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Agrochemical mixture compatibility for UAV and conventional sprayers in maize: bridging precision and practicality

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ABSTRACT

Efficient pesticide delivery in maize (Zea mays L.) using Unmanned Aerial Vehicles (UAVs) necessitates a comprehensive assessment of agrochemical compatibility under diverse field conditions. This study investigated the physical and chemical compatibility of commonly used insecticides Chlorantraniliprole 18.5% SC, Spinetoram 11.7% SC, and Emamectin benzoate 5% SG and fungicides Azoxystrobin 18.2% + Difenoconazole 11.4% SC and Tebuconazole 50% + Trifloxystrobin 25% WG applied alone and in binary mixtures using UAV-based ultra-low volume (ULV) and Taiwan sprayer-based high-volume protocols. Compatibility was evaluated across four water sources: deionized distilled water (DDW), tap, canal, and bore water. Over 90% of treatment combinations exhibited excellent physical stability with minimal coagulation, sedimentation, or foam formation. Emamectin benzoate showed moderate sedimentation under UAV concentrations (2.2–3.1 mL/L) but was redispersible upon agitation. Chemical profiling of spray solutions revealed that water quality significantly influenced pH stability. Chlorantraniliprole displayed consistent buffering (pH 7.10–7.62), maintaining formulation integrity. Spinetoram demonstrated a mildly alkaline profile (7.40–7.91), while Emamectin benzoate preserved an acidic environment (6.28–6.72), potentially minimizing hydrolytic degradation. Notably, mixtures containing Tebuconazole + Trifloxystrobin occasionally surpassed pH 8.5, indicating the need for pH modulation. These results underscore the importance of water chemistry and formulation interactions in UAV-enabled pesticide delivery. The study offers a strategic framework for selecting UAV-compatible agrochemical mixtures, contributing to precision application, reduced formulation failure, and enhanced sustainability in crop protection systems.

Keywords: *Drone-assisted pesticide application; Formulation pH stability; Water quality influence; Spinosyn insecticides; Avermectin stability; Alkaline hydrolysis etc.*

1. Introduction

Maize (*Zea mays* L.) is a cornerstone crop of global agriculture, cultivated over 200 million hectares worldwide and serving as a critical source of food, feed, and industrial raw material. In India, maize occupies around 10.88 million hectares, with an estimated production of 42.28 million tonnes in 2024–25. However, the national average yield (3.5 t/ha) remains below the global average due to a multitude of biotic and abiotic stresses (1& 2). Among the biotic threats, the Fall Armyworm (*Spodoptera frugiperda*), an invasive lepidopteran pest, has emerged as a major challenge since its first detection in India in 2018. It is known to cause yield losses ranging from 28–50% in maize, necessitating timely and effective pest management interventions (3-5). Conventionally, plant protection in maize involves ground-based spraying, which is often laborious, inefficient, and hazardous due to operator exposure and non-uniform deposition (6). The increasing complexity of pest dynamics and environmental concerns demands precision-based, technology-driven solutions.(7) demonstrated that UAV-based pesticide applications in almond orchards provided effective spray deposition and canopy penetration, comparable to conventional air-blast spraying methods.

In this context, drone-assisted pesticide application has gained momentum as a core component of smart and climate-resilient agriculture. Unmanned Aerial Vehicles (UAVs) enable efficient, site-specific delivery of agrochemicals with minimal resource use and exposure risks. As noted by (8-9), the global agricultural drone market is projected to reach USD 23.78 billion by 2032, underscoring its pivotal role in crop protection. In India, initiatives like the Kisan Drone Program have catalyzed adoption, providing a platform for scalable, eco-friendly plant protection practices (10). The increasing adoption of UAVs in crop protection highlights the need for optimized spray volumes and delivery precision, as illustrated by (11), who validated the CitrusVol tool for efficient pesticide application against aphids in citrus. Preliminary investigations have focused on establishing robust Standard Operating Procedures (SOPs) for drone-based spraying, optimizing parameters such as flight altitude, speed, nozzle type, and spray volume to ensure adequate canopy penetration and uniform deposition of active ingredients (12-14). Despite their potential, drones impose unique physicochemical challenges in pesticide delivery. The physical compatibility of tank mixes, particularly insecticides and fungicides at specific dilutions, must be optimized to prevent issues such as sedimentation, flocculation, nozzle clogging, and efficacy loss (15-16).

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Further, pH sensitivity of pesticides, especially biologicals and spinosyn-based formulations, directly influences their stability and performance. Recent studies by (17) developed Standard Operating Protocols (SOPs) for drone-based pesticide applications in cotton, emphasizing the critical need for compatibility evaluation under aerial spray conditions.

Considering these gaps, the present study investigates the physicochemical compatibility and pH behavior of selected insecticide and fungicide combinations under drone and Taiwan sprayer dilutions, using distilled, tap, canal and bore water as carriers. This research builds a framework for standardizing drone-compatible mixtures for effective pest and disease management in maize, ultimately contributing to safe, sustainable intensification of crop protection practices.

2. Materials and methods

2.1. Location of the study: The present investigation was carried out at the Maize Research Centre, Agricultural Research Institute, and the Department of Entomology, Professor Jayashankar Telangana Agricultural University (PJTAU), Rajendranagar, Hyderabad. These research facilities provided the necessary infrastructure and technical support to conduct comprehensive entomological studies under both laboratory and field conditions, thereby ensuring the generation of scientifically valid and region-specific data.

2. 2. Physical compatibility studies: The physical compatibility of five individual pesticides comprising three insecticides and two fungicides and their six binary combinations, prepared at concentrations recommended for drone and Taiwan sprayer applications (Table.1), was evaluated through a standardized jar compatibility test. Each mixture was prepared using 500 mL of pesticide solution in different water sources, including double-distilled water (DDW), tap water, borewell water from the field, and canal water, to assess the influence of water quality on formulation stability. Observations were recorded at 0.5 and 2 hours after preparation for pH and key physical parameters such as color change, wettability, clumping, and precipitate formation, thereby providing a comprehensive assessment of the physical compatibility of the pesticide mixtures under varying water conditions and application technologies. As per the guidelines of the Central Insecticide Board and Registration Committee (18) (http://ppqs.gov.in/divisions/cib-rc/major-uses-of-pesticides), the recommended per-hectare dosage of pesticides is based on a dilution volume of 375 litres of water for conventional application using a Taiwan sprayer and 36.75 litres for drone-assisted application. In the present study, treatments were categorized accordingly, with "D" denoting drone application concentrations and "T" representing Taiwan sprayer application concentrations.

Table 1. The details of the treatments and the respective dosages of the pesticide molecules used in the study are presented

Tr. No.	Treatments	Dose (g or ml/L)
T1D	Chlorantraniliprole 18.5% SC	5.44 ml/L
T2D	Spinetoram 11.7% SC	6.80 ml/L
T3D	Emamectin benzoate 5% SG	6.80 g/L
T4D	Azoxystrobin 18.2% + Difenoconazole 11.4% SC	13.60 ml/L
T5D	Tebuconazole 50%+ Trifloxystrobin 25% w/w WG (75 WG)	6.80 g/L
T6D	Chlorantraniliprole 18.5% SC+ Azoxystrobin 18.2% + Difenoconazole 11.4% SC	5.44 ml/L + 13.60 ml/L
T7D	Chlorantraniliprole 18.5% SC + Tebuconazole 50%+ Trifloxystrobin 25% w/w WG (75 WG)	5.44 ml/L + 6.80 g/L
T8D	Spinetoram 11.7% SC+ Azoxystrobin 18.2% + Difenoconazole 11.4% SC	6.80 ml/L +13.60 ml/L
T9D	Spinetoram 11.7% SC+ Tebuconazole 50%+ Trifloxystrobin 25% w/w WG (75 WG)	6.80 ml/L +6.80 g/L
T10D	Emamectin benzoate 5% SG+ Azoxystrobin 18.2% + Difenoconazole 11.4% SC	6.80 g/L+13.60 ml/L
T11D	Emamectin benzoate 5% SG+ Tebuconazole 50%+ Trifloxystrobin 25% w/w WG (75 WG)	6.80 g/L+ 6.80 g/L
T12T	Chlorantraniliprole 18.5% SC	0.53 ml/L
T13T	Spinetoram 11.7% SC	0.67 ml/L
T14T	Emamectin benzoate 5% SG	0.67 g/L
T15T	Azoxystrobin 18.2% + Difenoconazole 11.4% SC	1.33 ml/L
T16T	Tebuconazole 50%+ Trifloxystrobin 25% w/w WG (75 WG)	0.66 g/L
T17T	Chlorantraniliprole 18.5% SC+ Azoxystrobin 18.2% + Difenoconazole 11.4% SC	0.53 ml/L+1.33 ml/L
T18T	Chlorantraniliprole 18.5% SC + Tebuconazole 50%+ Trifloxystrobin 25% w/w WG (75 WG)	0.53 ml/L+0.66 g/L
T19T	Spinetoram 11.7% SC+ Azoxystrobin 18.2% + Difenoconazole 11.4% SC	0.67 ml/L+1.33 ml/L
T20T	Spinetoram 11.7% SC+ Tebuconazole 50%+ Trifloxystrobin 25% w/w WG (75 WG)	0.67 ml/L+0.66 g/L
T21T	Emamectin benzoate 5% SG+ Azoxystrobin 18.2% + Difenoconazole 11.4% SC	0.67 g/L+1.33 ml/L
T22T	Emamectin benzoate 5% SG+ Tebuconazole 50%+ Trifloxystrobin 25% w/w WG (75 WG)	0.67 g/L+0.66 g/L
T23	Untreated Control	-

2.3. Assessment of Sedimentation Volume and Physical Compatibility: The sedimentation volume of each pesticide mixture was assessed as a key indicator of physical compatibility, following standard procedures outlined by the Central Insecticides Board and Registration Committee (CIB&RC) and the methodology described by (19). After preparation, the mixtures were allowed to stand undisturbed, and the sedimentation volume was measured in millilitres per litre (ml/L). Based on the sedimentation range, the mixtures were classified as follows: 0–2.0 ml/L indicated physical compatibility with excellent suspension and minimal settling; 2.1–4.0 ml/L denoted moderate compatibility with some settling but easy re-suspension; and values exceeding 4.0 ml/L were considered physically incompatible due to excessive settling, which could lead to nozzle clogging and uneven spray application. Following this classification, observations on sedimentation volume, pH, and other physical parameters were systematically recorded for each treatment.

2.4. Evaluation of Foaming Characteristics of Pesticide Mixtures: Foaming behavior of the pesticide mixtures was evaluated to assess their suitability for field application using drone and Taiwan sprayer systems. Foam height was measured in millilitres per litre (ml/L) immediately after agitation, and the level of foaming was interpreted based on standard thresholds to determine operational safety and compatibility as per (CIB&RC). Excessive foaming can hinder uniform application, interfere with mixing, and potentially damage spraying equipment, whereas minimal to moderate foaming is considered acceptable for practical use mentioned in (Table.2).

Table.2.Foaming Range (ml/L)

Foam Height (ml/L)	Interpretation
0 – 25 ml/L	**Acceptable** – Minimal foaming, safe for sprayer operation.
26 – 50 ml/L	**Cautionary** – Moderate foaming, could affect mixing/agitation.
> 50 ml/L	**Unacceptable** – Excessive foam may interfere with uniform application and damage equipment.

2.5. pH values of various water sources: The pH values of various water sources used for pesticide dilution, prior to mixing with pesticide formulations, are presented in Table 3. These values varied based on the origin and quality of the water. These pH values were systematically categorized according to the classification system outlined by (20).

Table.3. General pH of Different Water Sources

Water Type	Typical pH Range	Remarks
Double Distilled Water	5.5 – 6.5	Slightly acidic due to CO_2 absorption from air
Tap Water	6.5 – 7.0	Depends on municipal treatment and pipe materials
Bore Water (Groundwater)	6.0 – 8.5	Varies with local geology and mineral content
Canal Water	6.5 – 9.0	Influenced by agricultural runoff and organic load

3. Results

3.1. Physical Compatibility Results from Jar Test Analysis

3.1.1. Individual insecticide Compatibility: The jar test analysis demonstrated that most individual pesticide formulations exhibited excellent physical compatibility across all application rates and water sources evaluated. Chlorantraniliprole 18.5% SC was fully compatible at both the drone rate (5.44 mL/L) and the Taiwan sprayer rate (0.53 mL/L), with no evidence of sedimentation or foam formation in any of the tested water types double-distilled water (DDW), tap water, borewell water, and canal water. Similarly, Spinetoram 11.7% SC showed complete compatibility at 6.80 mL/L (drone rate) and 0.67 mL/L (Taiwan rate), forming clear and stable solutions devoid of any physical incompatibility symptoms. Emamectin benzoate 5% SG exhibited moderate compatibility at the drone application rate of 6.80 g/L, producing a sedimentation volume of 3.1 mL/L, although no foam formation was observed (Fig.1). The sediment was easily resuspendable upon mild agitation, indicating acceptable physical behavior under field conditions. At the lower Taiwan sprayer rate of 0.67 g/L, the formulation showed improved compatibility, with only 1.0 mL/L sedimentation, classifying it as physically compatible (Table.4).

Table.4. Jar compatibility or physical compatibility of insecticides and fungicides at drone & Taiwan doses

Tr. No.	Treatments	Dose (g or ml/L)	Sedimentation ml/L (DDW, Tap, Bore & Canal water)	Foaming ml/L (DDW, Tap, Bore & Canal water)	Compatibility Reaction
T1D	Chlorantraniliprole 18.5% SC	5.44 ml/L	**0**	**0**	**Compatible**
T2D	Spinetoram 11.7% SC	6.80 ml/L	**0**	**0**	**Compatible**
T3D	Emamectin benzoate 5% SG	6.80 g/L	**3.1**	**0**	***Moderately compatible Sediment formation is observed at the bottom of the jar; however, the mixture resuspends easily upon agitation.***
T4D	Azoxystrobin 18.2% + Difenoconazole 11.4% SC	13.60 ml/L	**0**	**0**	**Compatible**
T5D	Tebuconazole 50%+ Trifloxystrobin 25% w/w WG (75 WG)	6.80 g/L	**0**	**0**	**Compatible**
T6D	Chlorantraniliprole 18.5% SC+ Azoxystrobin 18.2% + Difenoconazole 11.4% SC	5.44 ml/L + 13.60 ml/L	**0**	**0**	**Compatible**
T7D	Chlorantraniliprole 18.5% SC + Tebuconazole 50%+ Trifloxystrobin 25% w/w WG (75 WG)	5.44 ml/L + 6.80 g/L	**0**	**0**	**Compatible**
T8D	Spinetoram 11.7% SC+ Azoxystrobin 18.2% + Difenoconazole 11.4% SC	6.80 ml/L +13.60 ml/L	**0**	**0**	**Compatible**
T9D	Spinetoram 11.7% SC+ Tebuconazole 50%+ Trifloxystrobin 25% w/w WG (75 WG)	6.80 ml/L +6.80 g/L	**0**	**0**	**Compatible**
T10D	Emamectin benzoate 5% SG+ Azoxystrobin 18.2% + Difenoconazole 11.4% SC	6.80 g/L+13.60 ml/L	**2.2**	**0**	***Moderately compatible Sediment formation is observed at the bottom of the jar; however, the mixture resuspends easily upon agitation.***
T11D	Emamectin benzoate 5% SG+ Tebuconazole 50%+ Trifloxystrobin 25% w/w WG (75 WG)	6.80 g/L+ 6.80 g/L	**2.3**	**0**	
T12T	Chlorantraniliprole 18.5% SC	0.53 ml/L	**0**	**0**	**Compatible**
T13T	Spinetoram 11.7% SC	0.67 ml/L	**0**	**0**	**Compatible**
T14T	Emamectin benzoate 5% SG	0.67 g/L	**1**	**0**	**Compatible**
T15T	Azoxystrobin 18.2% + Difenoconazole 11.4% SC	1.33 ml/L	**0**	**0**	**Compatible**
T16T	Tebuconazole 50%+ Trifloxystrobin 25% w/w WG (75 WG)	0.66 g/L	**0**	**0**	**Compatible**
T17T	Chlorantraniliprole 18.5% SC+ Azoxystrobin 18.2% + Difenoconazole 11.4% SC	0.53 ml/L+1.33 ml/L	**0**	**0**	**Compatible**

T18T	Chlorantraniliprole 18.5% SC + Tebuconazole 50%+ Trifloxystrobin 25% w/w WG (75 WG)	0.53 ml/L+0.66 g/L	**0**	**0**	**Compatible**
T19T	Spinetoram 11.7% SC+ Azoxystrobin 18.2% + Difenoconazole 11.4% SC	0.67 ml/L+1.33 ml/L	**0**	**0**	**Compatible**
T20T	Spinetoram 11.7% SC+ Tebuconazole 50%+ Trifloxystrobin 25% w/w WG (75 WG)	0.67 ml/L+0.66 g/L	**0**	**0**	**Compatible**
T21T	Emamectin benzoate 5% SG+ Azoxystrobin 18.2% + Difenoconazole 11.4% SC	0.67 g/L+1.33 ml/L	**1**	**0**	**Compatible**
T22T	Emamectin benzoate 5% SG+ Tebuconazole 50%+ Trifloxystrobin 25% w/w WG (75 WG)	0.67 g/L+0.66 g/L	**1**	**0**	**Compatible**
T23	Untreated Control	-	**-**	**-**	

Fig.1. Sedimentation formed by the Emamectin benzoate 5% SG in alone & combinations

3.1.2.Fungicide Compatibility: The two tested fungicidal formulations displayed consistent and excellent physical compatibility across all water types and application rates. Azoxystrobin 18.2% + Difenoconazole 11.4% SC remained fully compatible at both drone (13.60 mL/L) and Taiwan (1.33 mL/L) application rates, showing no sedimentation or foam development. Similarly, Tebuconazole 50% + Trifloxystrobin 25% WG (75 WG) exhibited outstanding compatibility at 6.80 g/L (drone rate) and 0.66 g/L (Taiwan rate), maintaining a uniform suspension without phase separation or precipitate formation.

3.1.3Tank-Mix Compatibility: The physical compatibility of binary pesticide combinations largely reflected the behavior of their individual components. Tank mixes involving Chlorantraniliprole and either fungicide (T6D, T7D, T17T, T18T) were completely compatible, with no sediment or foam formation detected at both drone and Taiwan sprayer concentrations. Combinations containing Spinetoram (T8D, T9D, T19T, T20T) also demonstrated excellent physical compatibility, underscoring the formulation's robustness in mixture scenarios.

Tank mixes containing Emamectin benzoate demonstrated moderate compatibility consistent with its individual performance. The combination with Azoxystrobin + Difenoconazole (T10D) showed 2.2 mL/L sedimentation at the drone rate, yet remained acceptable due to ease of resuspension. At the Taiwan rate (T21T), the same combination resulted in 1.0 mL/L sedimentation and was considered fully compatible. The mixture of Emamectin benzoate with Tebuconazole + Trifloxystrobin (T11D) exhibited 2.3 mL/L sedimentation at drone concentrations, while the Taiwan application rate (T22T) resulted in only 1.0 mL/L, both falling within the compatibility threshold suitable for field use.

3.1.4. Effect of Water Source: The compatibility outcomes remained consistent across all tested water sources, including DDW, tap water, borewell water, and canal water. This stability across water qualities indicates that the physical compatibility observed is largely intrinsic to the pesticide formulations themselves and is not significantly influenced by variations in water pH or dissolved constituents, thus supporting their reliable use under diverse field conditions (Table.4).

3.2. Chemical compatibility of Insecticides and Fungicides at Drone and Taiwan doses various water sources

3.2.1. Comprehensive pH-based assessment of chemical stability: A detailed assessment of pesticide chemical compatibility was conducted by evaluating pH responses across four distinct water sources: double-distilled water (DDW), tap water, bore water, and canal water. This analysis revealed that water quality exerted a measurable, though secondary, influence on formulation stability. The overall pH hierarchy remained consistent across all treatments, following the order: bore water > tap water > canal water > DDW (Table.5 & Fig.2). Average pH elevations above DDW were recorded as 0.48 ± 0.15 (bore), 0.39 ± 0.12 (tap), and 0.36 ± 0.11 (canal), indicating that the natural buffering capacity of mineral-rich water sources modulated the chemical environment of the spray solutions.

Table.5. Chemical compatibility of insecticides and fungicides at drone & Taiwan doses with all the four type of water (DDW, Tap, Bore & Canal water)

Tr. No.	Treatments	Dose (g or ml/L)	pH (DDW)	pH (Tap water)	pH (Bore water)	pH (Canal water)
T1D	Chlorantraniliprole 18.5% SC	5.44 ml/L	7.1	7.58	7.62	7.55
T2D	Spinetoram 11.7% SC	6.80 ml/L	7.4	7.82	7.91	7.77
T3D	Emamectin benzoate 5% SG	6.80 g/L	6.28	6.65	6.71	6.62
T4D	Azoxystrobin 18.2% + Difenoconazole 11.4% SC	13.60 ml/L	6.61	6.95	7	6.93
T5D	Tebuconazole 50%+ Trifloxystrobin 25% w/w WG (75 WG)	6.80 g/L	6.57	6.89	6.95	6.86
T6D	Chlorantraniliprole 18.5% SC+ Azoxystrobin 18.2% + Difenoconazole 11.4% SC	5.44 ml/L + 13.60 ml/L	6.77	7.21	7.26	7.18
T7D	Chlorantraniliprole 18.5% SC + Tebuconazole 50%+ Trifloxystrobin 25% w/w WG (75 WG)	5.44 ml/L + 6.80 g/L	8.02	8.41	8.55	8.3
T8D	Spinetoram 11.7% SC+ Azoxystrobin 18.2% + Difenoconazole 11.4% SC	6.80 ml/L +13.60 ml/L	7.07	7.52	7.6	7.47
T9D	Spinetoram 11.7% SC+ Tebuconazole 50%+ Trifloxystrobin 25% w/w WG (75 WG)	6.80 ml/L +6.80 g/L	7.19	7.61	7.67	7.58
T10D	Emamectin benzoate 5% SG+ Azoxystrobin 18.2% + Difenoconazole 11.4% SC	6.80 g/L+13.60 ml/L	6.18	6.6	6.68	6.57
T11D	Emamectin benzoate 5% SG+ Tebuconazole 50%+ Trifloxystrobin 25% w/w WG (75 WG)	6.80 g/L+ 6.80 g/L	7.36	7.72	7.81	7.7
T12T	Chlorantraniliprole 18.5% SC	0.53 ml/L	7.1	7.55	7.6	7.52
T13T	Spinetoram 11.7% SC	0.67 ml/L	7.4	7.85	7.91	7.78
T14T	Emamectin benzoate 5% SG	0.67 g/L	6.28	6.65	6.72	6.61
T15T	Azoxystrobin 18.2% + Difenoconazole 11.4% SC	1.33 ml/L	6.61	6.98	7.01	6.9
T16T	Tebuconazole 50%+ Trifloxystrobin 25% w/w WG (75 WG)	0.66 g/L	6.57	6.91	6.96	6.87
T17T	Chlorantraniliprole 18.5% SC+ Azoxystrobin 18.2% + Difenoconazole 11.4% SC	0.53 ml/L+1.33 ml/L	7.65	8.02	8.1	7.95
T18T	Chlorantraniliprole 18.5% SC + Tebuconazole 50%+ Trifloxystrobin 25% w/w WG (75 WG)	0.53 ml/L+0.66 g/L	6.92	7.35	7.4	7.31
T19T	Spinetoram 11.7% SC+ Azoxystrobin 18.2% + Difenoconazole 11.4% SC	0.67 ml/L+1.33 ml/L	7.03	7.5	7.57	7.45
T20T	Spinetoram 11.7% SC+ Tebuconazole 50%+ Trifloxystrobin 25% w/w WG (75 WG)	0.67 ml/L+0.66 g/L	7.15	7.62	7.68	7.55
T21T	Emamectin benzoate 5% SG+ Azoxystrobin 18.2% + Difenoconazole 11.4% SC	0.67 g/L+1.33 ml/L	6.8	7.16	7.25	7.13
T22T	Emamectin benzoate 5% SG+ Tebuconazole 50%+ Trifloxystrobin 25% w/w WG (75 WG)	0.67 g/L+0.66 g/L	6.87	7.21	7.3	7.19

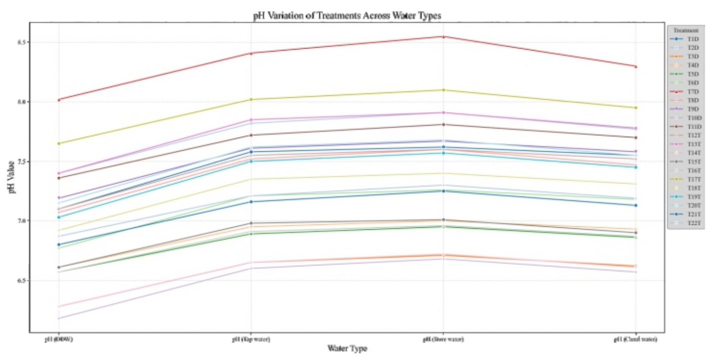

Fig.2. pH variation of treatments across water types

3.2.2. Individual Insecticide Stability Profiles: Chlorantraniliprole 18.5% SC exhibited remarkable formulation stability, with narrow pH ranges observed across both drone (5.44 mL/L) and Taiwan (0.53 mL/L) application rates. The pH remained between 7.10 and 7.62, regardless of water source, indicating a robust buffer system and minimal susceptibility to water-induced pH shifts (ΔpH = 0.52). Spinetoram 11.7% SC displayed the most alkaline pH profile, ranging from 7.40 in DDW to 7.91 in bore water, consistent across both drone (6.80 mL/L) and Taiwan (0.67 mL/L) dilutions. The data suggest optimal stability for spinosyn-class insecticides within a mildly alkaline range.

In contrast, Emamectin benzoate 5% SG demonstrated consistently acidic pH values across all water types (6.28–6.72), reflecting the intrinsic chemical characteristics of the avermectin molecule. This acidic environment is favorable for avermectin stability and mitigates the risk of alkaline hydrolysis.

3.2.3. Fungicide Formulations and Water Source Interactions: The fungicide combinations evaluated showed intermediate pH responses, promoting chemical compatibility with a wide range of insecticides. Azoxystrobin 18.2% + Difenoconazole 11.4% SC maintained a stable pH range of 6.61–7.01 across water sources and application rates, ensuring chemical integrity for both strobilurin and triazole moieties. Tebuconazole 50% + Trifloxystrobin 25% WG demonstrated slightly more acidic responses (6.57–6.96), with the WG formulation providing enhanced buffering capacity. The relatively narrow ΔpH values (0.39) indicate strong resistance to water quality-induced chemical fluctuations.

3.2.4.Tank Mix Interactions and pH Modulation: Binary mixtures revealed complex interactions with non-additive effects on final pH values.

Chlorantraniliprole-based combinations: The Chlorantraniliprole + Azoxystrobin + Difenoconazole combination (T6D, T17T) showed a concentration-dependent shift in pH. Drone applications resulted in pH values of 6.77–7.26, while Taiwan applications showed significantly higher pH (7.65–8.10), suggesting dilution-dependent chemical interaction mechanisms. The Chlorantraniliprole + Tebuconazole + Trifloxystrobin mixture (T7D) recorded the most alkaline conditions observed (8.02–8.55), indicating synergistic pH elevation. This may present a risk for instability or phytotoxicity, particularly under high pH-sensitive conditions, and may necessitate corrective pH adjustment application.

Emamectin-based combinations: Tank mixtures containing Emamectin benzoate exhibited formulation-dominant pH control. The Emamectin + Azoxystrobin + Difenoconazole mix (T10D, T21T) maintained an acidic to neutral profile (6.18–7.25), suggesting that the emamectin component governed the solution's chemical environment. In contrast, the Emamectin + Tebuconazole + Trifloxystrobin mixture showed a moderate upward pH shift, with drone applications reaching 7.36–7.81 and Taiwan applications 6.87–7.30. This trend may be attributed to interactions between the emamectin molecule and the WG fungicide matrix, potentially involving stabilizing complexation reactions.

Spinetoram-Based Tank Mixes: Spinetoram-containing mixtures demonstrated highly consistent alkaline pH ranges across all water sources and fungicide partners. The Spinetoram + Azoxystrobin + Difenoconazole combination (T8D, T19T) maintained pH values between 7.03 and 7.60, while the Spinetoram + Tebuconazole + Trifloxystrobin mix (T9D, T20T) ranged from 7.15 to 7.68. These pH profiles are favorable for both spinosyn and fungicide stability, with low variability indicating minimal risk of antagonistic chemical interactions.

3.3. pH-based classification of Pesticide formulations across different water sources: Based on the pH classification across various water sources (double distilled, tap, bore, and canal), none of the evaluated pesticide formulations either alone or in combinations were found to be extremely acidic, very strongly acidic, strongly acidic, or strongly to very strongly alkaline (Table.6 & Fig.3 & 4). A subset of treatments (e.g., T3D, T10D, T14T) exhibited slightly acidic characteristics (pH 6.1–6.5), predominantly in double-distilled water and to a lesser extent in tap, bore, and canal water. The neutral pH range (6.6–7.3) encompassed the majority of formulations, indicating their physicochemical compatibility with diverse water types, and suggesting chemical stability under such conditions. Several combinations, such as T2D, T13T, T19T, and T20T, were classified as slightly alkaline (7.4–7.8) across most water types, whereas only T7D and T17T consistently exhibited a moderately alkaline nature (7.9–8.4). This distribution highlights the relatively stable and near-neutral pH profiles of most tested formulations, with only a few showing marginal alkalinity.

Table.6. Classification of pesticides alone and in combinations based on the pH range

S.No	Nature	pH range	Double distilled water	Tap water	Bore water	Canal water
1	Extremely acidic	<4.5	None	None	None	None
2	Very strongly acidic	4.5-5.0	None	None	None	None
3	Strongly acidic	5.1-5.5	None	None	None	None
4	Moderately acidic	5.6-6.0	None	None	None	None
5	Slightly acidic	6.1-6.5	T3D, T4D, T5D, T10D, T14T, T15T, T16T	T3D, T10D, T14T	T3D, T10D, T14T	T3D, T10D, T14T
6	Neutral	6.6-7.3	T1D, T4D, T5D, T6D, T8D, T9D, T11D, T12T, T14T, T15T, T16T, T18T, T19T, T21T, T22T	T4D, T5D, T6D, T8D, T9D, T10D, T15T, T16T, T18T, T19T, T21T, T22T	T4D, T5D, T6D, T8D, T9D, T10D, T15T, T16T, T18T, T19T, T21T, T22T	T4D, T5D, T6D, T8D, T9D, T10D, T15T, T16T, T18T, T19T, T21T, T22T
7	Slightly alkaline	7.4-7.8	T2D, T8D, T9D, T11D, T13T, T17T, T19T, T20T	T1D, T2D, T12T, T13T, T17T, T19T, T20T	T1D, T2D, T12T, T13T, T17T, T19T, T20T	T1D, T2D, T12T, T13T, T17T, T19T, T20T
8	Moderately alkaline	7.9-8.4	T7D, T17T	T7D, T17T	T7D, T17T	T7D, T17T
9	Strongly alkaline	8.5-9.0	None	None	None	None
10	Very strongly alkaline	>9.1	None	None	None	None

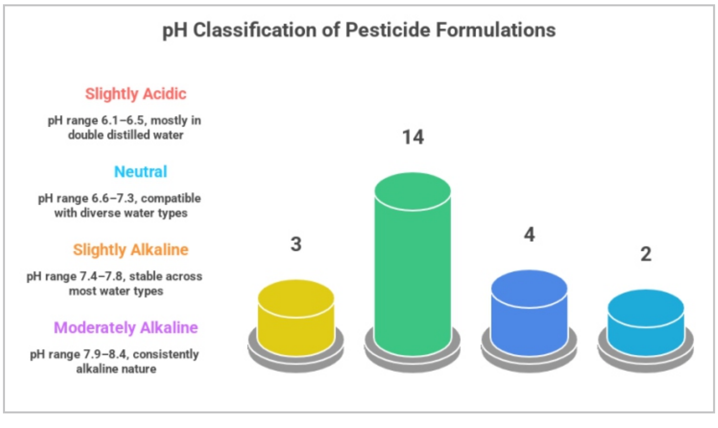

Fig.3. Classification of pesticides alone and in combinations based on the pH range

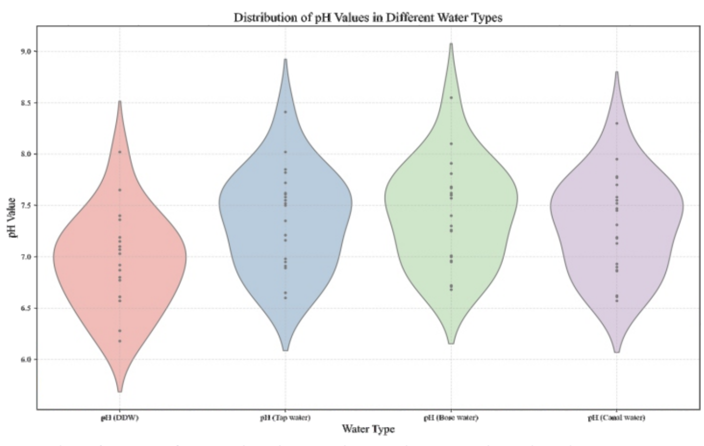

Fig.4. Classification of pesticides alone and in combinations based on the pH range

4. Discussion

In the present investigation, all insecticide and fungicide combinations tested through the jar compatibility method at drone and Taiwan sprayer dosages were found to be physically compatible, except emamectin benzoate when applied alone or in combination at drone dosage. The observed moderate physical incompatibility was likely due to the delayed dispersion and solubilization of the water-dispersible granule (WG) formulation, which required additional agitation for complete dissolution. Notably, no foaming was observed. These results align with the findings of (21) and (22) who reported that certain WG formulations required thorough agitation to ensure proper mixing and prevent settling when mixed with foliar inputs. Our findings are consistent with those reported by (23), who emphasized that "the rating index allows quantification and comparison of plant protection strategies, supporting more rational pesticide use and facilitating decision-making within integrated pest management programs."

4.1 Influence of Water Quality on Chemical Stability

Water source characteristics were found to influence final solution pH but did not override formulation-driven stability. Bore water consistently resulted in the highest pH shifts (mean increase of 0.48 ± 0.15), attributed to its high bicarbonate and mineral content. Tap water (0.39 ± 0.12) and canal water (0.36 ± 0.11) showed more moderate effects, influenced by treatment residuals and organic load, respectively. Despite these variations, the relative consistency of pH trends across treatments underscores the predominant role of formulation chemistry in determining tank mix compatibility.

The pH of spray solutions plays a critical role in determining the stability, efficacy, and overall performance of pesticide applications in agricultural systems. According to (24), many pesticide active ingredients are highly sensitive to hydrolysis, a degradation process accelerated under alkaline conditions (pH >8), leading to significant loss of potency before reaching the target pest. In the present study, all the tested pesticide formulations exhibited pH values close to or below 8.0, indicating a reduced likelihood of hydrolysis and other pH-dependent degradation processes (16). Chlorantraniliprole 18.5% SC exhibited stable pH behavior across drone and Taiwan spray concentrations (7.10–7.62; ΔpH = 0.52), irrespective of water source, in alone and combinations, indicating strong formulation buffering. These findings corroborate the observations of (25), who reported consistent pesticide stability under UAV-assisted applications across variable water conditions. Spinetoram 11.7% SC exhibited the most alkaline pH profile among the tested formulations, ranging from 7.40 (DDW) to 7.91 (bore water), consistent across both drone (6.80 mL/L) and Taiwan (0.67 mL/L) application rates. This pH range, favorable for spinosyn stability, aligns with previous observations by (17), supporting the formulation's compatibility under mildly alkaline conditions. Our findings revealed that Emamectin benzoate 5% SG consistently maintained an acidic pH range (6.28–6.72) across all tested water sources, aligning with the inherent physicochemical properties of avermectin compounds. This acidity supports the chemical stability of the formulation and minimizes degradation via alkaline hydrolysis. These observations are in agreement with the earlier report by (26), which also highlighted the formulation's compatibility with slightly acidic aqueous environments conducive to avermectin stability. As reported by (27), organophosphates such as dimethoate and carbamates like methomyl are particularly vulnerable to degradation under high-pH conditions, potentially compromising their biological efficacy. Conversely, pyrethroid compounds like deltamethrin demonstrate relatively better stability in acidic to neutral pH ranges but are prone to degradation under alkaline conditions, which aligns with our pH observations in several test mixtures. This pH-based chemical compatibility assessment confirms that pesticide formulation chemistry plays a primary role in determining solution stability, while water source characteristics serve as a secondary modulating factor. Notably, combinations such as T7D, which resulted in pH values exceeding 8.5, may require buffering interventions to prevent chemical degradation or phytotoxicity. Conversely, most mixtures demonstrated acceptable pH ranges across water sources, supporting their use in integrated pest and disease management strategies for maize. The findings reinforce the feasibility of drone and conventional sprayer applications using diverse water qualities, provided pH-sensitive actives are carefully managed.

Therefore, testing and adjusting the spray water pH using appropriate acidifiers or buffering agents before pesticide mixing is essential to minimize degradation, enhance field efficacy, and reduce economic losses. Integrating pH management into pesticide application protocols is a scientifically sound strategy to optimize pest control outcomes in precision agriculture.

5. Conclusion: The integration of UAV technology with optimized pesticide combinations requires not only innovation in application methods but also meticulous attention to formulation chemistry. This study underscores the importance of tailoring spray mixtures to specific water qualities to preserve the functional integrity of active ingredients during aerial deployment. Ensuring compatibility under varying pH conditions can significantly reduce the likelihood of nozzle clogging, formulation breakdown, or pest control failure. Future efforts should focus on developing ready-to-use, drone-compatible tank-mix formulations with built-in buffering systems to improve field efficacy and environmental safety.

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Authorship Contribution Statement

MR: Conceptualization, Methodology, Investigation, Data Curation, Writing – Original Draft. **CNR**: Supervision, Methodology, Writing – Review & Editing. **KV**: Validation, Formal Analysis, Writing – Review & Editing. **TKB**: Resources, Visualization, Data Interpretation. **SNCVL P**: Project Administration, Supervision, Final Approval of the Manuscript.

Compliance with ethical standards This article does not contain any studies with human participants or animals performed by any of the authors.

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Ethical issues: "None".

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