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ROLE OF FUNGICIDES IN AGRICULTURE AND THEIR IMPACT ON ENVIRONMENT: A REVIEW

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ABSTRACT

In agriculture, protecting crops from fungal infestations is a major global concern. On the market, there are numerous synthetic fungicides that work well against a variety of fungal species. Nevertheless, the fungicides that are now on the market are hazardous to nontarget creatures and pose several health risks. There has not been much focus on the risk and environmental effects of using fungicides as an agrochemical worldwide. The detrimental health effects on living things and the ecological functioning of several commonly used fungicides have not been studied in relation to their ecotoxicological aspects. Communities may be at risk if these various fungicides build up in environmental compartments, including the soil, water and air. This article covers the many kinds of fungicides and how they affect living things that are not targets in different habitats. Additionally, an effort has been made to describe bio-fungicides and their benefits over synthetic fungicides. This article will offer the scientific data required for disease control and application in the future. In conclusion, we delineate the primary research lacunae that presently impede our capacity to forecast fungicide exposure and the consequences and inadequacies of the existing environmental risk assessment for fungicides.

Key words : Control, Disease, Management, Sustainability, Usage.

Introduction

The agricultural landscape is rapidly evolving the world over, with a pressing need to elevate food production per unit of land to feed the constantly growing global population. The task before agricultural scientists is not only to come up to speed with the increased quantity requirement but also to focus on better-quality food materials. Agricultural scientists and farmers thus must explore ways to feed the global population, while being ecologically sustainable, financially viable and culturally acceptable (Arora and Mishra, 2019). Effectively managing crop health from the impacts of biotic stresses is crucial to getting optimal yields. Pest infestations take a significant toll on our crop yield every year, and their scenario keeps changing with the introduction of new agricultural technologies (Oerke and Dehne, 2004). A number of minor crop diseases have gained importance as the effects of climate change on agriculture become more apparent. Through the development of practical and affordable technology, plant pathologists can play a significant role in managing crop diseases. It is estimated that plant diseases account for over 20% of crop output losses in the world's primary crops. Roughly 20,000 of the all fungal species known to exist in the world cause one or more plant diseases. For their control, a number of integrated techniques were developed, including chemical management, biological tactics, agricultural practices, and regulatory activities (Schlundt, 2002). Different strategies are developed depending on the crop and the accessibility of management measures.

A significant global issue for meeting the essential food demand is the projected increase in the world population from 7 billion at present (1.2 billion in India alone) to 8.3 billion by 2030. Simultaneously, the amount of farmland per person is rapidly declining. Feed, food, and fiber will become increasingly necessary as a result

(Collins, 2007). In 2010–11, India produced 241 million metric tons of edible grains, but due to the country's increasing population growth rate, 400 million metric tons will be needed by 2050. Improvements in yield are only possible with effective agricultural inputs, such as fungicides. Although losses due to plant diseases may be reduced using resistant crop varieties, rotational cropping, or hygienic practices, fungicides are often essential to optimize crop production (Atwood and Paisley-Jones, 2017; Tudi *et al*., 2021). Fungicides can play an important role in ensuring plant health assurance by managing destructive diseases in agricultural crops (Cooper and Dobson, 2007; Pandya, 2018; Zhang, 2018). Fungicides are also crucial in raising the standard of food. They manage a variety of fungi that create mycotoxins, which helps to ensure the safety of food. About one-quarter of food crops worldwide are affected by fungal toxins such as aflatoxins, ergot toxins, *Fusarium* toxins, patulin, and tenuazonic acid (Knight *et al*., 1997; Hladik *et al*., 2018; Doan *et al*., 2021). In the U.S. alone, farmers use fungicides to control more than 200 diseases in 50 crops in the field. Fungicides are now well considered to be the secondary defense layer in plant disease control programs after resistance to diseases (Gianessi and Reigner, 2006). Fungicides have been in use since ancient times for the control of plant pathogens and have found a prominent place as an important tool in plant disease management. In some cases, these fungicides are the only means of defense in the absence of suitable host resistance and other control measures. While certain plant diseases can be controlled using resistant cultivars and modifications of cultural methodologies, some other diseases are effectively controlled only by the application of appropriate fungicides. For optimal effectiveness, fungicides are typically administered prior to the establishment of the infections in an adequate spray volume to ensure thorough crop coverage. Approximately 150 distinct chemical compounds categorized under various classes, with an expenditure of 4-5 billion US dollars are used as fungicides globally (Brent and Hollomon, 2007; Cullen *et al*., 2019).

While they are effective in managing plant diseases, their overuse, irrationality, and indiscriminate use present issues for consumer safety and endanger our ecosystem (Atreya, 2007; Damalas *et al*., 2006; Asogwa and Dongo, 2009). The major problems include residue accumulation, resistance buildup, and non-target impacts on other microflora. These fungicides decompose under high temperatures and oxidative conditions, yielding ethylene thiourea as one of their degradation products, which is carcinogenic. Previous studies have insinuated the hazardous effects of pesticides on humans by making them part of natural food chains (Köhler and Triebskorn, 2013).The residue problems are serious, especially when the fungicides are applied at the maturity stage and the minimum waiting period is not followed (Sandhu, 1980). Some fungicides get leached down into the lower soil layers or strata, contaminating the soil and ultimately the groundwater table. Some pathogens also develop resistance in response to the non-judicious use of these fungicides, thus resulting in the development of more virulent strains. Also, these fungicides affect non-target beneficial organisms such as nitrogen fixers, residential antagonists and mycorrhizal fungi (Prasad *et al*., 2017; Chaud*et al*., 2021; Grillo *et al*., 2021; Rajpoot, 2021). The first public awareness concerning the toxicity and non-target effects of fungicides came into light with the publication of Rachel Larson's "Silent Spring" in 1962, which led to a ban on DDT, which was believed to be responsible for the near extinction of bald eagles (Goswami *et al*., 2015).

The current status of fungicides in Indian agriculture

In India, a vast diversity of fungicides belonging to different chemical classes have been registered and are being used to manage a variety of diseases in fruits, vegetables, plantation crops and certain field crops. Benzimidazoles, dithiocarbamates, triazoles, sulfur, copper-based phthalimides and other well-known fungicides are now often used in Indian agriculture, with specialty fungicides reserved for high-value crops. Based on the demand for dyanamics, mancozeb is the most widely used fungicide in India, followed by copper oxychloride, sulfur compounds, copper sulfate, thiram, and carbendazim (Agnihotri, 2000). The group of six fungicides makes up more than 85% of all fungicides that are used, whereas mancozeb makes up only 25% of the total. Other fungicides that make up a sizeable share of the fungicide market in India are hexaconazole, propiconazole, metalaxyl-M+mancozeb, cymoxanil-mancozeb, edifenphos, flusilazole, triadimefon, tricyclazole and azoxystrobin. In India, the agrochemical industry is valued at over 4800 crores, with fungicides accounting for nearly 12% of total sales. When it comes to crops, pome fruits are the most consumed in India, followed by potatoes, tea, rice, coffee, grapevines, and chilies (Thind, 2005).

In addition to topical agents like sulfur, dithiocarbamates, copper-based mercurials, phthalimides, etc., several site-specific fungicides of the groups like benzimidazoles, oxathiins, thiophanates, organophosphorus, triazoles and related sterol inhibitors, phenylamides, cyanoacetamide oximes, cinnamic acid derivatives and some other modern fungicides are also used in India for disease control across a multitude of crops.

In India, a few new-generation fungicides have also been approved for use against certain diseases. These include valinamides against diseases in grapevine, potato, tomato, and cucurbits; oxyazolidinediones effective against potato late blight; and strobilurins (azoxystrobin, kresoxim methyl, trifloxistrobin and pyrachlostribin against powdery mildew and downy mildew in grapevine, cucurbits, and rice sheath blight). Phenyl-ureas (pencycuron, against rice sheath blight, black scurf of potato), and imidazoles (fenamidone, against grape downy mildew and potato late blight) Triazolinthiones (prothioconazole, against rice blast), melanin biosynthesis inhibitors (carpropamid, against rice blast) and manniamides (mandipropamid, against late blight of potato and downy mildew of grapevine). Novel chemicals, including cyazofamid (Cyanoimidazoles), fluopicolide (Bezamides), and zoxamide (Bezamides) are being evaluated for their ability to combat oomycete diseases.

The Central Insecticides Board of India has banned or restricted the use of certain outdated fungicides because of their harmful effects on the environment and ecology. Methoxy ethyl mercury chloride is used under strict monitoring, while mercury-based compounds such as phenyl mercury acetate and ethyl mercury chloride are prohibited due to their long ecological and food chain persistence. Pentachlorophenol and quintozene (PCNB) are prohibited as well because of their detrimental effects on the ecology and environment. These days, captafol can only be used to treat seeds; spraying it is not permitted. Similarly, the use of nickel chloride and ferbam has been discontinued (Anonymous, 2006).

Historical background

The earliest application of brining grain with salt water and subsequently liming it to manage bunt occurred in the middle of the 17th century, following the finding that wheat seeds recovered from the sea were free of bunt. This had occurred long before Tillet, in the year 1755, discovered that treating the disease by treating the seeds with lime or lime and salt would eradicate the fungal infection that produced the bunt of wheat. Since the early 1800s, researchers and scientists have been looking for creative and innovative fungicides to more successfully lower disease losses (Klittich, 2008).

In 1882, Millardet made a crucial discovery in France when he observed that grape vines treated with a bluish-white mixture of copper sulfate and lime to deter pilferers kept their leaves throughout the growing season, while the control grape vines lost their leaves. In the history of chemical disease control, the development of the Bordeaux mixture in 1885 is regarded as the first significant accomplishment. It is included alongside other inorganic compounds in the class of first-generation fungicides. Chemical disease control up until the 1940s relied on formulations of inorganic chemicals, often made by the user.

Several new chemical classes were introduced as fungicides between 1940 and 1960. In comparison to the previously employed inorganic fungicides, the dithiocarbamates and, subsequently, the phthalimides demonstrated notable improvements in terms of potency, phytotoxicity and ease of synthesis. In 1934, dithiocarbamates, quinines, captans and related compounds, pentachloronitrobenzene and low-soluble copper compounds were developed. These compounds constitute the second generation of fungicides, which are organic compounds. Individuals who did not want to spend the time and effort making their own proprietary items are now accessible. Similar to inorganic fungicides, all of these substances were surface protectants (Thind, 2007).

Two of the most popular protectant fungicides, mancozeb and chlorothalonil, were introduced throughout the 1960s and 1970s, sparking a sharp increase in both research and development and the fungicide business. The decade also saw the development of the first broad-spectrum systemic fungicide group, benzimidazoles (benomyl, thiabendazole, and carbendazim), as well as the systemic seed treatment compounds carboxin and oxycarboxin for the control of various foliar rusts in cereals and seed-borne smuts.

The more consequential modern fungicides have debuted since 1970. These third-generation organic fungicides were systemic in nature (Beffa, 2004). These included 2-aminopyrimidenes (ethirimol, dimethirimol), dicarboximides (iprodione, vinclozolin, procymidone), organophosphorous compounds (iprobenphos, edifenphos), triazoles (triadimefon, propiconazole, flusilazole, myclobutanil), piperazines (triforine), imidazoles (imazalil, prochloraz), phenylamides (metalaxyl, ofurace, benalaxyl, oxadixyl, mefenoxam), alkylphosphonates (fosetyl-Al), cyanoacetamideoximes (cymoxanil), cinnamic acid amides (dimethomorpph), morpholines (tridemorph, fenpropimorph) and piperidines (fenpropidine). During this period, the usage compensation rates per hectare saw a drastic reduction owing to the advent of more efficient and specific fungicides. For instance, the existing price below 100 g/ ha for many triazoles against the same pathogen represents a 200-fold drop.

The fourth generation of fungicides consists of compounds that have a somewhat broad spectrum, need minimal dosages, have a unique method of action, and are somewhat soluble. Leroux (2003) enumerates a number of these, such as benzamides (fluopicolide, zoxamide), valinamides (iprovalicarb, benthiocarb), phenylpyrroles (fenpiclonil, fludioxonil), spiroketalamines (spiroxamine), cyanoimidazoles (cyazofamid), thiocarbamates (ethaboxam), mandelamides (mandipropamid) and amidoximes (cyflufenamid). Most of them were developed to fight off oomycete diseases, highlighting the importance of controlling these pathogens. The most recent phenylamide to be registered in 2003 is called Boscalid from BASF. Boscalid is authorized for foliar treatment, either alone or in combination with pyraclostrobin, on a broad variety of nut-bearing fruits, vegetables and crops.

Since their introduction in 1996, sporbolurins have been applied widely to cereals and, more recently, to soybeans, making them the second most widely used class of fungicides. Recently, businesses have also emphasized the advantages of this class of fungicides for plant health when applied to maize and soybeans. The fungicides containing strobilurin have a broad application range, are very efficient and work well on a variety of crops. Due to the fact that certain disease resistance issues are having an adverse effect on sales, corporations are modifying application rules by creating new combinations and additional purposes, such as seed treatments. After azoxystrobin, kresoxim-methyl, trifloxystrobin, pyraclostrobin, kresoxim-methyl, picoxystrobin, and, more recently, fluoxasrobin are commonly used strobilurins (Ayesha *et al*., 2021).

Benthiavalicarb (from Kumiai) and mandipropamid (Syngenta) are recent active ingredients that have been introduced to address a variety of diseases across a variety of crops. Other active ingredients include fluopicolide (Bayer), metrafenone (BASF), proquinazid (DuPont) and zoxamide (Dow Agro), which are members of the carboxylic acid amide (CAA) fungicide group. The reader may consult the book edited by Krämer and Schirmer (2007) for a thorough technical overview of contemporary fungicides, including their chemistry. Agricultural chemical companies have more recently, in 2010 and 2011, produced novel fungicides with creative modes of action for use against a range of diseases. Examples include penthiopyrad (carboxamide) by Du Pont against rust, graymold, powdery mildew and apple scab; fluxapyroxad (carboxamide) by Agrow-BASF for seed treatment and protection for various crops and fluopyram (pyridinylethylbenzamides) by Bayer against powdery mildew.

Fungicides as inducers of host immunity

New anti-fungal chemicals that show strong biological activity—that is, low-dose application, specificity and minimum ecological impact—are essential for effective plant protection against a wide range of fungi. Growing regulatory and environmental restrictions lead to an interest in fungicides, or chemicals with indirect effects that interfere with fungal invasion processes in plants by strengthening host resistance against the fungal pathogen, like carpropamid (Fatma *et al*., 2018). By encouraging the accumulation of harmful compounds and enzymes connected to systemic acquired resistance in rice, probenazole functions as a systemic agent that indirectly treats rice blast and several bacterial rice illnesses; however, it is ineffective in other cereals. Of the non-fungitoxic chemicals that have been developed to date, acibenzolar-S-methyl (Actigard, Bion) has the widest range of effectiveness. It demonstrates efficacy against diverse fungi, bacteria, and viruses across multiple crops and stimulates plants's innate defense mechanisms when applied within a week of infection (Leadbeater and Staub, 2007). Actigard has shown optimal performance when integrated into a regimen of chemical sprays, since the inherent disease control level is rarely adequate when applied independently. This product has sparked an entirely new research domain towards using peptides for disease management and alternative methods to induce systemic acquired resistance (SAR) and the jasmonic acid pathway using chemicals and biological agents in plants. As these compounds do not directly exert selection pressure on the pathogen population, they are less likely to face resistance issues. Compounds with indirect effects on fungi are poised to gain prominence in future crop protection (Shetty *et al*., 2008; Kumar, 2012). Furthermore, innovative operational approaches are essential to counter resistance against current products (Waard *et al*., 1993; Pimentel, 2005). An intriguing realm of research involves employing antimicrobial peptides (AMP) to enhance resistance against fungi, utilizing transgenic plants as biofactories for the production of anti-fungal or antibacterial substances (Hamilton *et al*., 2000).

Non-target effects of fungicide application

A few observations have been made by workers in India related to the influence of a fungicide on other organisms or diseases against which that fungicide is not intended to be used. Singh *et al*. (1984) observed stimulation of soil saprophytes *Rhizopus stolonifer* and *Sclerotium rolfsii* when sugarcane sets steeped in a 0.1% suspension of Bavistin (carbendazim) before planting. These saprophytes caused the rotting of buds. Sawant and Kolte (1985) reported the iatrogenic effect of metalaxyl on *Alternaria* blight in rapeseed and mustard. When used as a seed treatment or spray for downy mildew and white rust control, it increased the severity of leaf blight on toria, yellow sarson, and mustard. Lower doses of copper oxychloride were reported to enhance conidial germination in *Alternaria brassicae* and increase blight severity on cruciferous crops, as reported by Thind and Jhooty (1985). Bavistin (carbendazim) sprays have been reported to increase the severity of bacterial leaf spots in grapes, although they effectively control anthracnose.

Immediate impacts of fungicide action on pathogenic activities Activity may hinder fungal growth or even prove fatal for the invading fungal pathogen. Application of these chemicals may also influence reproduction, including alterations in spores, sclerotia, microsclerotia, and nematode eggs. They may also affect the capability of the propagules to endure and sprout.

The secondary impacts of fungicides on fungi are less precisely outlined because they are associated with diverse and various ecological phenomena. These effects might be demonstrated in interactions among two fungi, among saprophytes and fungi, or among plants and microbes. The killing or inhibiting of soil microorganisms *in situ* by chemicals is a specialized segment of the general field of toxicity of chemicals to microorganisms.

Effects of fungicide application on soil bacteria and their activities

Fungicides may be predicted to have an indirect stimulatory effect on bacteria unless they directly inhibit them. This is because they provide additional organic substrate (such as destroyed fungi) for their growth, and in certain cases, they reduce the generation of antibiotics by fungi.

- **Bacterial Numbers:** Due to the removal of competition and the provision of additional substrate material in the form of killed fungi, the fungicides favor an increased bacterial population in soil or at least have no harmful effects upon them. As a result, there is an increase in bacterial diseases.
- **Nitrification:** Fungicides may severely suppress nitrification in soil. Captan adversely affected soil nitrification. Maneb, Zineb and tribaric copper, applied repeatedly to soil, resulted in decreased nitrification and nitrogen mineralization. Benomyl at 1.5–30 kg/ha in humus sand decreased nitrification after 4 weeks of incubation. In mix cultures of *Nitrosomonas* and *Nitrobacter* sp., however, Van Fassen (1974) found that 20 ppm benomyl inhibited the oxidation of NO_2^- to NO_3^- and that 200 ppm delayed the oxidation of NH_4^+ to NO_2^-, as well as the oxidation of NO_2^- to NO_3^-. Fungicides inhibit nitrification by disrupting the natural process in soil and represent an altered ecological system that may create stress within the entire ecosystem.
- **Nodulation:** Many fungicides show some degree of toxicity towards *Rhizobia* and legume nodulation. Toxicity is often more associated with some strains of *Rhizobia* than others. Quinooximebenzoylhydrazine has been found to be highly toxic to the strains of *Trifolium* and *Phaseolus*. Benomyl and tridemorph had little effect on strains of *Rhizobium leguminosarum*. Oxycarboxin decreased nitrogen fixation.
- **Free-living nitrogen fixation:** copper oxychloride at 40 and 400 ppm completely inhibited the growth of *Azotobacter chrococcum*. Captan applied at field rate to cotton cultivars inhibited *Azotobacter* in the rhizosphere soil.

Effects of fungicides on nematodes

Chlorinated nitrobenzene, and particularly PCNB, has been used to control *Longidorus elongates* and *Xiphinemadiver sicandatum* and the viruses they transmit to strawberries and raspberries. Application of PCNB reduced the populations of *Longidorus elongates* and apparently PCNB inhibited feeding of the nematodes, which resulted in lower numbers after long periods of contact with the fungicide. Among systemic fungicides, benzimidazole fungicides have anti-helminthic properties. Benomyl and thiobendazoles inhibited invasion of the roots of tomato, tobacco, and egg plants by the larvae of *Heterodera*. Benomyl also inhibited the feeding of *Xanthomonas americanum* on cucumber plants previously treated with the fungicides (Goode and McCuire, 1967).

Effect of fungicides on the combined activities of the soil microbial mass

- **Cellulolytic activity and organic matter degradation :** Domsch (1970) reported that captan seriously delayed the formation of cellulases by soil organisms. Low rates of copper sulfate in sand inhibited cellulolysis, but the effect could be overcome by the addition of lime and colloidal humic acid (Baroux and Secher, 1974).

- **Respiration :** *Rhizobium trifoli's* ability to absorb oxygen was reduced by concentrations of 400 and 500 ppm of ethrimol or 100–500 ppm of dodine and captan. Captan inhibited respiration in soils containing or without glucose, cellulose, or chitin; the longer the duration of the inhibited respiration phase, the more resistant the substrate was (Domsch, 1970).
- **Other soil-enzymatic activities :** Fenaminosuf decreased dehydrogenase activity and retarded glucose oxidation in soil (Karanth and Vasantharajan, 1973), while TCMTBC (5–30 kg/ha) in arable soil inhibited saccharase, urease, phosphatase and β-glucosidase activity in proportion to the concentration of the compound (Voets and Vandamme, 1970). Degradation of cutin, pectin, and glucose was severely delayed in soil treated with captan (Domsch, 1970).
- **Ammonification :** With increasing concentrations up to 30 kg/ha, TCMB reduced ammonification in a humus soil (pH 5.7) (Voets and Vandamme, 1970). In soil (pH 5.3) treated with benomyl, captan, quintozine, or Thiram, ammonification was likewise enhanced (Wainwright and Pugh, 1973). However, in sand inoculated with a soil suspension, low concentrations of copper sulfate hindered ammonification (Baroux and Sechet, 1974).

Induction of non-target pests

The application of disease management technology enables some secondary pests to become more important. The increased use of narrow-spectrum fungicides has also increased the significance of some non-target fungi. This has occurred where benzimidazole fungicides have been applied; e.g., *Pythium* blight of turf and *Pythium* stem rot of cowpea were more severe in the presence of benzimidazoles than in their absence. Many basidiomycetes are less sensitive to benzimidazoles than are most ascomycetes (Frazer, 1963). The application of these fungicides to suppress diseases induced by ascomycetes can increase diseases induced by basidiomycetes; e.g., benzimidazoles suppressed the pathogenic activities of *Fusarium* sp. on rye and increased yield, but at the same time, the severity of sharp eye rot disease caused by *R. solani* increased by about tenfold. A significant proportion of the fungicides used to control diseases find their way into the soil, where they may be degraded by microbial action, through direct chemical reactions, or move in the soil water and in direct run-off to water courses or to the underlying water table. The fungicides entering water courses may adversely affect aquatic life. Likewise, fungicides may affect soil microorganisms or may be consumed by animals and introduced into food webs. Therefore, all the new compounds must be investigated concerning their environmental fate and safety at an appropriate stage of development (Zyoud *et al.*, 2010).

Physiological basis of host-pathogen-fungicide interactions

A few reports are also available wherein the Indian workers have reported the interaction of the host or the pathogen with the activity of fungicides (Paul *et al.*, 2001). Modification of toxicity of cycloheximide by leaf exudates of tomato and higher inhibition of spore germination of *Cladosporium fulvum* on the leaf surface of tomato were observed, indicating some interaction between leaf exudates and cycloheximide (Grover *et al.*, 1976). Carbohydrates and amino acids in the leaf exudates were considered to modify the cycloheximide toxicity (Bakshi *et al.*, 2022). Thind and Jhooty (1985) observed that leaf exudates of cruciferous crops were responsible for the differential toxicity of fungicides on these hosts, and their interaction with copper oxychloride decreased its toxicity to a significant extent. The physiological effects of fungicides on some crop plants have been investigated by some workers in India (Xi *et al.*, 2022). Various physiological processes are documented to be influenced by the use of pesticides (Hatamleh *et al.*, 2022).

A good amount of work has been done on the effects of benzimidazole fungicides like carbendazim on the growth and biochemical parameters of host plants, as these fungicides are considered to have growth regulatory activity (Peng *et al.*, 2023). Mukhopadhyay and Bandopadhyay (1977) reported that carbendazim showed cytokinin-like activity on chlorophyll retention in wheat and oat leaves. Various effects on host physiology, like an increase in protein, total nitrogen, total phenols, peroxidase, and ascorbic acid, a decrease in sugar and amino acid contents, and other metabolic changes, have also been reported in groundnut following benomyl or carbendazim treatment by Vyas and Thomas (1986). Gautam and Thapliyal (1986) documented the physiological effects of Bayleton (triadimefon) and Baytan (triadimenol) on soybean plants. They observed temporary stunting of soybeans after seed treatment with these triazole fungicides, and the seedlings recovered after 40 days. However, seed treatment at higher rates reduced germination and nodulation. There was an increase in chlorophyll and photosynthetic rate at their low concentrations (Roman *et al.*, 2021).

Fungicide residues in agricultural produce

The residue problem is also the most important problem in fungicide use. The fungicide residue level in soil or edible parts varies with the dose of the fungicide used and with the total number of sprays done. If the dose used is high and is applied at an improper time, and the total number of sprays exceeds the recommended number, there are higher chances of residues left in the crop at harvest than the prescribed tolerance limits. Similar observations have been reported in the case of captan used as a spray against the storage rot of kiwi fruit by Beever *et al. (1984)*. Ladania *et al. (*1987) have also reported that the dose and number of sprays of Bavistin have considerable influence on carbendazim residues in grapes, and these residues may be reduced if they are washed with water. On betel vine also, with a 0.05% concentration, the residue of carbendazim was 6.35 ppm, as compared to 12.07 ppm with a 0.1% concentration (Guha *et al*., 1990). Jain and Agnihotri (1987) also reported the residues of thiophanate methyl and MBC on apples to be higher with higher doses as compared with the lesser doses used, and these residues persisted beyond 30 days. Sharma and Nath (1992) suggested a waiting period of 30 days between treatment with bitertanol and the harvesting of apples. The residues have been reported to decrease with time. The persistence of carbendazim residues in the rhizomes of ginger showed that the initial deposits of 23.46 ppm degraded to 7.3 ppm and 2.1 ppm in 30 and 90 days, respectively. No residue of carbendazim could be detected after 120 days of treatment (Sharma *et al*., 1991).

Plant-based products as fungicides

Plant-based products such as aqueous and alcoholic extracts of fresh and dry plant parts and oils from various plant species have been tried by several workers for their fungitoxic potential to control different plant fungi under laboratory and field conditions. Some of these have demonstrated good activity under controlled conditions when tested using laboratory bioassays, but very few have shown the desired activity to control the disease in the field. Generally, higher doses of these products are required to achieve the desired level of inhibitory effects compared to standard fungicides. Some of the products, notably essential oils from some medicinal plants, have been reported to be quite effective against powdery mildew fungi. Much of the work on the antifungal activity of plant products has been done at traditional universities. However, keeping into view the ill effects of chemical fungicides and the availability of diverse and rich flora in the Indian subcontinent, there is a need to strengthen the research on the anti-microbial potential of plant products and improve the delivery systems for field applications (Kaur *et al*., 2023).

Role of Seed treatment

Applying a chemical, biological, or physical treatment to seeds helps preserve them and promotes the growth of robust crops. During the germination phase, it offers the seed good protection against soil-borne and seed-borne diseases and promotes early plant development. A wide variety of fungicides for seed treatment are currently on the market. These include the more modern and safe combinations like mefenoxam + fludioxanil and azoxystrobin (Syngenta) and pyraclostrobin + metconazole (BASF), which were developed between 2008 and 2010. There are also conventional chemicals like carbendazim, mancozeb, thiram, captan and carboxin. Sedaxane (Syngenta) and fluxapyroxad (Agrow-BASF), two novel seed treatment fungicides, were more recently released in 2011. With the United States holding a larger than 50% share of the global market, the seed treatment industry is anticipated to be worth over $2.5 billion. This market is expected to grow further since seed treatments are thought to be an affordable way to preserve increasingly expensive seed. According to projections from the Directorate of Plant Protection, Quarantine and Storage, Faridabad, farmers' own stock provides 70% of the country's seed needs, with the majority of this seed being sown untreated. A significant portion of seed, whether bought from private or public sector organizations, is untreated. Furthermore, according to the estimations, 80% of the seed sown in the nation is untreated on average, compared to 100% in industrialized nations. This could be one of the various causes of our poorer crop productivity when compared to developed countries. Thus, there is a lot of room for improvement in our agricultural yields with the right seed treatment procedures. Future seed treatments might employ several compound products for a complete spectrum of pest and disease control.

The problem of Fungicide resistance and its management

However, the gravest issue is the emergence of fungicide resistance strains, leading to the failure of pathogen management. Fungicide resistance is now a widespread issue in global agriculture. The uncontrolled application of fungicides has led to the emergence of fungal resistance. This has led to ineffective disease management in many instances. The implementation challenges of fungicide resistance emerged much later with the introduction and extensive utilization of targeted systemic fungicides for controlling plant fungi. When initially uncommon mutants survive and proliferate after being exposed to fungicide treatment, resistance accumulates. This can happen gradually (known as polygenic development) or suddenly (due to a single gene mutation). Resistance mechanisms differ; however, they all primarily include changing the fungicide's principal site of action inside the fungal pathogen. Although growers are not typically thought of as the primary victims of fungicide resistance, resistance has larger consequences for sustainable farming (Wilson and Tisdell, 2001). Due to the possibility of yield losses from ineffective disease control, fungicide resistance endangers not only the effectiveness of individual fungicides but also the farm economy. Therefore, it is everyone's responsibility to guarantee the ongoing effectiveness of the greatest goods that are available for commercial use. More than 100 illnesses (crop-pathogen combinations) and around half of the known fungicide groups have been linked to field-related fungicide resistance issues (Brent and Hollomon, 2007).

The first cases of fungicide resistance in practice were reported soon following the registration and widespread application of the systemic fungicides benomyl (benzimidazole) and dimethrimol (aminopyrimidine) in the early 1970s (Bent *et al.*, 1971). Protectant fungicides, including maneb and mancozeb or copper compounds were widely employed and effective against a variety of diseases by growers prior to the discovery of benomyl. These fungicides are still in use today. One notable benefit of benomyl was its systemic activity, which, when given after the early stages of infection, provided disease management in addition to protecting plants from infection. When compared to the protective dithiocarbamates, benomyl was frequently more effective in controlling illness. However, when the fungicide was applied heavily, resistance issues surfaced after a few years, and diseases such as powdery mildews, apple scabs, peanut leaf spots, and *Botrytis* suddenly failed to respond to treatment (Brent, 1995).

Aside from having a site-specific mode of action, the majority of fungicides created and approved after benomyl's release (morpholines, dicarboximides, phenylamides, organophosphorus, sterol biosynthesis inhibitors, etc.) also carry the danger of developing resistance. With the exception of phenylamides, resistance concerns to many of these fungicides may not be as high as those to benomyl; still, strategies to manage the resistance risk should be devised and put into practice in order to prevent unanticipated failures in disease control and prolong the usable life of these fungicides. In comparison to most of the earlier fungicides, more novel compounds with distinct modes of action have been developed over the past ten years, including quinolines, phenylpyridylanines, spiroxamines, anilinopyrimidines, strobilurins, and phenylpyrroles. These compounds have a more potent action against a variety of fungi at much lower rates. But some of these newer drugs, like strobilurins, have been found to pose a resistance risk. As a result, appropriate measures must be taken to both achieve the intended disease control and preserve the new drugs' useful lives (Van der Werf, 1996).

Preventing target fungi from acquiring resistance and boosting the fungicides' efficiency against a wider spectrum of plant diseases are the two primary objectives of fungicide mixtures, which are composed of two or more fungicides with different modes of action (Van den Bosch *et al.*, 2014). When combined, these compounds often augment the potencies of each individual chemical by working together. Amistar Top (azoxystrobin + difenoconazole) against a variety of diseases on a variety of crops (Mahmoud *et al.*, 2016); Prosaro (prothioconazole + tebuconazole) against head scab in cereals (Sreš, 2011) are a few of the recently developed and extensively used fungicide mixtures (Nielsen *et al.*, 2021).

As a result, a management plan needs to be put in place before opposition causes issues. Delaying the onset of fungicide resistance is the goal of management strategies. The target pathogen or pathogens, the crop, and the various fungicide groups all have different specific resistance management strategies (Thind, 2011). In situations, where pathogen management is insufficient, surveillance is essential to determine whether resistance is the root cause and to confirm the effectiveness of resistance management strategies. The verification of approaches should be initiated at early stages to acquire essential foundational data before commercial application begins. Findings must be analyzed with precision to prevent misleading inferences. Resistance management should incorporate traditional cultural practices and optimum fungicide application strategies. The preferred outcome is to reduce selection pressure through a reduction in the time of exposure or the magnitude of the exposed population to the vulnerable fungicide. Based on the findings, application strategies are designed to mitigate the probability of fungicidal resistance accumulation or, worse, the diminution of the efficacy of fungicides.

The Fungicide Resistance Action Committee (FRAC) works closely with manufacturers due to the concern of fungicide resistance and the prevalence of cross-resistance to similar products from different manufacturers. Strategies to reduce the danger of resistance accumulation are produced by combining the results of studies on field monitoring, resistance risk, and mode of action. To help in understanding the resistance risk of the various fungicide groups, FRAC has developed many monographs on various aspects of fungicide resistance and has grouped the available fungicides according to various criteria. The unpredictable nature of cross-resistance complicates such estimations of resistance risk. Certain fungicide groups, such as phenyl amides, dicarboximides, benzimidazoles, and strobilurins, are more likely to cause resistance than others. Periodically, the FRAC working groups and FORA for the at-risk fungicides convene to propose strategies and tactics for mitigating the danger of resistance accumulation in key fungi. At the outset of introducing a new fungicide compound, it is important to take proactive measures.

Conclusion and Future Aspects

Fungicides, besides having some drawbacks, are likely to continue as the second line of defense to save our crops from the ravages of plant diseases. However, regular and irrational use of these chemicals often leads to problems with residues in edible plant parts and the development of fungal resistance, apart from environmental pollution. In order to cope with these problems, there is a strong need to rationalize the use of fungicides and make it need-based. The study of disease epidemiology can be useful in initiating fungicide applications through the development of disease prediction systems. In India, where most of the farmers have small lands, it may not be economically feasible to recommend regular fungicide applications. Technologies need to be developed for the integration of fungicides with bio-control agents to minimize their use. Research needs to be strengthened to explore the potential of plant-based bio-fungicides for the control of plant diseases, as India is a storehouse of diverse plant species, and extracts and oils of many species are known to possess antifungal efficacy. Some agrochemical companies have recently introduced eco-friendly compounds derived from microbial species, and these can be tried in India as well in order to replace existing, more toxic compounds.

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