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Innovative Approaches for Characterizing Chlorantraniliprole and Its Metabolites in Soil, Water and Plants

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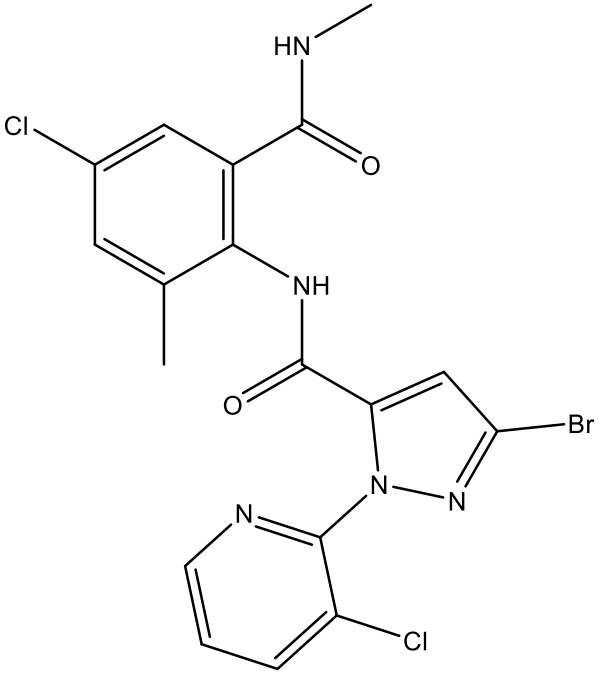
Abstract

The environmental effects and possible hazards of chlorantraniliprole, a frequently used insecticide, have recently come to the forefront. This article provides an in-depth look at novel methods for characterising chlorantraniliprole and its metabolites in soil, water, and plants. Various analytical procedures are covered in depth, including chromatographic methods, mass spectrometry, capillary electrophoresis, immunoassay-based procedures, and spectroscopic procedures. The difficulties and restrictions of chlorantraniliprole analysis, as well as its advantages, are discussed in length, along with sample preparation and extraction methods. The essay finishes by looking forward to several promising avenues of research and development, such as novel approaches, omics integration, and environmentally friendly analytic approaches. These findings aid in the advancement of chlorantraniliprole knowledge and open the path for more ecologically responsible pesticide application.

Keywords: *Chlorantraniliprole, pesticide analysis, environmental matrices, analytical methods.*

1. Introduction

In agriculture, chlorantraniliprole is a well-known chemical molecule used as an insecticide. An anthranilic amide core is ornamented with chlorinated substituents, revealing an unusual intricacy in its chemical structure. Chlorantraniprole is formally known as 3-bromo-4'-chloro-1-(3-chloro-2-pyridyl)-2'-methyl-6'-(methylcarbamoyl) pyrazole-5-carboxanilide (IUPAC name) (fig. 1). This crystalline solid, with the formula C18H14BrCl2N5O2 and the molecular weight of around 544.3 g/mol, is notable for being almost insoluble in water but dissolving rapidly in organic solvents including acetone, methanol, and dichloromethane [1].



Chlorantraniliprole

Fig 1: Structure of chlorantraniliprole

Chlorantraniliprole's value to the farming industry is enormous. Because of its role as a modulator of the ryanodine receptor, it causes paralysis and death in insects by upsetting the balance of calcium ions in their muscle cells. This powerful pesticide is very useful for protecting crops against a broad variety of pests, including those of the Lepidoptera, Coleoptera, Diptera, and Hemiptera orders. Cotton, soybeans, maize, vegetables, fruits, and nuts are only some of the crops that chlorantraniliprole is used to protect against the scourge of insect infestations [2]. Its particular mechanism of action allows for long-term control, less damage to non-target organisms, and a lower likelihood of resistance. Chlorantraniliprole and its metabolites must be characterised in environmental matrices such as soil, water, and plants. There are a number of compelling arguments that call for such categorization. First, it helps with environmental impact assessments by shedding light on chlorantraniliprole's movement and the consequences it may have on the environment [3]. Second, it maintains safety standards by allowing for precise measurement of pesticide residues in food and the environment. Thirdly, efficient pesticide management is bolstered by knowledge of chlorantraniliprole's persistence and behaviour, reducing the potential for groundwater pollution and ecological impact. Metabolite characterization also helps with risk assessment for ecosystem health and non-target species. This information is critical for reducing pesticide waste, improving crop yields, and fostering environmentally friendly farming methods [4]. Given these factors, this review article seeks to investigate novel methods for identifying chlorantraniliprole and its metabolites in natural environments such as soil, water, and plants. This study aims to provide a concise overview of state-of-the-art analytical methodologies and techniques for the specific detection and quantification of chlorantraniliprole and its metabolites. Improvements in analytical accuracy and sensitivity are also highlighted, as are current developments in sample preparation, apparatus, and data interpretation. In addition, the paper explores chlorantraniliprole's behaviour and destiny in the environment, providing insight into its transformation paths in different matrices. It covers the difficulties and restrictions of characterising chlorantraniliprole, and provides useful insights into its analysis by way of examples and case studies. Finally, the assessment offers a look forward at where the area is headed and what technologies are on the horizon, with a focus on green analysis and long-term viability. Overall, the paper wants to become a go-to reference for researchers, environmental scientists, and regulatory agencies working to improve pesticide monitoring and control for the benefit of safer, more environmentally friendly farming methods.

Analytical Methods for Chlorantraniliprole and Its Metabolites

Chlorantraniliprole and its metabolites must be analysed in different environmental matrices such soil, water, and plants to learn about their existence, behaviour, and possible influence on the environment. To do this, analysts use a wide variety of analytical approaches, each with its own set of advantages and disadvantages (fig 2).

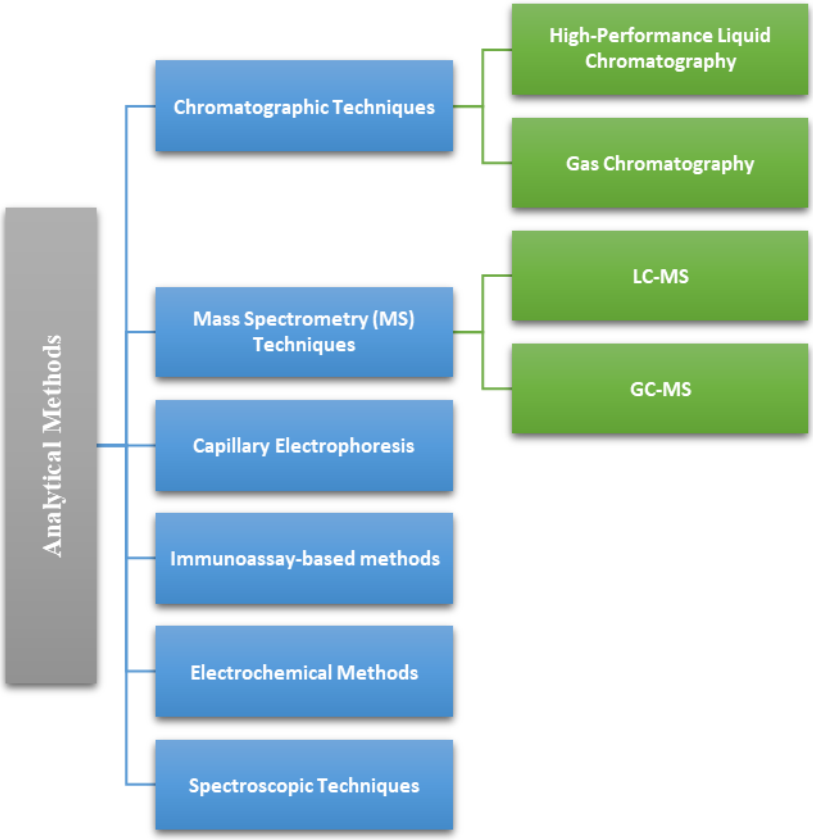


Fig 2: Various Analytical approaches for Chlorantraniliprole and Its Metabolites

This article will focus on the examination of chlorantraniliprole and its metabolites, and will provide a detailed explanation of two important chromatographic techniques: High-Performance Liquid Chromatography (HPLC) and Gas Chromatography (GC).

Chromatographic Techniques

High-Performance Liquid Chromatography (HPLC)

Separation and quantification of chlorantraniliprole and its metabolites in a wide range of environmental samples are common applications of High-Performance Liquid Chromatography (HPLC), a well-respected analytical method. Liquid chromatography is at the heart of high-performance liquid chromatography (HPLC), and the basic idea is to inject a sample containing chlorantraniliprole and its metabolites onto a specialized chromatographic column that includes a stationary phase, commonly made of solid adsorbent material. This stationary phase has a reaction with the target analytes. Then, the components of interest are eluted from the column using a mobile phase, typically a liquid solvent [5].

HPLC has a number of benefits that make it a good choice for analysing chlorantraniliprole. As its primary claim to fame, its extraordinary sensitivity makes it possible to detect and quantify chlorantraniliprole and its metabolites at very low concentrations with high precision. This quality is especially important when working with environmental matrices that may harbour minute quantities of these chemicals. In addition, HPLC is renowned for its accuracy, guaranteeing reliable findings. Accurate quantification of chlorantraniliprole and its metabolites in diverse environmental samples is crucial, and this precision is invaluable [6]. HPLC also has an impressive ability to separate molecules with widely varying chemical characteristics. Analysing chlorantraniliprole and its potential metabolites, each of which may have unique chemical properties, necessitates this capacity. HPLC's effective separation capabilities allow scientists to clearly differentiate between and precisely measure various substances. In addition to its flexibility and adaptability, HPLC's many available detector options—from UV-Visible to fluorescence to mass spectrometry—make it a very useful analytical tool. This adaptability increases its value in chlorantraniliprole investigation by giving researchers more options for how to identify the compound [7]. When it comes to analysing environmental samples for chlorantraniliprole and its metabolites, High-Performance Liquid Chromatography (HPLC) is crucial. Because of its high sensitivity, accuracy, separation capabilities, and flexibility to a wide range of detectors, it is the method of choice for scientists studying chlorantraniliprole's behaviour and effect in a variety of environmental matrices.

Gas Chromatography (GC)

Chlorantraniliprole and its metabolites are best analysed using gas chromatography (GC), a potent and frequently used chromatographic method in environmental study, especially when working with volatile compounds [8]. Unlike High-Performance Liquid Chromatography (HPLC), which uses a liquid mobile phase, Gas Chromatography (GC) depends on the evaporation of analytes and, hence, a gaseous mobile phase. GC has several benefits when doing analyses with chlorantraniliprole. Its primary strength is its ability to isolate and analyse molecules with low boiling points, making it particularly useful for the research of specific metabolites or degradation products. Second, the vapour pressures of analytes are the primary drivers of GC's high separation efficiency [9]. Chlorantraniliprole and its metabolites may be accurately identified and quantified, even in complex environmental matrices, because to the method's outstanding separation capabilities. For further sensitivity and specificity, GC may be coupled with mass spectrometry (GC-MS), which is one of the several detector choices that have made it so popular. GC's analytical capabilities for thorough chlorantraniliprole examination in a wide variety of environmental situations are greatly improved by its flexibility, allowing researchers and analysts to obtain sensitive and selective detection [10].

Mass Spectrometry (MS) Techniques

Liquid Chromatography-Mass Spectrometry (LC-MS)

Chlorantraniliprole and its metabolites may be studied in great detail in a wide range of environmental matrices using the flexible and indispensable analytical technology of liquid chromatography-mass spectrometry (LC-MS). Liquid chromatography and mass spectrometry (LC-MS) are two strong analytical methods that have been combined. Chlorantraniliprole and its metabolites may be extracted from a sample by passing it through a chromatographic column in a liquid chromatograph. Their distinct chemical features, such polarity and molecular weight, allow for this classification. The substances that have been eluted are then put into a mass spectrometer. After the molecules have been vaporised, the mass spectrometer ionises them, creating ions that may have their mass-to-charge ratios measured [11]. Several significant benefits may be gained by using LC-MS for the study of chlorantraniliprole. Extremely low amounts of chlorantraniliprole and its metabolites may be detected and quantified with this method, making it ideal for use with difficult environmental samples. When dealing with very low concentrations of these substances in soil, water, or plant tissues, this degree of sensitivity is crucial. The mass spectra and fragmentation patterns of chlorantraniliprole metabolites are also very well-suited to LC-MS for the purposes of identification and characterization [12]. Insight of chlorantraniliprole's environmental transformations is greatly aided by these data. Adaptability to diverse analytes is ensured by the fact that LC-MS may be set up with alternative ionisation procedures, such as electrospray ionisation (ESI) or atmospheric pressure chemical ionisation (APCI). Additionally, state-of-the-art LC-MS systems with high-resolution mass spectrometry (HRMS) capabilities provide higher resolution and accuracy, allowing for the differentiation of structurally similar compounds and the provision of additional information for chemical identification [13].

Gas Chromatography-Mass Spectrometry (GC-MS)

In the context of volatile chemicals, Gas Chromatography-Mass Spectrometry (GC-MS) is an important analytical method for analysing chlorantraniliprole and its metabolites. Gas chromatography mass spectrometry (GC-MS) depends on the vaporisation of analytes as opposed to the liquid mobile phase used in High-performance liquid chromatography (HPLC). This technique is superior than others for analysing chlorantraniliprole[14]. Low-boiling-point metabolites and degradation products are well-suited to GC-MS analysis because of the method's ability to provide a highly specific analysis of these chemicals. Vapour pressures power its outstanding separation performance, allowing for precise identification and quantification of chlorantraniliprole and its many metabolites in even the most complicated environmental samples. When combined with a detector like a mass spectrometer or flame ionisation detector (FID), GC-MS gains increased sensitivity and selectivity for analysing chlorantraniliprole[15]. This makes it the method of choice for scientists investigating chlorantraniliprole's existence and behaviour in environmental samples, especially when dealing with the chemical's flammability.

Capillary Electrophoresis (CE)

The examination of chlorantraniliprole and its metabolites is aided greatly by the use of capillary electrophoresis (CE) because of its many benefits. CE offers a strong platform for the isolation and quantification of chlorantraniliprole and related compounds, especially when working with charged or polar analytes. CE separates compounds based on their electrophoretic mobility by using an electric

field to drive ions through a small capillary filled with an electrolyte solution [16]. The primary benefit of this approach is its high separation efficiency, which enables the separation of structurally similar molecules, such as chlorantraniliprole metabolites. Chlorantraniliprole's behavior and change in soil, water, and plant tissues may be studied using CE because of the method's proficiency in ionic species analysis. Researchers interested in learning more about the presence and fate of chlorantraniliprole and its metabolites in environmental relevant materials may find CE to be a useful tool due to its effective handling of charged species and its possible adaption to diverse detection techniques [17].

Immunoassay-based Methods

Methods based on immunoassays are analytical procedures in which antibodies are used to bind specifically to substances of interest, such as chlorantraniliprole and its metabolites. These techniques use antibodies that have been engineered to recognise and bind to chlorantraniliprole or its metabolites in the context of chlorantraniliprole analysis [18]. The formation of antibody-antigen complexes, which may be measured or detected using colorimetric, fluorescence, or chemiluminescence signals, occurs when these antibodies come into contact with the target chemicals in a sample. The simplicity, speed, and user-friendliness of immunoassays make them ideal for the quick screening of environmental samples. Preliminary analytical approaches may help with the first evaluation of chlorantraniliprole and its metabolites in environmental samples [19], but they may not give the same degree of sensitivity and specificity as chromatographic or mass spectrometric procedures.

Electrochemical Methods

To detect and quantify analytes, such as chlorantraniliprole and its metabolites, electrodes are used in electrochemical techniques. Electrochemical reactions between analytes and electrodes create electrical signals proportional to the concentration of target chemicals, and hence form the basis of these techniques [20]. Analysis of chlorantraniliprole and its metabolites may be conducted using electrochemical techniques, which can offer quantitative data on their existence and concentration. These techniques are highly regarded because to their ease of use, low cost, and potential for use in the field. Their sensitivity and selectivity may vary depending on the electrochemical approach used [21], but they may be especially helpful when fast on-site observations are needed.

Spectroscopic Techniques

Chlorantraniliprole and its metabolites may be better understood by spectroscopic methods including UV-Visible and infrared (IR) spectroscopy. The existence and concentration of chromophores may be determined by UV-Visible spectroscopy, which analyses the absorption of light at various wavelengths. However, IR spectroscopy examines how infrared light is absorbed and vibrated by molecule interactions to provide information about functional groups and chemical structure [27]. These methods may not be as precise as chromatographic or mass spectrometric approaches, but they are useful for a quick, qualitative screening of environmental materials for chlorantraniliprole and its metabolites. Spectroscopic methods may quickly analyse the presence of these chemicals in different matrices by providing data and insights into their chemical properties [28].

Sample Preparation and Extraction Techniques

A. Solid-Phase Extraction (SPE)

The study of chlorantraniliprole and its metabolites from complicated environmental matrices often makes use of Solid-Phase Extraction (SPE), an essential sample preparation and extraction method. When preparing these substances for chromatographic or mass spectrometric analysis, SPE is especially helpful since it allows for their isolation, concentration, and purification. Chlorantraniliprole solid-phase extraction (SPE) entails running a liquid sample through a solid-phase cartridge or column filled with a specialised sorbent material, such as soil extract, water, or plant tissue extract. To remove unwanted matrix components while selectively retaining chlorantraniliprole and its metabolites, this material may be washed. Chlorantraniliprole and its metabolites are efficiently separated from the interfering compounds by loading the sample onto the SPE column and then using a succession of solvents with different polarity to elute the analytes of interest. This procedure yields a highly pure extract, ideal for sensitive and precise measurement using equipment like high-performance liquid chromatography-gas chromatography mass spectrometry (HPLC-GC-MS). Chlorantraniliprole analysis in environmental samples is more accurate and reliable when SPE is used because it lowers matrix effects and allows for lower detection thresholds [30].

B. Liquid-Liquid Extraction (LLE)

For the purpose of analysing chlorantraniliprole and its metabolites in a wide range of environmental matrices, the tried-and-true sample preparation method of Liquid-Liquid Extraction (LLE) is routinely used. LLE involves combining an immiscible solvent with a high affinity for the target chemicals with a liquid sample containing chlorantraniliprole and its metabolites, such as an extract of soil or water [31]. The analytes of interest, including chlorantraniliprole, preferentially migrate into the solvent phase during the partitioning process between the two immiscible phases. Distinctions in solubility and partition coefficients are responsible for this split. Separating the solvent phase, evaporating it, and reconstituting the residue are the next steps in partitioning followed by analysis. LLE is a flexible and well-established extraction method that has been successfully used to the isolation of chlorantraniliprole and its metabolites prior to chromatographic or mass spectrometric analysis [32].

QuEChERS (Quick, Easy, Cheap, Effective, Rugged, and Safe) Method: In order to detect chlorantraniliprole and its metabolites in soil and water samples, the QuEChERS technique has become standard practise. It provides a simple and quick method of obtaining and processing samples for analysis [33]. The first stage includes mixing the sample with a solvent containing salts that help partition chlorantraniliprole and its metabolites into the solvent phase; the second step involves mixing the sample with an organic solvent to further extract the analytes. Dispersive solid-phase extraction (d-SPE) is often used as a post-extraction cleaning step for removing matrix interferences. QuEChERS is widely used for pesticide residue analysis owing to its reputation for being quick, easy, and successful at extracting chlorantraniliprole and its metabolites from complicated matrices [34].

Soxhlet Extraction: Soxhlet extraction is a time-honored method for removing chlorantraniliprole and its metabolites from soil and plant tissue samples. An organic solvent is continually refluxed and condensed over a sample in a thimble, a technique known as Soxhlet extraction [35]. Chlorantraniliprole and its metabolites are removed from the sample when the solvent evaporates and condenses. In a separate flask, the extracted analytes wait to be concentrated and reconstituted before being analysed. Although Soxhlet extraction is well-known for its efficiency, it is not well-suited for high-throughput applications since it takes a long time and uses a lot of solvent [36].

Accelerated Solvent Extraction (ASE): Chlorantraniliprole and its metabolites are especially amenable to extraction from solid materials using the cutting-edge and automated extraction method of Accelerated Solvent Extraction (ASE). In ASE, the extraction process is sped up with the use of high pressure and temperature [37]. The sample is placed in a cell, and a solvent is injected into the cell, where it permeates the sample matrix and dissolves the analytes of interest in a controlled environment. The pressurised environment allows for effective extraction with little solvent use. The analytes are concentrated and analysed once the solvent has been recovered during the extraction process. ASE is advantageous in chlorantraniliprole analysis due to its rapid processing time, low solvent consumption, and high throughput capacity [38].

Microwave-Assisted Extraction (MAE): Extracting chlorantraniliprole and its metabolites from solid materials is made easier by using the sample preparation method of Microwave-Assisted Extraction (MAE). Microwave-assisted extraction (MAE) involves placing the sample and the appropriate solvent in a sealed container and heating the container in a microwave oven [39]. Rapid extraction may be achieved because microwave radiation increases solubility and diffusion of analytes into the solvent. Fast extraction times, decreased solvent use, and improved extraction efficiency are all hallmarks of MAE. In chlorantraniliprole analysis, it is used to increase extraction yields and decrease analysis time, both of which are very helpful when dealing with difficult sample matrices [40]. Different kinds of samples provide unique obstacles for pesticide residue analysis, and different preparation and extraction methods may be used to successfully isolate chlorantraniliprole and its metabolites from complex environmental matrices.

Environmental Fate of Chlorantraniliprole and Its Metabolites

A. Transformation Pathways in Soil

Chlorantraniliprole and its metabolites have the potential to have significant effects on ecosystems, making it essential to learn more about their environmental destiny. The ultimate destiny of these chemicals may be affected by a number of different transformation processes in soil[41-47]:

One major chlorantraniliprole transformation route in soil is hydrolysis. Chlorantraniliprole and its metabolites undergo a chemical reaction when water molecules are introduced. In order to make the parent molecule and its metabolites safer and less harmful to the environment, hydrolysis might result in the development of many different degradation products. Soil pH, temperature, and moisture content may all affect the particular breakdown products and the rate of hydrolysis.

Second, chlorantraniliprole and its metabolites break down when exposed to sunshine (ultraviolet radiation), a process known as photodegradation. New degradation products may be formed as a consequence of the breakage of chemical bonds within the molecules. Factors such as the compound's chemical structure, soil type, and sunshine intensity might affect the pace and amount of photodegradation. Chlorantraniliprole and its metabolites in soil may be degraded mostly by photodegradation in sunny locations.

Decomposition by Microorganisms Soil ecosystems rely heavily on microbial decomposition of chlorantraniliprole and its metabolites. These chemicals may be metabolised by microorganisms in the soil for carbon and energy. Enzymatic processes in this biodegradation process convert chlorantraniliprole and its metabolites into structurally simpler and less hazardous molecules. Soil microbial populations, temperature, moisture, and the availability of adequate carbon and energy sources all have a role in the pace and efficiency of microbial decomposition. The fate and persistence of chlorantraniliprole and its metabolites in the environment are mostly determined by the processes that occur in soil, such as hydrolysis, photodegradation, and microbial degradation. The environmental risk associated with chlorantraniliprole usage can only be accurately assessed, and effective methods for its sustainable management in agriculture and other uses can only be created, if the processes involved are well understood.

B. Role in Water Systems

In order to assess the environmental effect and dangers associated with chlorantraniliprole and its metabolites, it is crucial to understand where they go in water systems, such as surface water and groundwater [48-50].

One source of chlorantraniliprole and its metabolites getting into water supplies is runoff from treated fields or spills. There is uncertainty about what will happen to these substances once they reach the surface water. Chlorantraniliprole and its metabolites may be degraded in water by many mechanisms, including hydrolysis. In the higher layers of aquatic bodies, sunlight may also cause photodegradation [51]. varying degradation products with possibly varying environmental qualities may be formed throughout these processes. Surface water conditions, such as temperature, pH, and the presence of other chemicals, may all affect the destiny of chlorantraniliprole and its metabolites. In order to evaluate possible ecological repercussions and take appropriate mitigation measures, it is essential to have a firm grasp of their behaviour in surface water [52-54].

It is possible that chlorantraniliprole and its metabolites might seep into groundwater from treated fields, especially in areas with porous soils. The destiny of these chemicals after they enter groundwater is determined by a number of variables, such as their chemical composition and the features of the aquifer. Hydrolysis may take place in groundwater; however, it might be slower than in surface water owing to the differing circumstances there [55]. Chlorantraniliprole's destiny in groundwater is complicated by a number of factors, one of which being its potential immobility due to sorption to soil particles. In order to evaluate the possible dangers to drinking water sources and ecosystems, it is essential to monitor and understand the permanence and mobility of chlorantraniliprole and its metabolites in groundwater. There is a complicated interaction between chemical and environmental parameters that determines the final destination of chlorantraniliprole and its metabolites in both surface water and groundwater systems. Understanding these mechanisms is crucial for conducting accurate environmental risk assessments and coming up with workable management practises to lessen the chances of water pollution and ecological damage [56].

C.Uptake and Translocation in Plants

Important mechanisms that influence the movement of pesticides like chlorantraniliprole throughout plant tissues and their possible impacts on the plant and consumers include absorption and translocation. Here's how those processes work:

Uptake in Plants [55-57]

The main entry point for chlorantraniliprole into plants is via their roots. Roots of plants may take up chlorantraniliprole from the ground or water supply if it is present. Depending on the physicochemical features of the pesticide, either passive or active transport systems may be involved in the absorption process. Concentration gradients propel chlorantraniliprole over the root cell membranes and into the plant, where it is taken up passively. By contrast, chlorantraniliprole must be actively pumped into the plant through a concentration gradient via specialised transport proteins in the root cells. Root absorption is affected by a wide variety of variables, including soil type, moisture, pesticide dosage, and plant species.

Chlorantraniliprole, once absorbed by the roots, is carried throughout the plant through the xylem and phloem, the two primary vascular tissues[58-64].

Chlorantraniliprole travels predominantly via the xylem as it makes its way upward through the plant. Transpiration is the driving force behind this movement as water is moved from the soil to the leaves where it may evaporate. Chlorantraniliprole may be transported by water up the plant, where it will be applied to the stems, leaves, and fruits as they develop above ground.

Chlorantraniliprole and its metabolites may also travel via the phloem to reach other parts of the plant. Sugars and nutrients created by photosynthesis are transported by the phloem. Translocation of chlorantraniliprole from the nutrient stream to other plant tissues, such as fruits or grains, is possible.

Challenges and Limitations in Analyzing Chlorantraniliprole and Its Metabolites:

A. Matrix effect: Interference from other substances in the sample matrix (such as soil, water, or plant tissues) may be detected and corrected for in the analysis of chlorantraniliprole and its metabolites; this phenomenon is known as a matrix effect. These matrix elements may either attenuate or amplify the signal, so influencing the reliability of the analysis. In order to reduce matrix effects and produce accurate results, it is generally necessary to use proper sample preparation and cleaning techniques [65].

B. Analyte Stability: Chlorantraniliprole and its metabolites may degrade during sample collection, storage, and analysis, which brings up point. Changes in temperature, pH, and light may all affect their durability. To get reliable results from analytical procedures, it is crucial to keep these chemicals in tact [66].

C. Sensitivity and Selectivity: When analysing chlorantraniliprole and its metabolites, achieving appropriate sensitivity and selectivity is critical, particularly when working with trace levels in complex matrices. The analytical approach must be sensitive enough to detect low quantities of chlorantraniliprole and its metabolites while also being selective enough to identify and quantify these compounds without interference from other chemicals in the sample [67].

D. Trace Level Detection: Chlorantraniliprole residues in the environment are notoriously difficult to detect and quantify because of their low concentrations. To properly assess very tiny quantities, analytical procedures need to be extremely sensitive [68].

Environmental monitoring and risk assessment studies rely heavily on the rapid and accurate analysis of a large number of samples. Factors such as the difficulty of sample preparation and the length of time needed for analysis might slow down processes with a high throughput of samples. Finding a happy medium between speed and precision in analysis is crucial [69].

To overcome these obstacles, analytical chemists and environmental scientists use sophisticated tools like high-resolution mass spectrometers and methods that involve careful method development and validation, sample preparation that minimises matrix effects, and the use of stable isotope-labeled internal standards for quantification. To further maintain the safety of ecosystems and human health, chlorantraniliprole analysis in environmental samples has improved in accuracy, sensitivity, and efficiency because to continuing research and developments in analytical technology.

Case Studies and Applications

Chlorantraniliprole's destiny in a rice field ecosystem was investigated in depth, leading to the development of a reliable analytical technique for quantifying chlorantraniliprole concentrations in a wide range of environmental samples, such as soil, rice straw, paddy water, and brown rice. The QuEChERS (Quick, Easy, Cheap, Effective, Rugged, and Safe) approach was used for cleaning after acetonitrile extraction of chlorantraniliprole residues in the analytical procedure. After that, chlorantraniprole concentrations were determined by using high-performance liquid chromatography electrospray ionisation tandem mass spectrometry (LC-ESI-MS/MS). Soil, rice straw, paddy water, and brown rice samples all showed high levels of recovery using this approach, with averages between 76.9% and 103.1%. In every case, the relative standard deviation was less than 15%. Chlorantraniliprole's LODs in paddy water, soil, brown rice, and rice straw were all found to be 0.012 µg L^{-1}; 0.15 µg kg^{-1}; and 0.1µg kg^{-1}, respectively. Degradation kinetics of chlorantraniliprole residues in soil, water, and rice straw were also studied in this study. Degradation rates may be represented by the formulae $C = 0.01939e^{-0.0434t}$ for soil, $C = 0.01425e^{-0.8111t}$ for water, and $C = 1.171e^{-0.198t}$ for rice straw, each of which exhibits a unique pattern of behaviour. The half-lives corresponding to these equations were around 16.0 days, 0.85 days, and 3.50 days. Degradation was quickest in water, then in rice straw. Importantly, following a 14-day Pre-Harvest Interval (PHI), the final chlorantraniliprole residues measured in brown rice were considerably below the maximum

residue limit (MRL) of 0.02 mg kg−1. Therefore, it was suggested that a dose of 150 mL a.i.hm-2 be used to guarantee the safety of human and animal consumers alike. This study provides valuable insight into the ecological effects of chlorantraniliprole in rice fields and encourages the use of safe farming methods [70].

An effective and long-lasting adsorbent for detoxifying water of toxic pesticides was the topic of one research. Using aluminium chloride hexahydrate and tetrakis (4-carboxyphenyl) porphyrin as monomers, and with the aid of cetyltrimethylammonium bromide, scientists were able to create water-stable metal-organic framework (MOF) nanosheets termed Al-TCPP nanosheets. The Al-TCPP nanosheets were shown to be superior to bulk crystals in terms of their water stability, hydrophilicity, and porous structure (1359 m2 g−1. The greatest adsorption capacity of this structure for chlorantraniliprole was 371.91 mg g−1, which is much higher than the 222.11 mg g−1 achieved by using bulk crystals. Because of their hierarchical porosity structure and larger number of active sites, nanosheets are able to boost adsorption efficiency. The findings of this study support the use of MOF nanosheets in water treatment procedures as a promising material for the removal of harmful contaminants [71].

Chlorantraniliprole (CTP) was tested in a laboratory setting to see how quickly it degrades in two distinct soils, and its effects on soil microorganisms were studied in terms of population, microbial biomass carbon, and soil enzyme activity. Chlorantraniliprole residues treated at the RD of 40 g a.i./ha were not detectable in either alluvial soil or red soil after 60 days of incubation in microcosm research. Alluvial soil has a longer half-life for chlorantraniliprole than red soil does because of its greater clay content. Under laboratory circumstances, chlorantraniliprole was still not recoverable from the RD treatment 30 days after application. Chlorantraniliprole's half-lives in rice rhizosphere soil were significantly shorter for RD and DRD treatments, at 23.89 and 34.65 days, respectively. Soil microorganisms such as actinomycetes, fungi, biological nitrogen fixers, and phosphate-solubilizing bacteria were mostly unaffected by chlorantraniliprole at varying concentrations; nevertheless, the bacterial population was altered. Dehydrogenase, fluorescein diacetate hydrolase, acid, and alkaline phosphatase activities were all lowest in the DRD therapy, with the RD treatment coming in a close second. Carbon, -glycosidase, and urease levels in microbial biomass were not significantly different at varied CTP concentrations. Since soil microorganisms were unaffected by the RD treatment, chlorantraniliprole may be suggested for managing rice pests without reducing the activities of existing soil microbes and soil enzymes [72].

Using high-throughput sequencing, we looked at how different concentrations of CAP (Chlorantraniliprole) affected the microbial populations in soil. Our research showed that the number of different types of bacteria and fungus in the soil did not change significantly after CAP was applied. The structure of these societies was, however, affected. Soil bacterial and fungal populations were most variable in the low CAP concentration treatment group. We found that the bacterial phylum composition changed at 115 days and the fungal phylum composition changed at 175 days, as compared to the original condition (0 days). This points to a crucial connection between the diversity of soil microbes and CAP decomposition. Total Nitrogen (TN), Total Phosphorus (TP), and Nitrate Nitrogen (NO3-N) were the soil parameters that showed the strongest association with changes in the composition of microbial communities. These results provide essential information for advancing our understanding of the effects of pesticides on ecosystems and the methods for cleaning up polluted ground [73].

Two transformation byproducts derived from chlorantraniliprole in soil were the subject of another investigation for a full analysis. These byproducts were effectively identified as the results of dechlorination (referred to as Z1) and bromination (referred to as Z2) using nuclear magnetic resonance and high-resolution mass spectrometry. The half-lives of Z1 and Z2 in soil were determined to be 38 and 43 days, respectively, compared to 58 days for chlorantraniliprole, a significant result from the kinetic studies. In addition, we evaluated the ecological threat that chlorantraniliprole and its metabolites provide to the microorganisms in the soil. All of these chemicals were shown to be potentially harmful after further investigation, with varying effects on bacterial alpha and beta diversity and co-occurrence networks. Notably, Z2 was shown to be the byproduct most likely to have a major effect on soil bacteria, indicating a high-risk profile. The relevance of evaluating the environmental repercussions of a chemical and its transformation byproducts in ecological risk assessment procedures by comparing the impacts of these compounds on the soil bacterial community was highlighted [73].

Future Perspectives

Emerging methodologies and technology offer considerable potential for the future of chlorantraniliprole and pesticide analysis. The increased availability and simplicity of high-resolution

mass spectrometry and nuclear magnetic resonance spectroscopy should help scientists learn more about chlorantraniliprole and its metabolites as they move through different types of environments. The use of machine learning and AI together may improve data processing, leading to faster discovery of degradation routes and forecasting of environmental effects. Innovative methods for real-time monitoring of pesticide residues might be provided by nanotechnology and sensor-based technologies, leading to more effective and sustainable pest control. We will learn much more about how chlorantraniliprole affects the environment if we use omics methods like genomics, proteomics, metabolomics, and metagenomics. These methods have the potential to elucidate the genetic and metabolic responses of chlorantraniliprole-exposed species, hence providing clues as to possible biomarkers and causes of toxicity. In addition, metagenomic investigations can provide us a complete picture of the microbial communities in pesticide-contaminated settings, illuminating the roles these communities play in pesticide breakdown and bioremediation. Chlorantraniliprole's effects on the environment may be understood in their entirety if omics data is combined with more conventional methods of analysis. As environmental protection becomes more of a priority, scientists will work to perfect eco-friendly techniques for analysing chlorantraniliprole. Microwave-assisted extraction and supercritical fluid extraction are two environmentally friendly sample preparation methods that will get more attention from scientists. The usage of sustainable and biodegradable analytical reagents and materials will also gain prominence. There will be a marked increase in the availability of miniaturised and portable analytical instruments, allowing for more on-site pesticide monitoring and decreasing the need to carry samples to centralised labs. Green chemistry concepts will inform the development of future analytical procedures, reducing negative effects on the environment. Emerging technology, integrated omics approaches, and sustainable analytical methodologies are driving interesting improvements in chlorantraniliprole analysis and pesticide research in the future. These developments will not only improve our knowledge of chlorantraniliprole's environmental destiny and effect, but also lead to less harmful and more long-lasting methods of pest control.

4. Conclusion

In conclusion, the importance of understanding the behaviour and effects of pesticide use in our ecosystems is shown by this article's in-depth analysis of chlorantraniliprole and its environmental impact. Chlorantraniliprole's destiny, degradation processes, and ecological hazards have been dissected using cutting-edge technology and rigorous analytic approaches. The necessity for accurate and sensitive analytical methods has been brought to light by studies of chlorantraniliprole and its metabolites in soil, water, and plants. Methods including chromatography, mass spectrometry, and capillary electrophoresis have played crucial roles in this direction, giving scientists a way to evaluate chlorantraniliprole's presence and effect with more precision. Potential ecological dangers have also been shown by research into the impacts of chlorantraniliprole on soil microorganisms and the appearance of transformation byproducts. Recognising the effects of byproducts on environmental dynamics and understanding how changes in microbial populations affect soil health are both essential. The analysis of chlorantraniliprole has great potential in the future. New methods of monitoring and evaluating pesticide performance are on the horizon, thanks to developments in areas like as enhanced mass spectrometry, artificial intelligence, and nanotechnology. Understanding the function of chlorantraniliprole in agriculture and ecosystems will be facilitated by the incorporation of omics methodologies and the development of sustainable, eco-friendly analytical tools. Learning more about chlorantraniliprole and other herbicides is crucial for moving ahead. This information will help us safeguard our environment and maintain healthy ecosystems, as well as guide safer and more sustainable pest control practises. More study and creativity will bring us closer to a future where farming and nature may live in peace.

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