

farmers are faced with the constraints of significant labor, cost, and time.

- 2) *Chemical Control*: Chemical control involves the use of fungicides either preventively or curatively to control fungal diseases [66]. Chemicals that contain mancozeb, chlorothalonil, thiophanate methyl, or copper-based compounds are sprayed on ginger plants to reduce the impact of fungal infections. Another chemical control is the use of pesticides to manage insect vectors that can transmit viral diseases. The use of chemical control can provide immediate relief from pest and disease pressures; however, this can harm the environment and soil health [52].
- 3) *Planting Resistant Varieties*: Disease-resistant varieties are obtained from reputable sources to reduce the risk of introducing pathogens into the field. However, this is a long-term strategy. Finding disease-resistant rhizomes in ginger necessitates the use of an effective and trustworthy disease-screening technique. For instance, selection methods for locating resistance to bacterial wilt in ginger plants were investigated in [49]. This includes pseudostem inoculation, rhizome inoculation, soil inoculation, and an in vitro method. The result of the study shows that the soil inoculation method outperformed the other methods due to its simplicity and large-scale adoption in a short time for bacterial wilt resistance in ginger.
- 4) *Biological Control*: Some beneficial microorganisms, such as certain strains of *Trichoderma* spp. or *Bacillus* spp., can antagonize plant pathogens and help suppress disease development. These biocontrol agents can be applied to the soil or foliage as a part of an integrated disease management approach [45], [50], [51], [54]. This requires regular scouting of ginger plants for signs of fungal diseases, such as leaf spots or rhizome rot, and take prompt action if symptoms are observed.

B. Smart and Precision Methods

The emergence of innovative technologies and the need to minimize the huge loss of ginger are paving the way for innovative approaches to disease detection and management of ginger [67]. These involve the integration of advanced technologies to optimize disease management practices in ginger cultivation. These methods focus on the use of technologies, such as AI, IoT, and robotics, for precision, efficiency, and sustainability by leveraging data and automation. By combining these advanced technologies, growers can potentially enhance the efficiency and effectiveness of disease management strategies for ginger crops, leading to improved yields, reduced input costs, and minimized environmental impact. The different smart and precision methods are discussed as follows.

- 1) *Precision Agriculture Technologies*: The use of technologies, such as drones, satellites, and IoT, for remote sensing enables the capturing of high-resolution images and data, allowing for early intervention and targeted treatments. The ginger fields can be monitored to ascertain the health of the ginger plants, detect early signs of diseases, and assess the overall condition of the plants. Furthermore,

soil conditions can be monitored using IoT devices in real time. Various parameters, such as soil moisture, pH, temperature, and nutrient levels, can be analyzed to maintain the optimal condition of the soil. This helps to reduce the risk of diseases, such as root rot.

- 2) *AI Modeling and Data Analytics*: The use of collected soil data from sensors, weather data, and historical ginger crop performance can be used to predict disease outbreaks. This allows farmers to implement preventive measures before diseases become widespread. The adoption of ML models can be used to analyze the data to identify patterns and provide recommendations for disease management. These models can help optimize irrigation schedules, pesticide applications, and other management practices.
- 3) *Automated and Robotic Systems*: Smart irrigation and fertigation systems can be used to control the amount of water and fertilizers applied to the ginger plants. This involves the use of sensors to monitor the soil condition to prevent overwatering and also ensure ginger plants receive the right amount of resources. This helps reduce diseases, such as rhizome rots. In addition, robotics are used for precision spraying of fungicides, pesticides, weeding, planting, and even harvesting. They provide increased accuracy and efficiency of disease management operations while reducing labor costs. This promotes sustainable farming practices by minimizing the environmental impact of agriculture through precise application of inputs. The drawback is the initial investment, which can be a barrier for small-scale farmers.

V. GINGER DISEASE DETECTION

The detection of diseases can be classified into two categories, which are molecular methods and image processing methods. The two categories are discussed as follows.

A. Molecular Method

Polymerase chain reaction (PCR) is a powerful molecular biology technique used to amplify and detect DNA sequences associated with pathogens. For ginger diseases, PCR-based methods are used for precise and specific detection of various pathogens (viruses, bacteria, and fungi). Some of the PCR techniques are conventional PCR, real-time PCR (qPCR), reverse transcription PCR (RT-PCR), multiplex PCR, and nested PCR.

- 1) *Conventional PCR*: Fundamental for detecting specific DNA sequences, widely used due to its simplicity and cost-effectiveness.
- 2) *Real-Time PCR*: The qPCR provides real-time quantitative data, highly sensitive and specific, essential for assessing pathogen load and disease severity.
- 3) *RT-PCR*: The use of RT-PCR was employed in the detection of cucumber mosaic virus [43] and chlorotic fleck virus [45]. Targets RNA viruses by converting RNA to cDNA, crucial for detecting RNA-based pathogens, such as ginger mosaic virus (GMV) in ginger.