. .

Original Research Article

Chemical Control of Synthetic Pesticides on Garlic Germination and Performance

.

ABSTRACT

Background: Global garlic production has steadily increased over recent decades, with major producing countries including China, India, South Korea, and several Latin American nations contributing significantly to international markets
Among the most significant fungal diseases affecting garlic cultivation is rust, caused by *Puccinia allii* (Pers.) Rudolphi, which represents a major constraint to garlic production in many regions worldwide.
Aim: The objective of this study was to evaluate the efficiency of fungicides and bactericides, applied weekly as single treatments, in controlling garlic diseases.

Methodology: A randomised complete block design (RCBD) field trial was conducted with weekly applications of fungicides and bactericides, totalling 11 applications for each treatment, to compare their effects on disease incidence, severity, and crop performance. The experiment was carried out in garlic fields (26°49'16.8"S, 50°59'10.4"W) during one crop season, with evaluations performed from planting until 165 days after planting. Treatments included mancozeb (2.4 kg a.i./ha), difenoconazole (0.125 L a.i./ha), pyraclostrobin (0.1 L a.i./ha), propineb (2.1 kg a.i./ha), metiram+pyraclostrobin (1.1 kg a.i. + 0.1 kg a.i./ha), copper hydroxide [liquid formulation: 403.08 mL a.i./100 L (262.5 mL metallic copper); fluazinam (500 g a.i./ha), cuprous oxide (1.548 kg a.i./ha (1.35 kg metallic copper)), copper oxychloride (168 g a.i./100 L (100 g metallic copper)), and kasugamycin (0.07 L a.i./ha). Insect pests were managed using imidacloprid, formetanate hydrochloride, acetamiprid+etofenprox, or spinetoram, rotating active ingredients every two weeks. At 165 days, rust severity, bulb weight, and the percentage of green leaves were measured.

Results: Pyraclostrobin, mancozeb, metiram+pyraclostrobin, and propineb showed the lowest rust incidence and severity. For bacterial control, propineb and mancozeb were the most effective. The highest bulb weights were obtained from treatments with mancozeb, propineb, pyraclostrobin, metiram+pyraclostrobin, and fluazinam. The efficacy of some fungicides against bacteria may be related to indirect effects, such as plant resistance induction or interference with secondary infection establishment. Fluazinam, for example, possesses a unique mechanism of action that may interfere with energy metabolism in both fungi and some bacteria. Moreover, integration of cultural practices, such as planting in well-drained soils, crop rotation, and elimination of infected crop residues, should complement chemical control to maximise management efficacy.

Conclusion: The results demonstrate that multisite fungicides, particularly propineb and mancozeb, are effective tools for managing garlic diseases, contributing to improved plant health, yield, and bulb quality. Future management strategies may be designed focusing on fungicides with proven efficiency.

Keywords: *Rust, bacterial infection, bulb weight, yield improvement, fungicide efficacy, leaf health.*

1. INTRODUCTION

Garlic (*Allium sativum* L.) is one of the most economically important bulb crops worldwide, valued not only for its culinary applications but also for its medicinal properties and potential health benefits [1]. Its clove contains sulphur-based compound 'Alliin' (S-allyl-L-cysteine sulfoxide) predominantly as an active ingredient, which on physical injury to the clove becomes 'Allicin'. Allin and allicin are both devoid of lachrymatory factor, so it does not make one tear up while chopping garlic cloves (Chaudhari et al., 2022). Global garlic production has steadily increased over recent decades, with major producing countries including China, India, South Korea, and several Latin American nations contributing significantly to international markets [2]. It is a bulbous plant whose domestication is very old. Its primary centre is in Central Asia, while the Mediterranean and Caucasian regions are recognised as the secondary center of garlic (So et al., 2021). However, sustainable garlic production faces numerous challenges, particularly from fungal and bacterial diseases that can severely impact both yield and bulb quality.

Among the most significant fungal diseases affecting garlic cultivation is rust, caused by *Puccinia allii* (Pers.) Rudolphi, which represents a major constraint to garlic production in many regions worldwide [3]. Garlic rust typically manifests under specific environmental conditions, particularly during periods of high relative humidity and moderate temperatures (15-20°C), which create optimal conditions for spore germination and disease development [4]. The disease is characterised by the appearance of orange to reddish-brown pustules on leaf surfaces, leading to premature senescence, reduced photosynthetic capacity, and ultimately significant yield losses that can range from 20% to 60% in severely affected crops [5,6]. Recent reports of rust outbreaks, incursion events and biosecurity threats emphasised the economic importance and necessity of the correct identification of rust fungi occurring on Allium species (Boshoff et al., 2024).

In addition to fungal pathogens, garlic crops are susceptible to various bacterial diseases that can cause substantial economic losses. Bacterial pathogens affecting garlic include species such as *Pseudomonas marginalis* pv. *marginalis* [7], which can cause leaf blight that compromises plant vigour and marketable yield. The disease can occur at any stage of plant development. Its characteristic symptom is the yellowing of the leaf centre, which develops a water-soaked appearance accompanied by tissue softening and subsequently turns brown as the disease progresses. Initially, the leaf margins remain green and firm; however, over time, the entire leaf turns yellow, becomes brown, and eventually dries out, exhibiting a physiological maturation-like appearance [8].

This bacterial disease is particularly problematic under conditions of high moisture, temperatures between 18-20ºC [9] and poor air circulation, often occurring in conjunction with fungal infections to create complex disease scenarios that challenge effective management strategies.

The economic impact of garlic diseases extends beyond direct yield losses to include reduced bulb quality, increased storage losses, and elevated production costs associated with disease management practices [10]. Current disease management strategies in garlic production rely heavily on chemical control methods, including the application of fungicides and bactericides with different modes of action and efficacy profiles. Commonly used fungicides include protectant chemicals such as mancozeb and propineb, systemic compounds like difenoconazole and pyraclostrobin, and combination products that provide both contact and systemic activity [11]. Similarly, copper-based bactericides and antibiotic compounds such as kasugamycin are frequently employed for bacterial disease control [12].

Despite the widespread use of chemical control agents, there remains significant variation in their effectiveness under different environmental conditions and against various pathogen populations. Furthermore, concerns regarding pesticide resistance development, environmental impact, and food safety have increased the need for more targeted and sustainable disease management approaches [13]. Understanding the comparative efficacy of different chemical control agents is therefore crucial for developing integrated pest management strategies that optimise disease control while minimising negative environmental and economic impacts.

Previous research has demonstrated variable results regarding the effectiveness of different fungicide and bactericide treatments in garlic production systems. While some studies have shown promising results with certain active ingredients, there is a need for systematic evaluation of treatment efficacy under standardised field conditions to provide reliable recommendations for growers [14]. Additionally, the interaction between disease control effectiveness and overall plant performance parameters, such as yield, bulb quality, and plant vigour, requires further investigation to develop comprehensive management recommendations.

The objective of this study was to evaluate the efficiency of various fungicides and bactericides, applied as weekly single treatments throughout the growing season, in controlling rust and bacterial diseases in garlic, while simultaneously assessing their effects on crop performance and bulb quality parameters. This research aims to provide evidence-based recommendations for chemical disease management in garlic production systems and contribute to the development of more effective and sustainable disease control strategies.

2. MATERIALS AND METHODS

The experiment was conducted in an area located at coordinates 26°49'16.9"S 50°59'10.4"W at the EPAGRI experimental station in Caçador, Santa Catarina. After garlic planting, fungicide and insecticide applications were performed weekly. The treatments used were: mancozeb (2.4 kg a.i./ha); difenoconazole (0.125 L a.i./ha); pyraclostrobin (0.1 L a.i./ha); propineb (2.1 kg a.i./ha); metiram+pyraclostrobin (1.1 kg a.i. + 0.1 kg a.i./ha); copper hydroxide – liquid formulation (403.08 mL a.i./100L; 262.5 mL metallic copper); fluazinam (500 g a.i./ha); cuprous oxide (1.548 kg a.i./ha; 1.35 kg metallic copper); copper oxychloride (168 g a.i./100L; 100 g metallic copper) and kasugamycin (0.07 L a.i./ha). Insect management was performed using imidacloprid, formetanate hydrochloride, acetamiprid+etofenprox or spinetoram, alternating the active ingredient every two weeks. A concentration of 0.05 mL/L of the commercial product containing a poly (alkylene oxide) siloxane copolymer was applied as an adjuvant in all treatments to enhance spray performance. Each treatment received 11 applications in total. The spray volume used was 800 L/ha.

During the garlic differentiation phase at 120 days after planting, the incidence of rust and bacteria was evaluated, along with plant weight (g), plant height (cm), total number of leaves per plant, bulb diameter (mm), stem diameter (cm) and root weight (g). At harvest, 165 days after garlic planting, disease severity was measured at the end of the season, as well as the parameters bulb weight (g) and the leaves still green. In the incidence evaluation, for both rust and bacteria, total leaves were counted as well as leaves showing symptoms or signs of diseases, transforming the data to a percentage of diseased leaves. For the evaluation of incidence and severity, the data were transformed into a percentage of control relative to the untreated check. In each plot, five plants were evaluated, with three replications per treatment. Disease severity was assessed by considering the yellow portions of the leaves as the diseased area. The results were submitted to analysis of variance, and when significant by the F test, the means were compared by the Scott-Knott statistical test at 5% probability ($P \leq 0.05$).

3. RESULTS AND DISCUSSION

The results demonstrated that the most effective treatments in controlling rust, considering incidence and severity, were pyraclostrobin, mancozeb, metiram+pyraclostrobin, and propineb (Fig. 1 and 2). These treatments showed a lower incidence and severity of the disease compared to the other fungicides evaluated. The results obtained demonstrate that pyraclostrobin, mancozeb, metiram+pyraclostrobin, and propineb were the most effective treatments for controlling garlic rust, considering both disease incidence and severity. Previsouly, tebuconazol, pyraclostrobin, mancozeb, metiram+piraclostrobin, trifloxistrobin+tebuconazol and ciproconazol at the label dose were considered efficient in controlling garlic rust [15]. These findings corroborate previous studies highlighting the efficacy of these active ingredients in managing fungal diseases in *Alliaceae* crops.

Mancozeb, a multi-site contact fungicide belonging to the dithiocarbamate group, showed excellent performance in rust control, confirming its recognised efficacy in fungal disease management [16]. Its broad protective action and low risk of resistance development make it a valuable option for integrated disease management programs.

Piraclostrobin, a strobilurin fungicide (QoI), effectively controls garlic rust by inhibiting mitochondrial respiration in the bc1 complex, disrupting ATP production and halting fungal growth. With both protective and curative activity and systemic movement in plant tissues, it provides prolonged disease control and is a valuable tool in integrated management programs [17].

The metiram+pyraclostrobin combination demonstrated superior efficacy in controlling garlic rust. Combinations of dithiocarbamate fungicides with quinone oxidase inhibitors have been reported as effective strategies for rust control. This synergy can be explained by the complementarity of action mechanisms: while metiram acts as a multi-site contact fungicide [18], pyraclostrobin provides specific systemic action.

Propineb, another dithiocarbamate, also presented satisfactory results, confirming the efficacy of this chemical class in rust control. Dithiocarbamates, including mancozeb and propineb, share the ethylenedithiocarbamate group, which is responsible for their antifungal activity [18]. Although it is not registered for the control of garlic diseases, this study demonstrates that it could represent a potential option for disease management once approved by the relevant regulatory authorities.

Copper hydroxide is a widely used fungicide and bactericide in agriculture, acting by releasing copper ions that disrupt key enzymatic processes in pathogens, inhibiting their growth and reproduction. It is effective against rusts and bacterial diseases [19]. In the present study, however, phytotoxicity events were observed, with portions of the leaves developing white spots typical of leaf burn. Such symptoms occur when copper ions accumulate to levels that the plant tissue cannot tolerate, causing localised tissue damage.

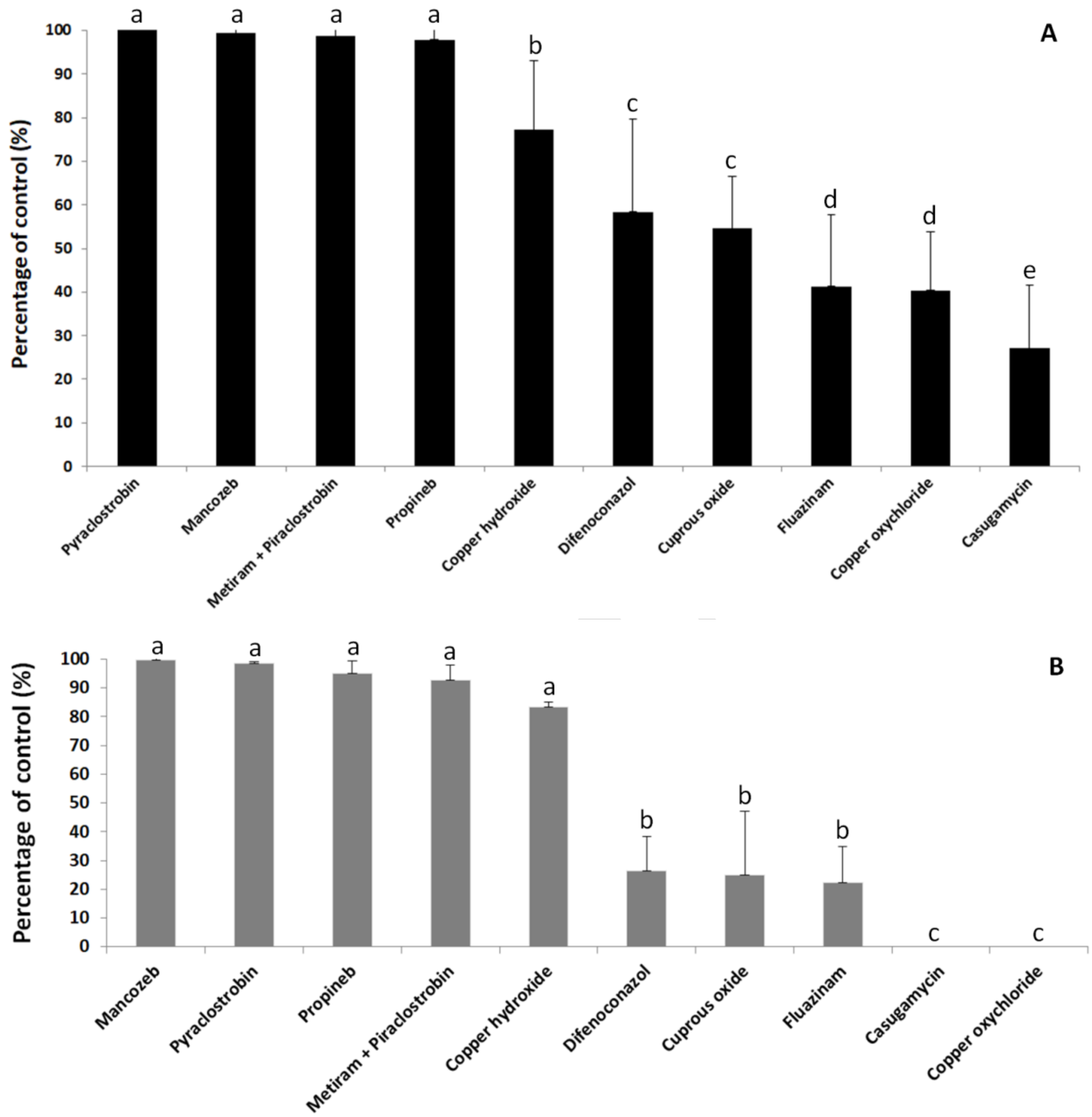

Fig. 1 – Effect of weekly fungicide application on garlic rust. A – Rust incidence as a function of weekly fungicide application evaluated during garlic differentiation. B – Rust severity as a function of weekly fungicide application on harvest day.

The active ingredients propineb, mancozeb, fluazinam, pyraclostrobin, difenoconazole and metiram+pyraclostrobin were the most efficient in controlling the incidence of bacterial diseases (Table 1). Controlling bacterial diseases in garlic represents an additional challenge, as conventional fungicides have limited efficacy against bacterial pathogens. Bacterial pathogens can remain latent in bulb tissues and contaminate soil through planting infected cloves. The efficacy of some fungicides against bacteria may be related to indirect effects, such as plant resistance induction or interference with secondary infection establishment. Fluazinam, for example, possesses a unique mechanism of action that may interfere with energy metabolism in both fungi and some bacteria [20].

Fig. 2 – General view of garlic health at the harvest day. A – Plot without fungicide application. B – Plot with mancozeb application. C – Plot with pyraclostrobin application. D – Plot with metiram+pyraclostrobin application. E – Plot with propineb application. F – Plot with kasugamycin application.

Table 1– Incidence of bacterial diseases at the stage of garlic differentiation.

Fungicide	Number of leaves with bacterial disease symptoms (%)
Propineb	5.61 a
Mancozeb	6.18 a
Fluazinam	10.54 a
Pyraclostrobin	11.08 a
Difenoconazol	11.42 a
Metiram + Pyraclostrobin	11.55 a
Casugamicin	12.98 b
Cuprous oxide	13.58 b
Copper hydroxide	15.30 b
Copper oxychloride	17.22 b
Control	22.41 b

Table 2 – Measurements of weight, height, number of leaves, bulb diameter, stem diameter, and root weight of plants at the stage of garlic differentiation.

Fungicides	Plant weight (g)	Plant height (cm)	Number of leaves	Bulb diameter (mm)	Stem diameter (cm)	Root weight (g)
Control	64.84 c	81.06 b	8.67 ns	24.50 b	14.03ns	3.84 b
Copper oxychloride	94.05 b	92.97 a	8.87	27.71 b	16.23	4.93 a
Copper hydroxide	86.72 b	92.01 a	9.73	27.89 b	15.52	4.22 b
Casugamicin	96.39 b	88.12 a	9.47	28.11 b	15.50	4.73 a
Metiram + Pyraclostrobin	101.22 a	92.89 a	9.47	28.29 b	16.95	5.83 a
Difenoconazol	90.12 b	89.76 a	9.47	28.33 b	15.18	4.90 a
Propineb	99.25 b	93.54 a	9.40	29.28 b	15.00	5.40 a
Cuprous oxide	94.85 b	93.27 a	9.13	29.79 b	15.75	3.98 b
Fluazinam	108.48 a	94.33 a	9.87	31.10 a	16.79	5.63 a
Mancozeb	112.47 a	97.62 a	9.53	33.33 a	16.18	5.10 a
Pyraclostrobin	92.41 b	92.47 a	9.00	34.64 a	15.98	3.63 a

For the total number of leaves and stem diameter, there were no significant differences among treatments. The active ingredients fluazinam, mancozeb and pyraclostrobin promoted the largest bulb diameters during the garlic differentiation phase (Table 2). For plant weight, the highest values were obtained applying metiram+pyraclostrobin, fluazinam and mancozeb. Fungicide treatments not only controlled diseases but also promoted significant improvements in growth parameters, likely due to disease prevention, which allows garlic to express its full productive potential.

At harvest, the active ingredients mancozeb, propineb, pyraclostrobin, metiram+pyraclostrobin, and fluazinam promoted the highest bulb weight (g), and the treatments where propineb and mancozeb were applied had the greatest number of leaves still green on harvest day (Table 3). This demonstrates that effective disease control translates directly into productive gains. Preventive rust management is crucial to maintain effective control [15], especially considering that rust sporulation represents the final stage of the pathogen's life cycle.

Table 3 – Bulb weight and number of leaves remaining green at harvest.

Fungicides	**Bulb weigth (g)**	**Leaves remaining green**
Casugamicin	21.95 c	0.07 e
Copper hydroxide	24.87 c	1.80 d
Control	26.58 c	0.20 e
Copper oxychloride	29.75 b	0.67 e
Cuprous oxide	31.97 b	2.47 c
Difenoconazol	32.19 b	3.93 b
Fluazinam	39.09 a	2.60 c
Metiram + Pyraclostrobin	42.96 a	3.67 b
Pyraclostrobin	43.47 a	4.27 b
Propineb	44.28 a	5.00 a
Mancozeb	45.76 a	6.07 a

The maintenance of a greater number of green leaves at harvest by propineb and mancozeb treatments indicates better preservation of the photosynthetic apparatus, resulting in greater reserve accumulation in bulbs. This effect is particularly important in garlic, where leaf area is directly related to bulb development as demonstrated for onion [21].

The variation in efficacy among different fungicides tested underscores the importance of active ingredient rotation and integrated resistance management. Currently, no garlic varieties are completely resistant to rust, although some California Early varieties demonstrate disease tolerance [22].

Copper-based fungicides (cuprous oxide and copper oxychloride) showed lower efficacy for both rust and bacterial diseases, possibly due to selection pressure exerted by continuous use of these products. Copper-based products continue to play an important role as protective fungicides in many management systems, particularly in organic production systems [23].

The use of multi-site fungicides like mancozeb and propineb should be prioritised in resistance programs, as they present a lower risk of resistance development compared to site-specific fungicides [24]. Alternation between different chemical groups, as demonstrated by the efficacy of pyraclostrobin (group 11) and dithiocarbamates (group M), is fundamental for the sustainability of control programs.

The results indicate that preventive spray programs using the most effective fungicides (pyraclostrobin, mancozeb, metiram+pyraclostrobin, and propineb) can provide satisfactory garlic rust control. Weekly application of these products during critical crop development periods proved effective, although future studies should evaluate optimised application intervals to reduce costs and environmental impact.

Integration of cultural practices, such as planting in well-drained soils, crop rotation, and elimination of infected crop residues, should complement chemical control to maximise management efficacy [3].

This study evaluated fungicides under specific field conditions, and efficacy may vary according to edaphoclimatic factors, disease pressure, and pathogen population resistance. Complementary studies should evaluate the efficacy of these treatments in different producing regions and under different environmental conditions.

The search for sustainable alternatives to intensive synthetic fungicide use has led to the development of integrated management strategies. The development of eco-friendly strategies for garlic disease management has been a growing priority. Future research should focus on developing integrated management strategies that combine chemical, biological, and cultural control, aiming to reduce dependence on synthetic fungicides and promote garlic production sustainability.

4. CONCLUSION

The active ingredients pyraclostrobin, mancozeb, metiram+pyraclostrobin and propineb were the most effective options for controlling garlic rust. Propineb, mancozeb, fluazinam, pyraclostrobin, difenoconazol and metiram+pyraclostrobin were the active ingredients that were observed to have fewer bacterial symptoms in the plots.

Disclaimer (Artificial intelligence)
Option 1:
Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.) and text-to-image generators have been used during the writing or editing of this manuscript.
Option 2:
Author(s) hereby declare that generative AI technologies such as Large Language Models, etc. have been used during the writing or editing of manuscripts. This explanation will include the name, version, model, and source of the generative AI technology and as well as all input prompts provided to the generative AI technology
Details of the AI usage are given below:
1.
2.
3.

REFERENCES

1. Kamenetsky R, Rabinowitch HD. The genus Allium: a developmental and horticultural analysis. Horticultural Reviews. 2006;32:329-78.
2. FAOSTAT. Food and Agriculture Organization of the United Nations Statistics Division. 2023. Available from: http://www.fao.org/faostat/
3. Schwartz HF, Mohan SK. Compendium of Onion and Garlic Diseases and Pests. 2nd ed. St. Paul, MN: APS Press; 2008.
4. Mallmann G, Monteiro FP, Fernandes JMC, Cardoso DA, Valmorbida J, Wamser AF, Lins Junior JC. Number of pustules of garlic rust under different temperatures and leaf wetness. Plant Pathol Quarantine. 2022;12(1):114–8.
5. Koike ST, Smith RF, Davis RM, Nunez JJ, Voss RE. Characterization and control of garlic rust in California. Plant Disease. 2001;85(6):585-91.
6. Marcuzzo LL, Paulakoski AC, Mariano DD. Epidemiologia temporal da ferrugem do alho. Rev Agron Bras. 2022;6:1-5.
7. Bradbury JF. Guide to plant pathogenic bacteria. Wallingford: CAB International; 1986.
8. Becker WF. Queima bacteriana do alho. Agropecuária Catarinense. 1991;4(3).

9. Marcuzzo LL, Füchter D. Influência da temperatura e da duração do molhamento foliar na severidade da queima bacteriana do alho. Rev Agron Bras. 2021;5.
10. Brewster JL. Onions and Other Vegetable Alliums. 2nd ed. Wallingford: CAB International; 2008.
11. McGrath MT. What are fungicides? The Plant Health Instructor. 2004. doi:10.1094/PHI-I-2004-0825-01.
12. McManus PS, Stockwell VO, Sundin GW, Jones AL. Antibiotic use in plant agriculture. Annu Rev Phytopathol. 2002;40:443-65.
13. Brent KJ, Hollomon DW. Fungicide Resistance in Crop Pathogens: How Can It Be Managed? 2nd ed. FRAC Monograph No. 1. Brussels: Fungicide Resistance Action Committee; 2007.
14. Lorbeer JW. Garlic rust caused by Puccinia allii in New York. Plant Dis. 1992;76(5):465-7.
15. Mallmann G, Lins Junior JC, Monteiro FP, Wamser AF, Ogoshi C, Valmorbida J. Evaluation of the fungicides efficiency in garlic rust control. Stud Environ Anim Sci. 2025;6(2):e19302.
16. Gullino ML, Tinivella F, Garibaldi A, Kemmitt GM, Bacci L, Sheppard B. Mancozeb: past, present, and future. Plant Dis. 2010;94(9):1076-87.
17. Bartlett DW, Clough JM, Godwin JR, Hall AA, Hamer M, Parr-Dobrzanski B. The strobilurin fungicides. Pest Manag Sci. 2002;58(7):649-62.
18. Thind TS, Hollomon DW. Thiocarbamate fungicides: reliable tools in resistance management and future outlook. Pest Manag Sci. 2018;74(7):1547-51.
19. Pscheidt JW, Ocamb CM. Copper-based Bactericides and Fungicides. In: Pacific Northwest Pest Management Handbooks. Corvallis: Oregon State University; 2022.
20. Leadbeater AJ. Recent developments in practical disease control. In: Modern Crop Protection Compounds. Weinheim: Wiley-VCH; 2015. p. 225-39.
21. Ishii T, Suto M, Suzuki N, Ikeda H. Growth and gene expression related to bulb development and day-length responses in onion cultivars during overwinter cultivation. Hortic J. 2022;91(4):514-21.
22. Koike ST, Smith R, Davis RM, Nunez JJ, Voss RE. Rust disease continues to threaten California garlic crop. Calif Agric. 2001;55(5).
23. Burandt QC, Deising HB, von Tiedemann A. Further limitations of synthetic fungicide use and expansion of organic agriculture in Europe will increase the environmental and health risks of chemical crop protection caused by copper-containing fungicides. Environ Toxicol Chem. 2024;43(1):19-30.
24. FRAC - Fungicide Resistance Action Committee. FRAC Code List 2023: Fungal control agents sorted by cross-resistance pattern and mode of action. 2023. Available from: www.frac.info
25. Chaudhari, G. V., Hedau, N. K., Ram, H., Khade, Y. P., Kant, L., & Khar, A. (2022). Garlic: retrospect, status quo and dimensions. *Genetic Resources and Crop Evolution*, *69*(8), 2645-2660.
26. So, T. K. A., Abdou, R., Sani, I. S., Toudou, A. K., & Bakasso, Y. (2021). Garlic (Allium sativum L.): Overview on its biology and genetic markers available for the analysis of its diversity in West Africa. *Asian Journal of Biochemistry, Genetics and Molecular Biology, 7*(3), 1–10.
27. Boshoff, W. H., Visser, B., Bender, C. M., & Pretorius, Z. A. (2024). Pathogenicity of Puccinia porri on Allium in South Africa. *Australasian Plant Pathology*, *53*(1), 15-30.