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Fluorinated Pesticides in Modern Pest Control: Potential and Challenges

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ABSTRACT

Purpose: Fluorinated pesticides (FPs) have emerged as powerful tools in modern pest control, offering unique chemical properties that enhance efficacy, stability, and selectivity. However, their use also presents significant environmental and regulatory challenges. The synthesis provides an integrated perspective on the current advancements, challenges, and prospects of FPs.

Methods: This review critically evaluates the potential of FPs in modern pest control, highlighting their advantages in pest management while addressing the associated environmental risks, regulatory concerns, and future research directions. We analyzed recent scientific literature (articles, reviews, and regulatory reports) on various aspects of FPs by exploring major scientific databases.

Results: The evolution of FPs has progressed from simple compounds, such as sodium fluoride, to highly advanced insecticides, herbicides, fungicides, and rodenticides. FPs are widely used in pest management due to their high efficiency and target specificity, which are attributed to the unique chemical properties of FPs, such as strong carbon-fluorine bonds, lipophilicity, and electronegativity. Their mechanisms of action vary across pesticide classes, affecting neural pathways in insects, amino acid synthesis in plants, fungal cell membranes, and metabolic cycles in rodents. Despite their benefits, FPs pose significant environmental and health risks due to their chemical persistence and bioaccumulation.

Conclusions: FPs hold significant promise for advancing pest control strategies due to their exceptional chemical and biological properties. Their environmental persistence and potential health risks remain a critical challenge. Development of biodegradable or less persistent FPs, improved methods for environmental monitoring, and deeper investigation into their long-term ecological and toxicological effects should be prioritised to benefit from their toxicity.

Keywords: *Fluorine; perfluorooctanesulfonate; Florasulam; Fluindapyr; Fluorinated pesticides*

INTRODUCTION

Modern agriculture depends substantially on pesticides i.e. insecticides, herbicides and fungicides to protect crops from destructive pests, weeds, and diseases, respectively [1]. The development of these chemicals essentially aims to improve their effectiveness, targeted action, and environmental compatibility. There is a growing interest in exploring simpler, more sustainable compounds that can effectively control pest populations with reduced environmental impact. These compounds, often derived from natural sources or designed to mimic natural mechanisms, offer a promising alternative for integrated pest management. Natural pesticides such as nicotine and pyrethrum have been extracted from tobacco and chrysanthemum flowers, respectively [2, 3]. Sodium salts such as Sodium fluoride is toxic to all forms of life [4]. It can be used as an insecticide, rodenticide, herbicide and fungicide [5]. Fluoride is a known neurotoxin and may cause neurobehavioral defects [6]. During the late 19th century, public health officials used sodium fluoride compounds to combat cockroaches and poultry lice infestations [7, 8]. The exceptional chemical characteristics of fluorine, like high electronegativity and a powerful carbon-fluorine bond, encourage and enable chemical engineers to manufacture highly efficient and effective agrochemicals [9]. These properties enable pesticides to maintain metabolic stability, thus extending their active duration. The unique chemical properties of fluorine may also result in persistent environmental pollutants and their potential accumulation in living organisms [10, 11]. This study aims to assess both positive and negative aspects of fluorine utilisation in pest management.

Fluorine in Agrochemicals: Historical Progress

Fluorine in agrochemicals has been a major innovation in the quest for more potent and selective management of herbs and pests [8]. Cryolite (Na_3AlF_6) was the first ever natural fluorine-containing pesticide used in pest management for centuries [12]. As the synthetic chemistry progressed, Fluorine was integrated into herbicides and insecticides to improve their efficacy, persistence, and residual effects [13]. Isopyrazam, Benzovindiflupyr and Fluindapyr are fluorinated fungicides of the modern pesticide era [13]. Florasulam (sulfonamide herbicide) and Flupyrsulfuron-methyl (fluorinated sulfonylurea) containing fluorine are very effective and highly selective herbicides [14]. Flubendiamide that targets lepidopteran pests and Cyantraniliprole fluorinated insecticides of diamide group that are effective against sucking and chewing insects of crops. In recent times, more fluorine-based compounds have been evaluated against various pests of agricultural significance. This is indicative of great prospects for fluorine in the agrochemical industry.

Evolution of FPs and their impact

Pesticides containing fluorine atoms have experienced significant advancements throughout the history of pesticide development. The evolution of fluorinated pesticides reflects a broader trend in chemical innovation aimed at improving pesticide efficacy, stability, and selectivity [15]. According to research, adding fluorine atoms to pesticide molecules improves both their physical and chemical properties, which results in better performance. The improvement of fluorinated pesticides brought sustainability challenges and medical issues surrounding their implementation [8, 16]. The incorporation of fluorine into agrochemicals began in the mid of 20th century, largely due to the unique chemical properties fluorine imparts, such as enhanced metabolic stability, increased lipophilicity, and improved bioavailability [13]. Dalapon (2,2-dichloropropionic acid), first commercially available herbicide containing fluorine which paved the path for the development of Trifluralin, Fluometuron, and Fluazifop-butyl which were selective herbicides used against grasses in broadleaf crops [17, 18].

Lipophilicity and Bioavailability

Physical traits of pesticide molecules transform substantially after fluorination because it boosts their affinity for fats. The capacity of fluorinated pesticides to dissolve in fats, along with lipids and penetrate biological membranes, increases when fate prefers lipophilicity [19]. When pesticide molecules infiltrate biological tissues more quickly due to enhanced penetration, they can efficiently traverse the vascular system of organisms [20]. The excellent retention of fluorinated pesticides occurs in target organism membranes because of their increased lipophilicity, thus improving both bioavailability and biological activity duration. Pesticides possessing fluorination receive improved bioavailability, which reduces the number of required applications, leading to decreased total pesticide usage but improved results. The high lipophilicity of these compounds poses problems because it allows the compounds to build up within the fat tissues of beneficial insects, wild animals and humans [21, 22].

Stability and Environmental Persistence

Pesticide stability receives enhancement through fluorination as it extends its field lifespan. When fluorine atoms enter pesticide molecules through modification, their stability against hydrolysis, oxidation and microbial breakdown results in prolonged presence in water and soil. The extended existence of fluorinated products reduces the necessary applications but raises concerns regarding their prolonged presence in the environment [23]. FPs accumulation in soil affects both the microbiological activity of soil and the health of plants. These substances break down very slowly, which allows them to stay active in the environment for multiple years, thus threatening the non-target species [24].

Fluorinated pesticides: Mechanisms of action

Different types of FPs, like insecticides, herbicides, and fungicides, are used in pest management due to their eco-friendly nature. Different types of fluorine-based pesticides and their mode of action have been summarised in Table. The physicochemical properties of compounds can be altered by introducing fluorine atoms and fluorine-containing motifs [15]. The following is the mode of action of FPs:

Table. Different types of fluorine-based pesticides and their mode of action

Pest / Pesticide	Fluorinated Compounds	Mode of Action	Examples	Citations
Insects / Insecticides	Fluorinated neonicotinoids Pyrethroids	Disrupts the nervous system by binding to sodium channels and nicotinic acetylcholine receptors.	Flonicamid Fluvalinate	[15, 27, 45]
Herbs / Herbicides	Fluorine-based ALS inhibitors	Inhibits acetolactate synthase (ALS), blocking amino acid synthesis and plant growth.	Flucarbazone Fluoroxypyr	[15, 28]
Fungi / Fungicides	Fluorinated azoles	Inhibits ergosterol biosynthesis, thereby disrupting the fungal cell membranes.	Fluopyram Fluquinconazole	[46, 47]
Rodents / Rodenticides	Sodium fluoroacetate	Disrupts the citric acid cycle, leading to energy failure in cells.	Sodium Fluoroacetate Fluroacetamide	[48-50]
Nematodes / Nematicides	Fluorinated organophosphates	Inhibits acetylcholinesterase, causing neuromuscular disruption.	Fluopyram	[51, 52]
Mites / Acaricides	Fluorinated acaricides	Affects the nervous system and metabolic pathways.	Fluvalinate	[53, 54]

Fluorinated Insecticides

Fluorinated insecticides (FIs) are pesticides that contain fluorine atoms in their molecular structure, designed to control insect pests more effectively. Fluorine-containing neonicotinoids, diamides and Pyrethroids disrupt insect nervous system function by targeting specific neural pathways. Neonicotinoids activate and bind to nicotinic acetylcholine receptors (nAChRs), thus stimulating the neurons continuously until they become paralysed and lead to insect death [25]. The binding capabilities of these compounds toward their target receptors experience an enhancement due to fluorine addition, which makes them more selective [26]. FIs, for example, pyrethroids, prevent sodium channels from closing correctly, thereby creating excessive nerve cell excitation. Fluorinated pyrethroids rapidly knock down insects, which makes them ideal against mosquito strains that have developed resistance [27]. Perfluorophenyl-trichloromethyl-ethanol (PFTE) is an effective fluorinated insecticide against resistant mosquito strains. Through fluorination, insecticides receive increased stability and better lipophilicity properties, enhancing systemic distribution and penetration inside insect tissues [15]. Flubendiamide and Cyantraniliprole are important insecticides used against several crop pests as part of IPM in many countries.

Fluorinated Herbicides

Fluorinated herbicides (FHs) are chemical weed killers that incorporate fluorine atoms into their molecular structure to improve their effectiveness, stability, and selectivity. The effectiveness of FHs against weed comes from their ability to block essential amino acid synthesis in plants through targeting acetolactate synthase (ALS). ALS inhibitors as a necessary part of plant growth and development, inhibit the biosynthetic pathway for branched-chain amino acids (valine, leucine, and isoleucine). New herbicidal functionality arises from fluorine in these compounds, which enhances their potency even at lower doses [28]. FHs make systemic weed control possible because these compounds are capable of efficient transportation through plant tissues. The repeated application of ALS inhibitors has resulted in resistance to weed populations, so researchers must develop new weed control approaches. Soil contamination and extended soil residency are environmental problems attributed to FHs because these chemicals can stay in the soil and potentially seep into groundwater reservoirs. Federal agencies record how fluorinated ALS inhibitors affect microbial communities in soil and non-target plants [29, 30]. Important fluorinated herbicides include Isopyrazam, Benzovindiflupyr and Fluindapyr.

Fluorinated fungicides

Fluorinated fungicides (FFs) are chemicals that contain fluorine atoms in their structure and kills fungus [31]. Fluorine-containing fungicides have become crucial in crop protection, and fluorinated organic compounds represent commercially viable agrochemicals with novelty of mode action [32]. The introduction of fluorine into these chemicals enhances their bioactivity, chemical stability, lipophilicity, and improves their resistance to degradation [33]. FFs act as succinate dehydrogenase inhibitors (SDHIs), which are chemicals that inhibit the enzyme succinate dehydrogenase (complex II) in the mitochondrial respiratory chain [34]. This enzyme plays an important role citric acid cycle and the electron transport chain for catalyzing the oxidation of succinate to fumarate and providing electrons to the electron transport chain [35].

Potential and challenges of FPs

Fluorine enhances the efficacy of pesticides by improving biological activity through increased binding affinity to target receptors in pests or enzymes [36]. The addition of fluorine can increase chemical stability due to the strong C–F bond. This could prevent degradation by light, heat, or microbial action and extend field persistence [37]. Fluorination can modify molecular properties (such as lipophilicity and polarity), which allows more selectivity in targeting a specific pest while minimising effects on non-target organisms [15]. The bioavailability of FPs is another important feature allowing the penetration of FPs into biological membranes, boosting their systemic action within plants or pests [11]. Pest resistance is one of the greatest issues for the chemical control. New fluorine-based structures can help overcome existing pesticide resistance in pests by introducing novel modes of action. Thus, it provides opportunity to develop, modify and discover insecticidal properties of many compounds that could be used in the pest management.

Pest management strategies change over time due to issues and constraints posed by existing technologies employed in the agriculture sector. A recent trend of a surge in the use of FPs [38]. The use of fluorine-based pesticides (FPs) presents several challenges when used in the pest management programs. Environmental contamination by FPs (like perfluorooctanoic acid-related compounds, can persist in soil and water for decades, posing threats to biodiversity [39, 40]. Bioaccumulation is another major concern associated with FPs; for example, fluorinated compounds such as perfluorooctanesulfonate (PFOS) can accumulate in the tissues of various aquatic taxa, leading to persistence and magnification throughout the food chain [41, 42].

Some FPs are have shown endocrine disruption, imitating the action of endocrine hormones, as seen with certain fluorinated herbicides [43]. Environmental persistence of FPs is largely due to the strength of the carbon-fluorine bond, slowing down the process of natural degradation [44]. Additionally, FPs have been linked to genotoxicity, raising concerns about their potential to damage DNA, as observed in some laboratory studies with fluorinated agrochemicals [16, 38]. The issue of incomplete degradation leads to the formation of persistent, often toxic by-products [55]. Furthermore, the increasing prevalence of FPS in agricultural and urban settings amplifies exposure risks [38, 56]. Although some progress has been made in microbial biodegradation, such as bacteria capable of partially degrading fluorinated pollutants, these processes are often inefficient and slow [57, 58]. Finally, the structural complexity of many FPs makes their breakdown and risk assessment challenging, complicating efforts for environmental remediation and regulatory approval.

CONCLUSION

FPs have enhanced pest management by improving stability, availability, and targeted action due to their strong carbon-fluorine bond, high electronegativity, and lipophilic properties. Their specificity allows effective pest control while minimising off-target effects. However, their widespread use raises environmental concerns, including persistence in ecosystems, bioaccumulation in non-target organisms, and toxicity to microbial and aquatic life. The challenges of using FPs include environmental contamination, bioaccumulation, endocrine disruption, environmental persistence, genotoxicity, incomplete degradation, microbial biodegradation, and structural complexity. To mitigate these risks, research should focus on developing eco-friendly FPs with improved biodegradability. Integrated Pest Management (IPM) strategies, combining biological control and precision farming, should be prioritised to reduce reliance on synthetic chemicals. Regulatory frameworks need to be updated to balance pest control benefits with environmental sustainability, ensuring responsible pesticide use in agriculture.

CONFLICT OF INTERESTS

The authors declare no conflict of interest.

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