western potato leafhopper	Celery	(50)
		2.25 kg a.i. ha ⁻¹	DuPont SL	Melon aphids and leafminers	Muskmelon	
		3.00 kg ha ⁻¹	Technical grade (98 %)	<i>Tetranychus urticae</i>	Cotton	(37)
1B - Organophosphates	Dimethoate	2.70 kg a.i. ha ⁻¹	Standard	<i>Monolepta hieroglyphica</i>	Corn	(56)
	Oxydemeton-methyl	0.56 kg a.i. ha ⁻¹	Mobay EC	Melon aphids and Leafminers	Muskmelon	(50)
	Disulfoton	1.1 kg a.i. ha ⁻¹	8 EC	<i>Brachycorynella asparagi</i>	Asparagus	(15)
29-Flonicamid	Flonicamid	0.20 kg a.i. ha ⁻¹	Beleaf 50 SG	<i>Planococcus ficus</i>	Grapes	(51)
		0.238 kg a.i. ha ⁻¹	Upstage 50 % WG	<i>Thrips tabaci</i>	Onion	(42)
4C - Sulfoximines	Sulfoxaflor	0.700 kg a.i. ha ⁻¹	Transform 50 % WDG	<i>Aphis gossypii</i>	Cotton	(43)
4D - Butenolides	Flupyradifurone	0.00045 kg a.i. tree ⁻¹	-	<i>Diaphorina citri</i>	Citrus trees	(57)
		0.49 kg a.i. ha ⁻¹	Sivanto 240 SL	<i>Bemisia tabaci</i>	Muskmelon	(49)
17-Moulting disruptors-insect growth regulators	Cyromazine	0.14 kg a.i. ha ⁻¹	Cyromazine SC Cyromazine WP	Leafminers	Bell peppers	(50)
34-Flometoquin	Flometoquin	0.190 kg a.i. ha ⁻¹	Kajura 10 % SC	<i>Thrips tabaci</i>	Onion	(42)

IRAC: Insecticide Resistance Action Committee; a.i.: active ingredient; WG: water-dispersible granules; SC: suspension concentrate; SL: soluble concentrate; F: flowable; FC: flowable concentrate; SP: soluble powder; WSG: water-soluble granules; SG: soluble granules; EC: emulsifiable concentrate; WDG: water-dispersible granules; WP: wettable powder.

The moderate persistence of these insecticides ensures their continued availability in the soil for sustained uptake. Proper irrigation management, including controlled water application and timing of injection, enhances effectiveness by reducing leaching

and maintaining insecticide concentration within the root zone. Overall, the success of neonicotinoids in drip chemigation is due to a combination of high solubility, optimal soil mobility, systemic translocation and proven field performance. In addition to vegetable crops,



neonicotinoids have also opened-up their potential for use in drip chemigation systems for sugarcane pest management. The persistence of imidacloprid, thiamethoxam and clothianidin in the soils of sugarcane ecosystem was studied (58–60). Thiamethoxam, imidacloprid and clothianidin were reported to persist in the soil of tropical cane ecosystem for 21, 75 and 90 days, respectively when they were applied as soil drench at their respective recommended doses. The moderate level of persistence of these molecules in the soil suggests that the insecticides can remain available in the rhizosphere for a sufficient duration to support root uptake and systemic translocation. Since both drenching and drip chemigation deliver insecticides directly into the soil and the root zone, in particular, the effectiveness of these neonicotinoids through drenching highlights their suitability for application via drip chemigation systems. Therefore, thiamethoxam, imidacloprid and clothianidin can be considered as promising candidates for managing difficult-to-control subterranean pests such as termites and white grubs in sugarcane through drip chemigation. However, additional field investigations are needed to verify its performance under drip-chemigation conditions, including its uptake, translocation, persistence and pest control efficacy, before definitive recommendations can be formulated. Given that, foliar spraying of insecticides over six feet sugarcane crop is impractical and also associated with occupational health hazards, drip-chemigation would serve as a viable option in managing late-season pests of sugarcane. However, further field-based studies are necessary to validate their efficacy, distribution and persistence under drip-chemigation conditions.

Anthranilic diamides in drip-chemigation systems

In recent times, anthranilic diamide insecticides, especially chlorantraniliprole, has shown effective against lepidopteran pests in vegetable crops. They activate ryanodine receptors in insect muscles, which causes uncontrolled calcium release, paralysis and eventual death (61). Their unique mode of action makes them highly effective against target pests while relatively safer to non-target organisms. One of the key reasons for the success of chlorantraniliprole in drip chemigation is its strong systemic behaviour and xylem mobility, consistent with the favourable physicochemical properties as presented in Table 4. After application, the insecticide moves with soil water to the root zone, where it is absorbed and translocated to the aerial plant parts, enabling effective control of pests such as leaf miners (*Liriomyza trifolii*) and armyworms (*Spodoptera* spp.) in crops like tomato (22). This systemic movement allows control of pests that are difficult to be managed through surface applications.

Chlorantraniliprole is one of the important insecticides having label claim for managing major pests of sugarcane viz., early shoot borer, top borer and termites. While early shoot borer and termites can easily be managed by conventional application methods such as foliar spraying and soil drenching, top borer remains

difficult to be controlled with existing methods by the cane entomologists. Though granular formulation of this insecticide is often used to manage the late-season attack of this pest, drip chemigation may be considered as an alternate option to manage this pest using the suspension concentrate of this molecule after detailed investigation and validation. Chlorantraniliprole persisted in the soil of tropical cane ecosystem for 30 days when drenched at its recommended dose of 100 g a.i. ha⁻¹ (62). This level of persistence suggests that the molecule may remain available in the root zone for sufficient uptake to potentially provide protection against top borer when applied through drip chemigation. However, this hypothesis requires validation through field studies evaluating insecticide uptake, translocation, persistence and efficacy under drip-chemigation conditions before practical recommendations can be made.

Several field studies demonstrated the effectiveness of chlorantraniliprole when applied via drip irrigation system. Drip chemigation significantly reduced the fruit damage caused by *O. nubilalis* in bell pepper, with two drip applications being as effective as multiple foliar sprays (20). Similarly, drip application reduced damage caused by *Helicoverpa zea* in tomato (55). In leafy vegetables, early drip applications provided long-lasting control of pests such as *Trichoplusia ni*, *Spodoptera exigua* and *Liriomyza* spp. in romaine lettuce (63). The success of anthranilic diamides in drip chemigation is due to their systemic activity, soil stability and target specific action against chewing pests. They provide effective pest control with fewer applications by reducing labour and pesticide use. Emerging molecules such as cyantraniliprole are expected to further expand their use, offering broader pest control and improved management of lepidopteran and leaf-mining insects (64, 65). Overall, anthranilic diamides represent an effective group of insecticides for drip chemigation, combining strong biological activity with efficient delivery for sustainable pest management.

Scope for other insecticide groups

Similar to neonicotinoids and anthranilic diamides, other insecticide groups have also shown potential for use in drip chemigation systems, although their performance is highly variable. Earlier studies demonstrated that drip chemigation can deliver insecticides, nematicides and fumigants directly into the root zone, improving target-specific delivery and reducing environmental losses. Among these, carbamate insecticides such as oxamyl have shown promising results due to their relatively high-water solubility and systemic or translaminar activity. For example, oxamyl applied at 2.25 kg a.i. ha⁻¹ through drip irrigation effectively controlled green peach aphid in bell pepper, western potato leafhopper in celery and melon aphids and leaf miners in muskmelon (50). These findings indicate that certain carbamates can be effectively used in drip systems when their solubility and mobility support root uptake and distribution. Organophosphate insecticides such as dimethoate and oxydemeton-methyl have been shown effective in drip

chemigation. Dimethoate applied at 2.70 kg a.i. ha⁻¹ in maize effectively controlled *M. hieroglyphica* (56), while higher doses were effective against *Tetranychus urticae* in cotton (37). Oxydemeton-methyl also showed effectiveness against aphids and leaf miners in muskmelon (50). Although these insecticides exhibit moderate systemic activity, their effectiveness is generally lower than that of neonicotinoids due to limitations in their mobility and persistence as shown in Table 4.

Drip systems can also facilitate the delivery of certain water-soluble soil fumigants and nematicides; however, these applications are outside the primary scope of this review. Drip chemigation can effectively suppress soil-borne pests with reduced emissions and improved safety. Carbamates, organophosphates and other insecticide groups can thus, be used in drip chemigation, their efficiency is however, completely depending on water solubility, systemic behaviour and soil mobility (66). They are better candidates for managing soil-dwelling insects and nematodes through drip chemigation.

Sprinkler chemigation

Sprinkler chemigation enables pesticide injection with irrigation hydraulics for uniform distribution of insecticides over larger crop canopy. Delivery is achieved using centre-pivot irrigation systems, which deposit spray droplets onto foliage and soil. The system consists of an overhead sprinkler line that rotates around a central pivot, irrigating large, unobstructed fields (67). During operation, insecticides are introduced into the irrigation water using injection devices such as Venturi injectors or positive displacement pumps, which regulate the rate of chemical entry. Once injected, the insecticide is transported through the pipeline network along with flowing irrigation water, with movement governed by hydraulic pressure and flow dynamics to ensure continuous mixing and delivery to all sprinkler outlets. At the sprinkler heads, the pressurised liquid is converted into droplets through nozzle action.

Droplet size plays a vital role in deposition efficiency. Depending on nozzle type and operating pressure, droplets of varying sizes influence coverage, drift and canopy penetration. Larger droplets deposit quickly on soil and lower canopy, while smaller droplets improve foliar coverage, but are more prone to drift. The rotating motion of the centre-pivot system ensures spatial uniformity. After deposition, insecticides may function through foliar contact or move into the soil with irrigation water, enabling systemic uptake in the case of systemic compounds. The effectiveness of sprinkler chemigation is further influenced by application timing, irrigation rate, environmental conditions (wind, temperature, humidity) and physicochemical properties such as solubility and adsorption.

Design and operational requirements for sprinkler chemigation

Efficiency of sprinkler chemigation depends on application uniformity, which ensures uniform distribution of insecticide across the field. Designed sprinkler system must attain a coefficient of uniformity (CU) of at least 80 % and preferably 90 %. Even at higher uniformity levels ($\approx 90\%$), some spatial variation may occur, highlighting the importance of proper system design and operation (28). Uniformity is strongly affected by pressure regulation within the irrigation system. The maximum pressure variation should not exceed 20 % of the sprinkler's operating pressure in lateral lines, while a variation of 10 % or less is acceptable (28). Where pressure fluctuations are observed, the use of flow-control nozzles or pressure regulators is recommended. The spacing between sprinklers plays a critical role in achieving uniform coverage. For stationary systems, spacing between sprinklers and laterals should not exceed 50 % of the wetted diameter. Under heavy wind conditions (wind speeds $> 5 \text{ km hr}^{-1}$), spacing should be reduced to 40 % to reduce drift and maintain uniform deposition (28). Sprinklers should be operated within the recommended pressure range, with a rotation time of not more than one minute to improve uniformity. The system should run for at least 15 min to ensure adequate mixing and uniform application of the insecticide solution (28). Once the system is properly designed and operated with appropriate parameters, insecticide delivery can be achieved more uniformly and efficiently.

Effectiveness of insecticide formulations in sprinkler chemigation

As centre-pivot irrigation technology has improved, the application of agrochemicals through this irrigation system has become more common worldwide. This method enables delivery of water and insecticides together by improving operational efficiency and reducing labour and energy requirements compared to other conventional spraying system (68). Sprinkler chemigation can enhance the uniform distribution of agrochemicals across the field (69–71). The success and efficiency of this system depend on the physicochemical properties of insecticides and their formulations, particularly solubility and compatibility with the carrier medium. Several studies have shown that low water-soluble insecticides such as permethrin and endosulfan can perform effectively in sprinkler chemigation when applied using spray oil as a carrier. In contrast, water-soluble insecticides such as monocrotophos were shown less efficiency under sprinkler-chemigation, but performed well in conventional spraying (72). Similar trends have been observed in other pest systems. Chemigation with permethrin and sulprofos provided better management of *H. zea* compared to water-soluble insecticides such as methomyl and monocrotophos. High-volume chemigation of permethrin achieved up to 99 % reduction of pests such as *T. ni*, *Plutella xylostella* and *Brevicoryne brassicae*. These studies clearly

demonstrate that oil-based formulations enhance insecticide effectiveness more than other formulations in sprinkler chemigation systems, especially against lepidopterans and aphids.

Impact of irrigation volume and its application on chemigation efficiency

The efficiency of sprinkler chemigation is strongly influenced by the volume of irrigation water and the application method. Studies have shown that effective pesticide delivery through irrigation often requires higher water volumes compared to conventional spraying. Overhead irrigation systems may require nearly 300 times more water per hectare than ground spray applications to deliver comparable pesticide amounts (73). However, reducing irrigation volume can improve pesticide performance. Lower irrigation volumes enhance uniformity of pesticide distribution within the plant canopy, leading to better deposition. In contrast, excessive irrigation increases the risk of runoff and leaching, resulting in soil contamination and exposure to non-target organisms (74).

Along with water volume, the type of sprinkler system and application parameter highly influence its efficacy. Sprinkler chemigation has been used to control *O. nubilalis* and *Diatraea grandiosella*, with impact sprinklers providing better pest control than drop-nozzle systems, highlighting the importance of spray dynamics and droplet formation (75). Further, application method and insecticide characteristics are crucial for reliable pest control. The effectiveness of bifenthrin against *Striacosta albicosta* varied with application technique in

which aerial spraying achieved high pest control compared to chemigation at lower rates (76). This suggests that sprinkler chemigation may require adjusted application rates or suitable insecticides based on mode of action and delivery efficiency. These findings clearly suggest that successful chemigation depends on optimising irrigation volume, sprinkler configuration along with insecticide selection.

Selection of insecticides for sprinkler chemigation

Insecticide efficiency in sprinkler chemigation is strongly influenced by their physicochemical properties, including water solubility, adsorption coefficient, octanol-water partition coefficient, persistence, systemic nature and leachability, as shown in Table 5. These parameters determine how the insecticide behaves in irrigation water, deposits on plant surfaces and moves within the soil and plant system. Insecticides with low water solubility and high adsorption capacity, such as pyrethroids including fenvalerate, bifenthrin, permethrin, cypermethrin and esfenvalerate, tend to bind strongly to soil particles because of their high Koc and log Kow values, thereby limiting their movement with water. This makes them unsuitable for drip chemigation, but effective in sprinkler systems, where they are delivered as spray droplets onto foliage and upper soil layers. They act by contact mode of action which allows efficient pest control, although higher application rates or oil-based formulations required to improve their efficacy (72, 77, 78).

Table 5. Physicochemical properties, environmental fate and suitability of insecticide for sprinkler chemigation delivery

IRAC-group	Active ingredient	Water Solubility (mg L ⁻¹) at 20 °C	Log P (Log Kow) /octane water partition coefficient)	Koc (mL g ⁻¹)	DT ₅₀ (days)	Systemicity	Leachability	Common Formulation	Country/region of practice	Ref.
3A - Pyrethroids	Fenvalerate	0.001	5.01	5273	77	non-systemic	Low leachability	EC	United States	(44, 77)
	Bifenthrin	0.001	6.6	236610	86.8	non-systemic	Low leachability	EC	United States	(44, 76)
	Permethrin	0.011	6.1	100000	42	non-systemic	Low leachability	EC	United States	(44, 72)
	Cypermethrin	0.009	5.55	307558	21.9	non-systemic	Low leachability	EC	United States	(44, 78)
	Esfenvalerate	0.001	6.24	251717	19.2	non-systemic	Low leachability	EC	United States	(44, 78)
1A - Carbamates	Carbaryl	9.1	2.36	300	-	non-systemic	Transition state	Oil	United States	(44, 72)
	Methomyl	55000	0.09	72	-	non-systemic	Transition state	SL	United States	(44, 72)
1B - Organophosphates	Chlorpyrifos	1.05	4.7	5509	27.6	non-systemic	Low leachability	EC and Oil	United States	(2, 44, 78)
	Acephate	790000	-0.85	302	3	highly	Low	SP	United	(44,

							leachability		States	79)
	Methyl parathion	55	3	240	10	non-systemic	Low leachability	EC	United States	(44, 72)
2A - Organochlorines	Endosulfan	0.32	4.75	11500	86	non-systemic	High leachability	EC	United States	(44, 72)
28 - Diamides	Chlorantraniliprole	0.88	2.86	362	204	highly	High leachability	SC	United States and Ukraine	(44, 45, 76)
	Thiamethoxam	4100	-0.13	56.2	39	highly	High leachability	WG and SC	Ukraine	(44, 45)
	Imidacloprid	610	0.57	225	174	highly	High leachability	SL and SC	United States and Ukraine	(44, 45, 80)
4A - Neonicotinoids	Acetamiprid	2950	0.8	200	3	highly	Low leachability	SP	Ukraine	(44, 45)
	Thiacloprid	184	1.26	-	8.1	highly	Low leachability	SC	Ukraine	(44, 45)

IRAC: Insecticide Resistance Action Committee; Koc: soil organic carbon adsorption coefficient; DT50: dissipation half-life; EC: emulsifiable concentrate; SL: soluble concentrate; SP: soluble powder; SC: suspension concentrate; WG: water-dispersible granules; Oil: oil-based formulation.

Similarly, insecticides such as chlorpyrifos and endosulfan, which exhibit low solubility and strong adsorption, are better candidates for sprinkler delivery where direct deposition compensates for limited mobility (2, 78). In contrast, insecticides with high water solubility and low to moderate adsorption, such as methomyl and acephate, which dissolve readily in irrigation water and move efficiently within the soil profile, are best-suited for both sprinkler and drip chemigation, often at lower application rates. Neonicotinoids (thiamethoxam, imidacloprid, acetamiprid and thiacloprid) are particularly well-suited for chemigation due to high solubility, systemic activity and moderate mobility, enabling root uptake and translocation within plant tissues. However, their high leachability requires careful irrigation management. Certain insecticides, such as carbaryl, methyl parathion and chlorantraniliprole, exhibit intermediate behaviour, where suitability depends on formulation, irrigation volume and system management. For example, chlorantraniliprole has high persistence and systemic properties, but its moderate mobility requires proper irrigation scheduling. Persistence also influences performance, as longer persistence provides extended control, but may increase environmental risks, while shorter persistence may require repeated applications. Highly soluble insecticides with high leachability may move to deeper soil layers if not properly managed. Overall, sprinkler chemigation is particularly suitable for low-soluble, contact insecticides relying on surface deposition, while highly soluble and systemic insecticides perform well in both sprinkler and drip systems. Therefore, selecting insecticides based on

physicochemical properties and aligning them with the appropriate chemigation method is essential for optimising pest control and minimising environmental risks.

Success of contact and systemic insecticides in pest management via sprinkler chemigation

Contact insecticides such as pyrethroids (fenvalerate, bifenthrin, permethrin, cypermethrin, esfenvalerate), some carbamates and few organophosphates, require direct contact with pests and therefore show limitations in drip chemigation. However, they can contribute to pest management when targeting soil-dwelling or surface-active pests. For instance, fenvalerate and bifenthrin have been used against *O. nubilalis*, *D. grandiosella* and stink bugs, while chlorpyrifos has been effective against lepidopteran pests in corn. These insecticides must go with higher doses or oil-based formulations to improve its distribution and contact efficiency. Carbaryl and methomyl have also shown moderate efficacy depending on application conditions. Sprinkler-chemigation system can also be used to apply microbial insecticides. *Bacillus thuringiensis* (Bt) has been used for the management of *O. nubilalis* in corn. Similarly, acetamiprid and thiacloprid have been applied through sprinkler chemigation systems for the management of corn borers as shown in Table 6. Overall, systemic insecticides are most effective in drip chemigation due to their mobility within plants, while contact insecticides require higher doses and suitable formulations. The contact insecticides may be applied through sprinkler chemigation.

Table 6. Pest management through sprinkler-chemigation in different crop ecosystems

IRAC-Group	Active ingredient	Rate (kg a.i. ha ⁻¹)	Formulation	Target pest	Crop	Reference	
4A - Neonicotinoids	Thiamethoxam	0.3 kg a.i. ha ⁻¹	Actara 25 WG	<i>Ostrinia nubilalis</i>	Corn	(45)	
	Imidacloprid	0.25 kg a.i. ha ⁻¹	Confidor 200 SL	<i>Ostrinia nubilalis</i>	Corn	(45)	
		0.31 kg a.i. ha ⁻¹	Admire Pro SC	<i>Bagrada hilaris</i>	Broccoli	(81)	
	Acetamiprid	0.05 kg a.i. ha ⁻¹	Mospilan 20 SP	<i>Ostrinia nubilalis</i>	Corn	(45)	
	Thiacloprid	0.375 kg a.i. ha ⁻¹	Calypso 480 SC	<i>Ostrinia nubilalis</i>	Corn	(45)	
			0.168 kg a.i. ha ⁻¹	Pydrin 2.4 EC	<i>Ostrinia nubilalis</i> and <i>Diatraea grandiosella</i>	Corn	(70)
0.17 kg a.i. ha ⁻¹			Pydrin 2.4 EC	<i>Diatraea grandiosella</i> and <i>Ostrinia nubilalis</i>	Corn	(68)	
3A - Pyrethroids			0.1 kg a.i. ha ⁻¹	2.4 EC	Tomato fruit worms and stink bugs	Tomato	(65)
		Bifenthrin	0.1 kg a.i. ha ⁻¹	2.4-oil	Leafhoppers and corn earworms	Peanuts	(65)
			0.1121 kg a.i. ha ⁻¹	Brigade EC	<i>Striacosta albicosta</i>	Corn	(69)
			0.11 kg a.i. ha ⁻¹	-	<i>Nezara viridula</i> , <i>Euschistus servus</i> and <i>Halyomorpha halys</i>	Cotton	(66)
	Permethrin	0.1 kg a.i. ha ⁻¹	2 EC	Corn earworms, Stink bugs	Lima beans	(65)	
	Cypermethrin	1.47 kg a.i. ha ⁻¹	Ammo 2.5 EC	<i>Helicoverpa zea</i> and <i>Spodoptera frugiperda</i>	-	(71)	
	Esfenvalerate	0.39 kg a.i. ha ⁻¹	Asana XL 0.66 EC	<i>Helicoverpa zea</i> and <i>Spodoptera frugiperda</i>	-	(71)	
	28 - Diamides		0.4 kg a.i. ha ⁻¹	Coragen 20 SC	<i>Ostrinia nubilalis</i>	Corn	(45)
		Chlorantraniliprole	0.075 kg a.i. ha ⁻¹	Prevathon 5 SC	<i>Striacosta albicosta</i>	Corn	(69)
			0.075 kg a.i. ha ⁻¹	Prevathon 0.43 SC	<i>Striacosta albicosta</i>	corn	(69)
	1A - Carbamates	Carbaryl	2.2 kg a.i. ha ⁻¹	4-oil	Colorado potato beetle potato aphid	Tomato	(65)
2.2 kg a.i. ha ⁻¹			4-oil	Tomato fruit worms and stink bugs	Tomato	(65)	
1.1 kg a.i. ha ⁻¹			4-oil	Leafhoppers and corn earworms	Peanuts	(65)	
Methomyl		0.6 kg a.i. ha ⁻¹	1.8 SL	Corn earworms	Peanuts	(65)	
		2.35 kg a.i. ha ⁻¹	Lorsban 4 EC	<i>Helicoverpa zea</i> and <i>Spodoptera frugiperda</i>	-	(71)	
1B - Organophosphates		0.56 kg a.i. ha ⁻¹	Lorsban 4 EC	<i>Ostrinia nubilalis</i>	Corn	(2)	
		1.12 kg a.i. ha ⁻¹	-	<i>Diatraea grandiosella</i> and <i>Ostrinia nubilalis</i>	Corn	(68)	
		1.1 kg a.i. ha ⁻¹	6-Oil	Colorado potato beetle Potato aphid	Tomato	(65)	
		1.1 kg a.i. ha ⁻¹	6-oil	Corn earworms	Peanuts	(65)	
		1.12 kg a.i. ha ⁻¹	Lorsban 4 EC	<i>Ostrinia nubilalis</i> and <i>Diatraea grandiosella</i>	Corn	(70)	
		Acephate	1.12 kg a.i. ha ⁻¹	ORTHENE 75 SP	<i>Mamestra configurata</i>	Peppermint	(82)
	2A - Organochlorines	Methyl parathion	0.5 kg a.i. ha ⁻¹	4 EC	Stink bugs	Lima beans	(65)
Endosulfan		0.6 kg a.i. ha ⁻¹	2 EC	Tomato fruit worms	Tomato	(65)	
		1.1 kg a.i. ha ⁻¹	2 EC	Colorado potato beetle, Potato aphid, fruitworm and stink bug	Tomato	(65)	
11A-Bacillus thuringiensis and the insecticidal proteins they produce	Bacillus thuringiensis subsp. kurstaki	24 oz. acre ⁻¹	DiPel ES	<i>Ostrinia nubilalis</i>	Corn	(2)	

IRAC: Insecticide Resistance Action Committee; a.i.: active ingredient; ha⁻¹: per hectare; EC: emulsifiable concentrate; WG: water-dispersible granules; SL: soluble concentrate; SC: suspension concentrate; SP: soluble powder; FC: flowable concentrate; Oil: oil-based formulation; ES: emulsifiable suspension.



Advantages of chemigation over conventional method of application

Both drip and sprinkler chemigation systems offer several advantages over conventional insecticide application methods, particularly in terms of efficiency, precision and environmental safety. When properly managed, these systems can improve pest control, while reducing input costs and ecological risks. A major advantage is the uniform and precise application of insecticides. These systems deliver insecticide through irrigation ensuring better distribution. In drip systems, insecticides are applied directly to the root zone, while in sprinkler systems, chemicals are distributed over the crop foliage, which is more similar to foliar application. A key advantage of drip irrigation is due to their efficient use of water, as it delivers water and insecticide directly to the root zone by reducing losses due to evaporation and runoff. Sprinkler systems, although they consume more water compared to drip, they are still more efficient than traditional surface irrigation and conventional application. Both systems are also energy-efficient compared to conventional method as they combine irrigation and insecticide application into a single operation which reduces labour, time and fuel costs, especially by reducing soil compaction and crop damage.

Another important factor is improved operator safety. Since insecticides are applied through a closed system, human exposure is reduced compared to manual spraying. In terms of environmental point of view the drip chemigation is particularly advantageous as it reduces off-target losses such as spray drift and runoff, thereby reducing environmental pollution. It is also safer for pollinators and beneficial insects, as insecticides are delivered to the soil rather than directly onto foliage as shown in Fig. 1. Drip chemigation with flonicamid provided extended control of *A. gossypii* for up to 40 days, compared to 20 days with foliar spraying with minimal effects on beneficial insects. Prolonged efficacy coupled with safety to natural enemies make the drip chemigation an eco-friendly approach for applying insecticides (83).

In crops like sugarcane, where plant height and dense crop canopy limits foliar spraying, chemigation stands as a viable and only approach to manage late season pests. Once drip system is installed, insecticides can be applied with irrigation water without entering into field. In large-scale farming systems, particularly under monocropping, both drip and sprinkler chemigation offer high operational efficiency and better resource management, making them most suitable for modern precision agriculture with less environmental impact.

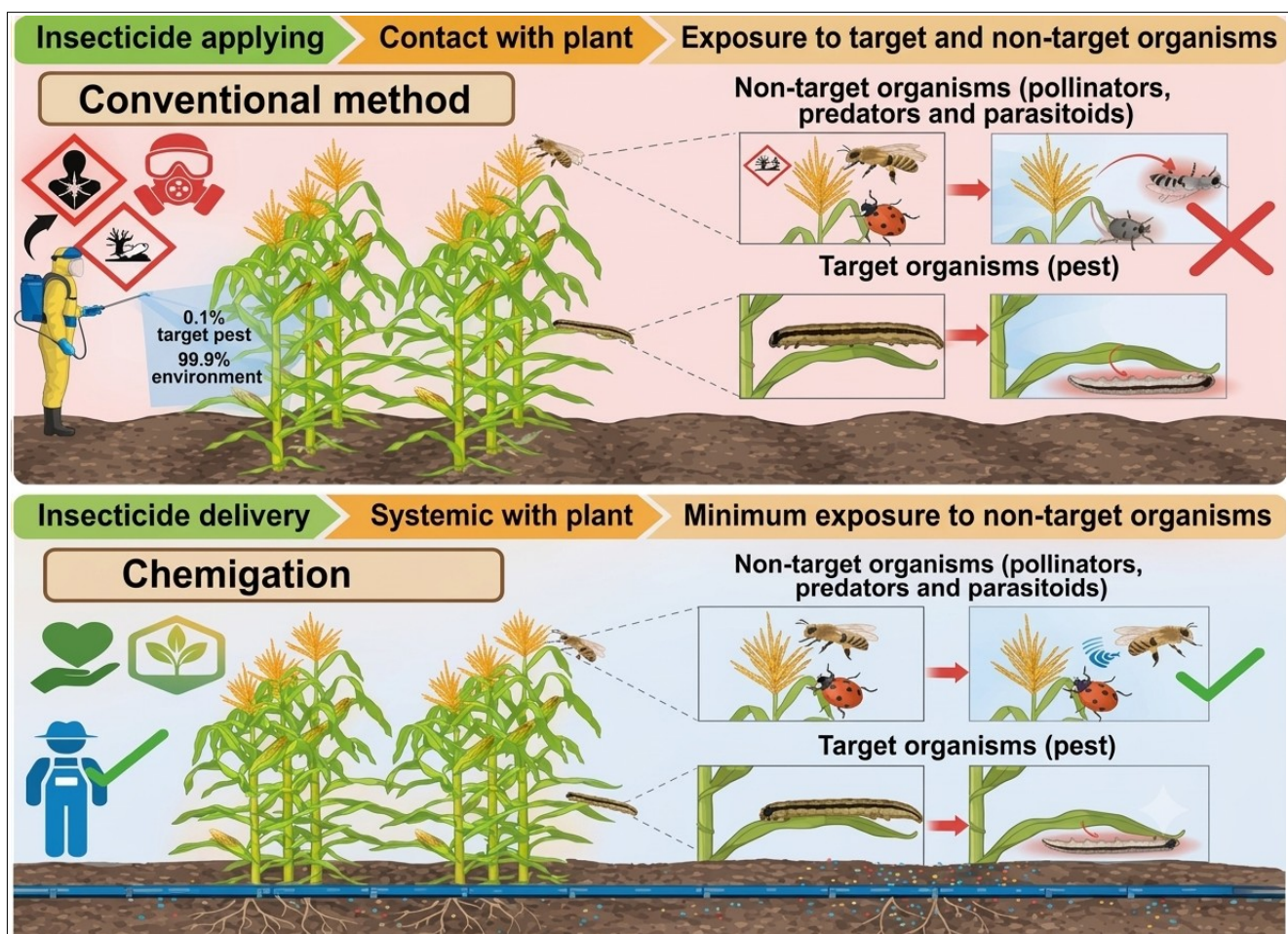


Fig. 1. Advantage of drip-chemigation over the conventional application method.

Disadvantages and challenges faced in drip and sprinkler chemigation

Impact on soil due to excessive agrochemical use via drip and sprinkler-chemigation

Modern agricultural practice has become heavily reliant on chemical inputs, including fertilisers and pesticides. While these agrochemicals can increase crop production, their injudicious use can definitely harm the environment by disturbing ecosystem balance and affecting soil health. Many non-target organisms, including soil microbes, which play a vital role in nutrient cycling and soil fertility are affected. Indiscriminate insecticide use can reduce these populations, leading to poor nutrient availability and long-term decline in soil productivity (84). Agrochemicals can also move through the environment by binding to soil particles, accumulating in plant tissues and entering the food chain, where they can be biomagnified and pose risk to animals and humans.

Pesticides particularly affect soil microorganisms, which are vital for maintaining soil health. Their impact depends on dosage, soil type and environmental conditions. These chemicals can interfere with microbial processes such as respiration, growth and nutrient transformation, altering community structure (85). Although initial application may reduce microbial populations and enzyme activity, some microbes can adapt and degrade the compounds over time. While some studies report limited overall effects, Certain microorganisms can degrade pesticides through specialised metabolic pathways, contributing to natural bioremediation. Soil enzyme activity is often used as an indicator of these changes.

Pesticide use can also alter microbial composition and diversity, affecting processes such as carbon and nutrient cycling. Insecticides can modify microbial genes involved in carbon degradation, particularly in acidic soils (86). Neonicotinoids such as thiamethoxam, imidacloprid and clothianidin reduce microbial diversity depending on soil conditions. Though these agrochemicals are important for crop protection, but their excessive use can harm soil ecosystems. Proper use of drip and sprinkler chemigation systems can reduce pesticide losses, minimise groundwater contamination and help conserve beneficial soil microbiota, supporting sustainable agricultural production.

Effect of systemic insecticides on ecosystem and pollinators

Groundwater contamination due to insecticides represents a major environmental concern largely influenced by insecticide properties, soil type, farming practices, plant uptake and environmental conditions such as climate and geology. Some insecticides are highly mobile and can move through soil profile later into groundwater. The detection of aldicarb in groundwater in Suffolk County, New York (87), which concerns the leaching potential of certain compounds. Many insecticides used in agriculture have potential to contaminate groundwater due to their frequent

application, more extensive coverage and higher doses. Insecticide such as carbofuran, imidacloprid, methomyl, trichlorfon and aldicarb metabolites are highly prone to leaching, which highlight the need for careful selection of insecticide for management. Insecticide runoff also poses risks to aquatic ecosystems, as residues like azinphos-methyl are toxic to aquatic ecosystem (82).

Another major concern is the impact of neonicotinoids on pollinators' safety. Group neonicotinoids such as imidacloprid, thiamethoxam, clothianidin and dinotefuran are widely used, but highly toxic to pollinators like honey bees. Bees are exposed to these insecticides through pollen and nectar (81) and exposure levels depend on application method and timing. Foliar sprays and drip chemigation during flowering stages result in higher residue accumulation, whereas applications at planting lead to lower residues. To overcome this, understanding pesticide behaviour and adopting precise application methods are essential for reducing groundwater contamination, protecting aquatic ecosystem and pollinators along with sustainable pest management.

Limitations and operational challenges of drip and sprinkler chemigation

Both drip and sprinkler chemigation systems offer efficient methods for pesticide application. However, they also present several technical, environmental and economic challenges. Drip irrigation systems require intensive maintenance and monitoring, with issues such as pressure fluctuations, leakage and emitter clogging affecting uniform delivery. Similarly, sprinkler systems face problems such as nozzle blockage, pressure variation and wind drift, leading to uneven distribution and off-target movement. In both systems, poor uniformity can reduce pest control efficiency and increase environmental risks (7). Chemigation also has limitations regarding the types of pesticides that can be effectively used. Only certain chemicals, particularly systemic compounds, are suitable for uptake through irrigation systems (50). In addition, abiotic factors such as soil type, rainfall, temperature and irrigation scheduling influence pesticide movement, persistence and plant uptake. Environmental concerns include groundwater contamination due to leaching, especially with highly soluble insecticides. In sprinkler systems, spray drift and runoff can contaminate nearby water bodies and affect non-target organisms. Accumulation of pesticide residues in crops is another concern, requiring careful monitoring and adherence to recommended doses.

The effectiveness of chemigation depends on proper timing and field conditions. Drip systems, insecticides must reach the active root zone for optimal uptake, while in sprinkler systems, evaporation, sunlight exposure and canopy coverage influence deposition and effectiveness (39). Economic and structural constraints can substantially limit the adoption of chemigation. Both drip and sprinkler systems are generally more feasible in large-scale and relatively



uniform cropping systems, particularly under monocropping, where the costs of infrastructure can be distributed over larger production areas. The substantial initial investment required for injection units, filtration systems, backflow prevention devices and associated irrigation infrastructure may be prohibitive for smallholder farmers. In addition, the economic viability of chemigation depends on whether reductions in labour, water use, pesticide losses and application costs can offset the initial installation and maintenance expenses. Drip systems typically involve higher installation and maintenance costs, whereas sprinkler systems may require greater energy inputs due to the pressure requirements for operation. Consequently, the economic feasibility of chemigation is highly context-dependent and should be evaluated according to farm size, crop value, existing irrigation infrastructure, labour availability, energy costs and expected improvements in pest management. Regular inspection and maintenance are essential, as poorly maintained systems can lead to ineffective pest control and increased environmental risks (7).

Comparative assessment of chemigation delivery methods: Practical implications and research gaps

Evidence across the reviewed studies indicates that no single insecticide delivery method is universally superior; rather, the success of chemigation depends on the interaction between irrigation system characteristics, insecticide physicochemical properties, target pest biology, crop architecture and environmental conditions. Drip chemigation and sprinkler chemigation each offer distinct advantages over conventional foliar spraying, but their suitability varies according to the mode of insecticide delivery and the intended target.

Drip chemigation is particularly effective for systemic insecticides such as neonicotinoids and anthranilic diamides because their high-water solubility, suitable soil mobility and xylem translocation facilitate efficient movement from the root zone to aerial plant tissues. This enables effective management of concealed, soil-dwelling and vascular-feeding pests while reducing pesticide losses, operator exposure and the need for repeated foliar applications. Moderate persistence of molecules such as thiamethoxam, imidacloprid, clothianidin and chlorantraniliprole further supports sustained root uptake and prolonged pest suppression. Consequently, drip chemigation is especially advantageous in crops equipped with drip irrigation systems and where foliar spraying becomes difficult, such as mature sugarcane.

In contrast, sprinkler chemigation relies primarily on canopy deposition and is therefore more suitable for contact insecticides. Unlike drip systems, its performance is strongly influenced by irrigation volume, sprinkler configuration, droplet characteristics and application timing. Lower irrigation volumes generally improve pesticide deposition and canopy distribution, whereas excessive irrigation may increase runoff and leaching, reduce efficacy and increasing environmental contamination. Likewise, differences in sprinkler type

and spray dynamics have been reported to influence pest control, indicating that equipment configuration is an important determinant of application efficiency. These factors explain why some studies report sprinkler chemigation to be comparable with conventional foliar spraying, while others observe reduced efficacy, particularly when irrigation management or application parameters are not optimised.

The physicochemical properties of insecticides largely determine the most appropriate delivery system. Highly soluble and systemic insecticides generally perform well through drip chemigation and can also be effectively applied through sprinkler systems under suitable irrigation conditions. Conversely, insecticides with low water solubility and high adsorption coefficients, such as many pyrethroids, are more compatible with sprinkler chemigation because they rely on direct foliar deposition rather than root uptake. Therefore, successful chemigation requires matching insecticide characteristics with the irrigation method instead of adopting a single application strategy for all pest management situations.

From a practical perspective, drip chemigation is the preferred option for systemic insecticides targeting soil-borne, concealed, or internal-feeding pests, particularly in perennial and high-value crops where repeated foliar applications are impractical. Sprinkler chemigation is more appropriate for contact insecticides and pests requiring uniform canopy coverage, if irrigation volume, sprinkler configuration and application timing are carefully managed. Conventional foliar spraying remains valuable for rapid suppression of exposed pest populations but generally requires greater labour input and is associated with higher risks of spray drift, operator exposure and off-target contamination.

Despite considerable advances, several important knowledge gaps remain. Direct comparisons among drip, sprinkler and conventional foliar application are limited because most studies differ in crop species, irrigation systems, environmental conditions, insecticide formulations and evaluation methods. Standardised multi-location field trials are needed to establish robust recommendations across diverse agroecosystems. Future research should also focus on optimising irrigation scheduling, injection timing, formulation compatibility, residue behaviour, environmental fate, integration with integrated pest management programmes and economic feasibility to facilitate wider adoption of chemigation as a sustainable insecticide delivery strategy.

3. Conclusion

Chemigation has evolved from a simple method of delivering crop protection products through irrigation systems to a more targeted insecticide delivery strategy with considerable potential for sustainable pest management. Evidence reviewed across different cropping systems demonstrates that chemigation can

provide effective control of both soil- and plant-feeding insect pests while reducing labour requirements, operator exposure, spray volume and overall application costs. Its effectiveness, however, is strongly influenced by irrigation system design, insecticide physicochemical properties, application timing, calibration accuracy and crop-specific management practices. Although adoption has increased in regions with well-developed irrigation infrastructure, wider implementation remains constrained by regulatory restrictions, limited farmer awareness, inadequate technical expertise and concerns regarding pesticide movement, environmental contamination, leaching, residue and effects on non-target organisms.

Future research should focus on developing chemigation-specific formulations, improving irrigation-based delivery technologies, integrating chemigation with precision agriculture and sensor-based irrigation systems and generating robust data on pesticide fate, leaching, residue dynamics and non-target impacts under diverse agroecosystems. Harmonisation of regulatory frameworks and development of crop- and irrigation-specific application guidelines will also be essential to facilitate safe and effective adoption.

Overall, chemigation represents a valuable component of integrated pest management rather than a replacement for conventional application methods. When supported by appropriate technology, scientific validation and sound regulatory oversight, it has the potential to improve insecticide use efficiency while contributing to economically viable and environmentally sustainable crop protection.

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Authors' contributions

GS contributed to literature collection, conceptualisation, writing-original draft preparation and data compilation. RT contributed to supervision, content validation, manuscript revision, integrity and accuracy of content and final approval. SK contributed to supervision, technical validation and content development. RK and KR contributed to technical validation and content development. All authors have read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest

Authors do not have any conflict of interests to declare.

Ethical issues

None

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