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THE ADVANCED EVOLUTION OF FUNGICIDES: ENHANCING PLANT DISEASE MANAGEMENT IN THE MODERN ERA

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ABSTRACT

Plant diseases, which alone result in production losses of 15-25%, make it more difficult for contemporary agriculture to increase crop yield in the face of diminishing resources. The main instrument for managing diseases has been chemical fungicides; conventional methods frequently provide health and environmental hazards. The development of fungicides has advanced over the last 20 years, producing a new generation that is more specific, leaves fewer residues, and works at lower dosages. These developments include a variety of chemical classes that target particular fungal vulnerabilities with less of an influence on the environment, such as valinamides, phenylpyrroles, and strobilurins. The efficiency of these fungicides against resistant strains is highlighted by their shift towards single-site modes of action, such as strobilurins produced from *Strobilurus tenacellus*. New-generation fungicides that combine systemic and contact activities with microbial disruption, such as Cabrio Duo and Serifel, are recent innovations that provide broad-spectrum disease control while reducing phytotoxicity and environmental effect. These developments are essential for maintaining agricultural output while addressing environmental issues, which calls for continued study into new fungicide classes and resistance management. The best fungicides should be inexpensive, come in a variety of formulations, have a long shelf life, be compatible with other agrochemicals, and have low phytotoxicity. Their various uses in crop protection are further highlighted by their classification according to mobility (systemic vs. contact), chemical nature (benzimidazoles, triazoles), and method of action (inhibition of mitochondrial function, melanin biosynthesis, etc.)
Keywords : Benzimidazoles fungicides, plant diseases, strobilurins

Introduction

Given the rapidly growing population and the steadily depleting land and water supplies, modern agriculture faces challenges in boosting output. Over 15–25% of the yield loss resulting from the various biotic and abiotic variables is attributable to plant diseases alone. Crop productivity will rise and production will be improved with effective control of certain plant diseases. The most popular approach to managing fungal diseases among the different disease management options is chemical control with fungicides. The usage of conventional fungicides, which were less effective and had a wider range of effects, has had numerous detrimental impacts on the environment and human health. Over the past two decades, numerous new fungicides with unique modes of action have been developed in an effort to overcome the limitations of these existing ones. These so-called new generation fungicides are more target specific, leave no or very little residue on the product, and are extremely effective even at low dosages (Adeniyi *et al*., 2021). Over time, there has been a notable shift in the process of discovering fungicides. In the last 20 years, a number of innovative action fungicides of various chemical classes have been created, after the age of broad spectrum multisite and site-specific systemic fungicides. Compared to the earlier chemicals, these are utilized at considerably lower levels, making them more environmentally friendly.

The most significant of these are the strobilurins (QoIs), which are obtained from the wild mushroom *Strobilurus tenacellus* (Kumar and Gupta 2012). Other significant fungicides that have been introduced in the past ten years to manage a variety of illnesses include valinamides (iprovalicarb, benthiocarb), oxyazolidinediones (faoxadone), phenoxyquinolines (quinoxyfen), and anilinopyrimidines (cyprodinil, pyrimethanil). Phenylpyrroles (fenpicloil, fludioxonil), Mandelamides (mandipropamid), and MBIs (carpropamid) Phenoxyquinolines (quinoxyfen), Imidazoles (fanmidone), Benzamides (fluopicolide, zoxamide), Thiocarbamates (ethaboxam), Cyanoimidazoles (cyazofamid), and Spiroketalamines (spiroxamine) are examples of compounds with distinct chemistries and modes of action (Thind 2012; Kumar 2009). These newly released next generation fungicides highlight significant technological advancements in terms of selectivity, safety, potency against target diseases, and rate reduction. They may be impacted by target site resistance, because they typically have single site modes of action (Leadbeater, 2015). As a result, it is now crucial to preserve current products while also proactively developing recommendations for new fungicide classes based on resistance management techniques.

Characters of an ideal fungicide

- It should have minimal phytotoxicity.
- It should have long shelf life
- Stability during dilution
- It should be less toxic to human being, cattle, earth worms, microorganisms etc.
- It should be a broad range of action
- It must be less expensive and compatible with other agrochemicals
- It needs to be provided in several formulations.
- It should be portable.

Classification of Fungicides

1. **Plant dispersion mobility**: systemic and contact fungicides
2. **By chemical nature**: Copper fungicides, inorganic and organic sulfur, mercury fungicide, heterocyclic nitrogen compounds, benzene compounds, quinones, acylalanines, carbamates, dithiocarbomates, benzimidazoles, carboximides, imidazoles, pyridines, strobilurins, triazoles etc.
3. **By mode of action**: Inhibitors of mitocondrial electron transport, nucleic acid synthesis, mitosis and cell division, protein synthesis, lipid and membrane synthesis, glucan synthesis, sterol biosynthesis inhibitors (SBIs), cell wall melanin formation inhibitors.
4. **By general use**- Fruit protectants, foliar and flower protectants, seed protectants, soil fungicides, eradicants, Fungicides for tree wound dressings etc.

Throughout the history of plant diseases, many diseases have appeared as epidemics, such as the Bengal Famine and the Irish Famine, which are caused by rice brown spot. In the same way, there are numerous illnesses that have historical significance and affect human life. The nineteenth century saw the introduction of chemical fungicides into agriculture when B. Prevost found that copper fungicides were efficient against seed-borne bunt. Numerous fungicides have been developed since the nineteenth century to control plant diseases. A number of new fungicides that work better than previous ones and are more effective at low dosages have also been found in the last 20 years (Nabi *et al.*, 2017).

Development of Fungicides

In the 18th and 19th centuries, growers experimented with a variety of compounds, including sulfur, lime sulfur, sodium chloride, copper sulfur, copper carbonate, ammonium sulfur, ammonium carbonate, and more. The actual interest in the creation and application of fungicides began in France in 1885 when Millardet discovered the Bordeaux mixture to combat grape downy mildew (Koledenkova *et al.*, 2022).

Fourth-Generation / New-Generation Fungicides (Novel Modes of Action)

1. Strobilurins 2. Melanin biosynthesis inhibitors

3. Phenylpyrrole 4. Anilinopyrimidines

5. Phenoxyquinolines 6. Spiroketalamines

7. Benzamides 8. Oxazolidinediones.

Strobilurins

The wood-decomposing basidiomycete fungus *Strobilurus tenacellus* is the source of a novel class of fungicides known as strobilurins. The class of fungicides known as strobilurins prevents fungus from respiring their mitochondria. The cytochrome bc1 complex's Qo site, which is located at the inner mitochondrial membrane of fungus, prevents ubiquinol from oxidizing (Knight *et al.*, 1997). QoI fungicides are the latest term for these fungicides. These are the most common fungicides in the world (Bartlett *et al.,* 2002). These fungicide classes are effective against a wide variety of diseases and have broad-spectrum activity. It is advised to use these fungicide classes for furrow application, foliar treatment, and seed treatment. Commercial strobilurins include pyraclostrobin, trifloxystrobin, azoxystrobin, and kresoxim-methyl. This family of fungicide has the benefit of being effective against fungal strains that have gained resistance to phenylamide, DMIs, dicarboximide, and benzimidazoles, which makes it more significant. Microorganism that can breakdown strobilurin (Fig.1) are active in a variety of environmental settings.

Melanin Biosynthesis Inhibitors

This class of fungicides stops the pathogen from penetrating and stops the synthesis of melanin in *Pyricularia oryzae* appressoria. MBI works effectively to prevent rice blast disease. (Koichiro *et al.*, 2003). *Colletotrichum* spp. are also well controlled by MBI inhibition. They impact the dihydroxynaphthalene (DHN). They impact the dihydroxynaphthalene (DHN) enzymes that are involved in the formation of melanin. Fungicides such as carpropamid inhibit the dehydration stage in this process, while phthalide, tricyclazole, and pyroquilon inhibit the reduction step. MBI stops pathogens from penetrating the host's epidermis; these are typically anti-penetrants. The pathogen's ability to successfully penetrate the host epidermis depends on the melanization of the appressorial walls. Pathogens *P. grisea* and enzymes that are involved in the formation of melanin. Fungicides such as carpropamid inhibit the dehydration stage in this process, while phthalide, tricyclazole, and pyroquilon inhibit the reduction step. MBI stops pathogens from penetrating the host's epidermis; these are typically anti-penetrants. The pathogen's ability to successfully penetrate the host epidermis depends on the melanization of the appressorial walls. Pathogens *P. grisea* and *Colletotrichum* spp. are also well controlled by MBI inhibition of melanin formation.

Phenylpyrroles

Pseudomonas pyrrocinia produces secondary metabolites called pyrrolnitrin, which have antifungal qualities and are the basis for phenylpyrroles (Floss *et al.* 1971). Since pyrrolnitrin is unstable in the presence of light, it cannot be used effectively to manage disease (Corran *et al.*, 2008). By optimizing this compound's photostability, two commercial fungicides fenpiclonil and fludioxonil were created. These are employed as foliar spray and seed dressing, respectively. The elongation of the germ tube, mycelial growth, and spore germination are all inhibited by phenylpyrroles (Leroux *et al.*, 1992).

Anilinopyrimidines

Pyrimidines, another name for anilinopyrimidines, are broad-spectrum fungicides. A wide range of crops can be treated with this kind of fungicide. Mepanipyrim and pyrimethanil are effective against *Venturia inaequalis* on apples and *Botrytis cinerea* on grapevines and other fruits (Neumann *et al.*, 1992). Although their exact molecular mechanism of action is yet unknown, anilinopyrimidines are thought to play a role in inhibiting methionine production. (Leroux, 1996). In addition to being single-site inhibitors of the amino acid biosynthesis pathway, they also have an impact on the release of hydrolytic enzymes when the target pathogens infiltrate plant tissue.

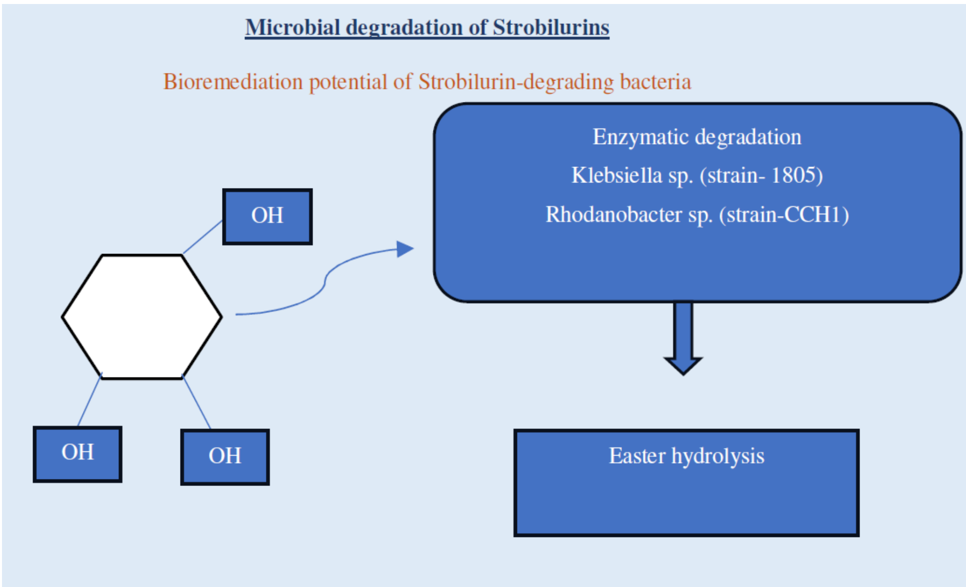

Fig. 1 : Bio-degradation of Pyraclostrobin (Strobilurins)

Phenoxyquinolines

Phenoxyquinolines consist of protectant fungicide (Longhurst *et al*., 1996). Quinoxyfen was first used in 1996 to treat powdery mildew on grapevines and cereals. Quinoxyfen interferes with signaling pathways that are essential for development and growth; this fungicide alters powdery mildew in its early stages of growth. Additionally, it disrupts the target fungus's life cycle by interfering with the germination of conidia and the production of appressorium.

Spiroketalamines

Spiroxamine, first introduced in 1996, is the representative chemical of spiroketalamines. Spiroxamine is a new inhibitor of ergosterol production, which is necessary for structure's organization and functionality (Dutzmann *et al*., 1996). It controls grape and cereal powdery mildew. Spiroketalamines exhibit resistance to both piperidines and morpholines.

Benzamides

Zoxamide is a member of the benzamide class, which is also known as an anti-tubulin fungicide. The fungicide zolamide inhibits β-tubulin. Like benzimidazoles, benzamides have shown promise in controlling oomycete infections by interfering with the microtubule skeleton and inhibiting nuclear division (Young and Richard 2001). It is highly active against a wide range of oomycetes, including *Plasmoparaviticola*, *Phytophthora infestans*, and different species of *Pythium* (Chao *et al*., 2011). Additionally, it inhibits some non-oomycete fungus, including *Monilinia* spp., *Mycosphaerella* spp., *Sclerotinia* spp., *Venturia* spp., and *Botrytis* spp. (Young and Richard 2001).

Oxazolidinediones

Famoxadone is the representative of this class of fungicide. This class is a member of the bc1 complex QoI family and has broad spectrum action (Abrue *et al*., 2006). Famoxadone functions as a protective substance. It is used for combating downy mildew in grapes and late blight in potatoes (Thind, 2012). Famoxate is a newly developed fungicide that can be used for both prevention and treatment of fungal diseases in crops. This novel class of fungicide affects the bc1 mitochondrial cytochrome's catalytic activity (Douglas *et al*., 1999).

Recently Developed New-Generation Fungicides

While some newly produced new-generation fungicides and active components are still being evaluated for various diseases, others have been registered for use on crops and farmlands. A small number of new-generation fungicides are used to combat serious infections that affect fruits, vegetables, cash crops, and annual crops. The following are a few examples of these new-generation fungicides:

Table 1: New-Generation Fungicides (*Source:* Adeniyi *et al*., 2021)

Trade Name	Formulation & Doses	Mode of action	Toxicity	Advantages & Effectiveness	Compatibility & Phytotoxicity
Cabrio - Duo. (Adamas Company)	Pyraclostrobin 5% and Dimethomorph 55%. Doses- 150-175ml in 15l of H_2O	Systemic fungicides like pyraclostrobin prevent electron transport. The protective and contact fungicide Dimethomorph- Stops spores from germinating.	Cause organ damage and irritation very toxic to aquatic life	Broad spectrum, longer duration control, improvement in quality & yield of crop. Control downy mildew, powdery mildew, anthracnose, late & early blight.	Incompatible with plant protection products. Non phytotoxic.
Pergado F (Syngenta)	Folpet 400g/kg and Mandipropamid50g/kg Doses- 2 to 3kg/ha	Mandipropamid – Translaminar action. Folpet prevents spore germination by forming a protective barrier.	Harmful, toxic to aquatic life	Highly efficient against omycetes	Compatible. Non phytotoxic.
Serifel (BASF)	*Bacillus amyloliquefacie*strain MBI 600.	Microbial disrupters of cell membrane by	No negative effects	Use as part of IDM, broad spectrum disease control, excellent	Suitable for a variety of possible tank mix partners. not harmful to plants.

	110g/kg. Doses- 0.28 to 0.5kg/ha	producing metabolites iturin&surfactin.		adaptability, and efficacy against powdery mildew, downy mildew, white mold, anthracnose, and leaf spot.	Non phytotoxic.
Custodia (Adama)	Azoxystrobin 11% and tebaconazole 18.3%. Doses- 1ml/liter of water.	Azoxystrobin inhibit fungal respiratio, interferes ETC, stops ATP synthesis.	Not obstrusive, extremely harmful to aquatic life.	Good curative and preventative qualities which work well against early blight, downy mildew, powdery mildew and fruit rot	Compatible with other fungicides.Extremely phytotoxic.
Veltyma (BASF)	Mefentrifluconazole of 200g/l and pyraclostrobin. 200g/l. Doses- 7 floz/A	Isopropanol azole provides broad-spectrum disease control by binding firmly to fungal cells. By blocking the cytochrome bc1 complex in the fungal mitochondria, the fungicide pyraclostrobilurin interferes with the synthesis of energy.	Harmful	Potent remedy that manages the toughest diseases, has a long-lasting residue, and is quickly absorbed.	Compatible with other fungicides. Non phytotoxic
Sphaerex (BASF)	112.5g/l of metconazole and 100g/l of prothioconazole. Doses- 7.3 fl oz/A	DMIs, or demethylation inhibitors They can be both preventive and therapeutic, and they range from locally systemic to non-systemic.	Causes severe skin and eye irritation. dangerous if inhaled. and could irritate the respiratory system. extremely harmful to aquatic life.	Improved output and protection of quality superior efficacy in treating fusarium head blight (FHB) for better quality management. Effective against powdery mildew, rust, Septoria blotch, and black point (also known as kernel blight or smudge).	Compatible for use with liquid fertilizers, insecticides, herbicides, and fungicides. Phytotoxic
Ortiva Top® (Syngenta)	Azoxystrobin: 200 g/liter and Difenoconazole: 125 g/liter. Doses- 0.75 to 1.0 liters per hectare	Prevents the early stages of spore production and fungal development. It offers protection against a range of diseases due to its anti-sporulant properties.	Abdominal pain, diarrhea, vomiting, and nausea are possible side effects. harmful to aquatic life	Ortiva Top is highly effective fungicide for leaf spot, rust, and powdery mildew. It is also stress-relieving and environmentally safe.	Compatible with a large variety of fertilizers and plant protection products. In smaller doses, it is not phytotoxic.
Vercoras FC (BASF)	(Metalxyl group 4, fluopyram group 7, fluxapyroxad group 7, pyraclostrobin group 11,	Prevents electrons from moving between the respiratory chain of the mitochondria. inhibits the	Irritate the skin, avoid contact with skin & eyes.	It works well against root rot, seed rot, and seedling blight. and diseases that are spread by seeds and soil which include alternaria spot and	Incompatible with other fungicides Not highly phytotoxic

	Clothianidin group 4. Doses- 600ml/100kg of seed	growth of mycelia, germ tubes, and spores. selectively interferes with DNA synthesis		blackleg in crops like mustard and canola.	
Miravis Duo (Syngenta)	Pydiflumetofen (also known as ADEPIDYN technology) & difenoconazole	In fungal cells, pyriflumetofen inhibits succinate dehydrogenase, which interferes with growth and energy production. Fungal cell function and proliferation are impacted by the triazole fungicide defenoconazole, which inhibits the synthesis of ergosterol in fungal cell membranes.	After a single intake, it is moderately poisonous, harmful to aquatic life, and has long-lasting effects.	Long-lasting, broad-spectrum disease management that works effectively against leaf spot, powdery mildew, and other fungal diseases in a variety of crops	Compatible with a wide variety of widely used fertilizers, pesticides, and fungicides. Phytotoxic

Conclusion and Future Perspective

The treatment of plant diseases in contemporary agriculture has greatly improved with the creation and use of next-generation fungicides. These cutting-edge fungicides provide an efficient and long-lasting solution to the growing strain on food production brought on by a growing world population and depleting natural resources. New-generation fungicides are distinguished from conventional ones by their targeted modes of action, increased effectiveness at lower dosages, and decreased risks to human health and the environment. By providing broad-spectrum protection and increased crop yield, classes like oxazolidinediones, phenylpyrroles, melanin biosynthesis inhibitors, and strobilurins have revolutionized disease control. These contemporary fungicides have demonstrated efficacy against resistant infections while increasing agricultural output due to their tailored modes of action, low application doses, and no environmental impact. Melanin biosynthesis inhibitors, phenylpyrroles, and strobilurins are examples of innovations that have broadened disease control tactics and provided both preventive and therapeutic advantages. They must be used carefully within integrated disease management frameworks, nevertheless, because their single-site activity also raises the possibility of resistance. Additionally, formulation technology, resistance monitoring, and bio-based substitutes that complement chemical restrictions should be prioritized. Flexible and ecologically friendly fungicide techniques will be crucial to securing global food production and guaranteeing the resilience of contemporary agriculture as climate change brings new disease concerns.

References

Abreu, S.M., Caboni, P., Pirisi, F.M., Garau, V.L. (2006). Residues of the fungicide famoxadone in grapesand its fate during wine production. *Food Additives and Contaminants*. **23**:1-3

Adeniyi, D.O., Kunwar, D., Dongo, L.N., Animasaun, D.A. and Aravind, T. (2021). New-Generation fungicides for sustainable production and disease suppression. *Emerging trends in plant pathology*, pp 249-256.

Bartlett, W.B., Clough, J.M., Godwin, J.R., Hall, A.A., Mick, H., Bob, P.D. (2002) The strobilurin fungicides.*Pest Management Science*, **58**, 649–662

Chao, Y., Chantal, H., Vladimir, V., Yantai, G. (2011). Fungicide: modes of action and possible impacton non-target microorganisms. *Ecology*. **21**:1-8.

Corran, A., Knau, G., Zeun, R. (2008). Fungicides acting on signal transduction. In: Krämer W,Schirmer U (eds) Modern crop protection compounds. Wiley-VCH Verlag GmbH, Weinheim. pp 561-580

Douglas, B.J., Robert, S.L., John, J.B., Keith, E.D., Stephen, O. (1999). Mode of action of famoxadone.*Pesticide Science*, **55**, 105-118.

Dutzmann, S., Berg, D., Clausen, N. E., Kramer, W., Kuck, K. H. (1996). A novel foliar fungicide with aparticular activity against powdery mildew. Proceedings of the Brighton Crop Protection Conference on Pests and Diseases. **1**, 47-52.

Floss, H.G., Manni, P.E., Hamill, R.L., Mabe, J.A. (1971). Further studies on the biosynthesis ofpyrrolnitrin from tryptophan by *Pseudomonas*. *Biochemical and Biophysical Research Communications*, **45**, 781-787

Knight, S. C., Anthon, V. M., Brady, A. M., Greenland, A. J., Heaney, S. P. (1997) Rationale and perspectiveson the development of fungicides. *Annual Review of Phytopathololoogy*, **35**, 349-372.

Koichiro, K., Makiichi, T., Tsutomu, S., Kozo, N. (2003) Diagnosis of dehydratase inhibitors in melaninbiosynthesis inhibitor (MBI-D) resistance by primer-introduced restriction enzyme analysis inscytalone dehydratase gene of *Magnaporthe grisea*. *Pest Management Science*, **59**: 843-846

Koledenkova, K., Esmaeel, Q., Jacquard, C., Nowak, J., Clément, C. and Ait Barka, E. (2022). *Plasmoparaviticola* the causal agent of downy mildew of grapevine: from its taxonomy to disease management. *Frontiers in Microbiology*, **13**, 889472.

Kumar, S. (2009). Plant disease management in India: advances and challenges. *African Journal of Agricultural Research*, **9**(15), 1207–1217

Leadbeater, A. (2015). Recent Developments and Challenges in Chemical Disease Control. *Plant Protection Science*, **51** (4).

Leroux, P. (1996). Recent developments in the mode of action of fungicides. *Pesticide Science*, **47**, 191–197.

Leroux, P., Lanen, C., Fritz, R. (1992). Similarities in the antifungal activities of fenpiclonil, iprodioneand tolclofos-methyl against *Botrytis cinerea* and *Fusarium nivale*. *Pesticide Science*, **36**, 255-261

Longhurst, C., Dixon, K. and Mayer, A. (1996). DE- 795- a novel fungicide for the control ofpowdery mildew in cereals. In Proceedings of the Brighton Crop Protection Conference Pests and Diseases. pp. 21 – 26. Farnham, UK: British Crop Protection Council.

Nabi, S.U., Raja, W.H., Dar, M.S., Kirmani, S.N. and Magray, M.M. (2017). New generation fungicides in disease management of horticultural crops. *Indian Horticulture Journal*. **7**(1): 01-07.

Neumann, G.L., Winter, E.H., Pittis, J.E. (1992). Pyrimethanil: a new fungicide. Proceedings of the Brighton Crop Protection Conference on Pests and Diseases. **1**, 395-402.

Thind, T.S. (2012). New generation fungicides. National symposium on plant health management annual meeting of IPS, NZ September 28–29. pp 148–149

Young, D.H., Richard, A.S. (2001) Mode of action of Zoxamide, a new Oomycete fungicide. *Pesticide Biochemistry and Physiology*, **69**, 100-111.