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Review article

A comprehensive review on soft rot disease management in ginger (*Zingiber officinale*) for enhancing its pharmaceutical and industrial values

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A R T I C L E I N F O

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Bio management

A B S T R A C T

Zingiber officinale L. Roscoe is a significant herb that possesses many medicinal and ethno-medicinal properties. Due to the presence of various bioactive compounds, it has immense healing capacity. However, ginger as a crop is susceptible to several fungal pathogens. Among all the fungal pathogens, *Pythium* and *Fusarium* spp. are of most concern, causing soft rot (rhizome rot) disease, majorly responsible for the downfall in its production by 50–90%. Pesticides and fungicides spray is generally recommended for the control of soft rot. Ample use of chemicals not only affects the quality of the crop but also disturbs ecological integrity. Therefore, biological methods of disease management involving suitable microbial agents such as *Trichoderma harzianum, Pseudomonas* spp., *Bacillus subtilis, Streptomyces* spp. and plant extracts are attracting and gaining importance as a part of integrated approaches (IPM) to manage the soft rot and sustainably enhance the production and improve the medicinal and pharmaceutical values of ginger. The present review is aimed to discuss various means of controlling soft rot disease by physical, chemical, biological, and nanotechnology-based methods. Moreover, various bioactive constituents of ginger and their pharmaceutical importance have been also discussed.

1. Introduction

A tropical herb called ginger is grown for its food and medical benefits in many countries across the world, including China, Japan, India, Nigeria, Taiwan, Sri Lanka, Fiji, Hawai, Australia, and Korea. India is among these countries' top ginger growers, with the plant taking up the most space and yielding the most [1,2] Fig. 1(a). Meghalaya, Orissa, Arunachal Pradesh, Gujarat, Karnataka, Kerala, and Assam are key ginger-producing states of India, and combined they account for roughly 65% of the nation's overall ginger productivity [3] Fig. 1(b). The annual global commerce in ginger is thought to be worth around US$190 million. Approximately 60–70% of ginger is produced globally. Of this, roughly 30% is transformed into dry ginger, 50% is used to make greenish ginger, and the remaining 20% is turned into a seed [4]. Since ginger is among the most significant species of the family Zingiberaceae and contains such significant medical, nutritive, and indigenous medicinal characteristics, it has received widespread usage as a spice, culinary ingredient, and traditional cure around the globe [5]. In terms of its therapeutic benefits, ginger has qualities that include antibacterial,

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anti-inflammatory, antipyretic, antioxidant, anti-diabetic, hepatoprotective, renal, and anti-carcinogenic [6,7].

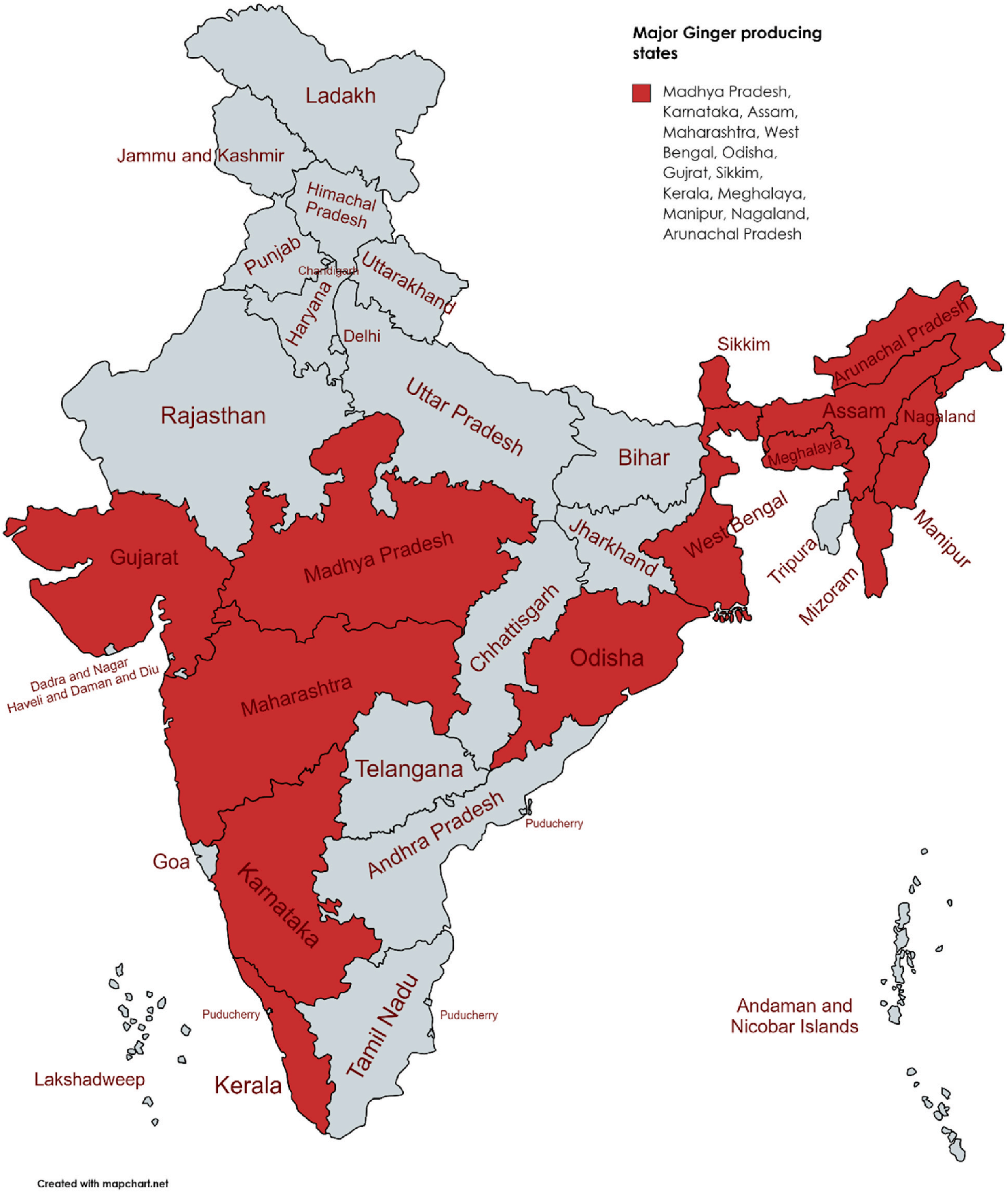
Ginger's rhizome typically comprises water, aromatic oils, carbohydrates, proteins, lipids, and fibers. Ginger has prospective implications in conventional therapy for numerous therapeutic advantages in complement to its nutritive and taste properties [8]. Owing to soft rot illness, ginger productivity has regrettably decreased with time despite periodic increases in the overall territory for agricultural production attributable to the enormous significance of ginger. One of the prevalent illnesses affecting ginger is known as soft rot, which is typically brought on by the fungi *Pythium* and *Fusarium* spp. as well as the bacteria *Ralstonia* spp. The microorganisms affect the root, collars, and juicy sections of the rhizome to cause the malady. The most harmful and damaging ailment of ginger recorded worldwide is soft rot. Although it is challenging to obtain precise data, it is believed that ginger soft rot causes a yield decline of between 50 and 90% [9]. Since then, numerous different *Pythium* spp. have been implicated in the soft rot of ginger. When investigating the 11 *Pythium* varieties linked to ginger soft rot, Dohroo et al. [9] found both *P. aphanidermatum* & *P. myriotylum* were the most common.

Over 15 *Pythium* varieties were identified as ginger pathogens, as indicated in research by Le et., al [8]. Additionally, *P. aphanidermatum* has been recovered in ginger soft rot, which accounts for around 60% of yield reduction. Le et al. [10] identified 11 distinct *Pythium* taxa linked to ginger rhizomes off fields in Queensland, Australia, as well as tested these for pathogenesis against ginger in a subsequent investigation. Additionally, reports of many additional *Pythium* subspecies, including *P. myriotylum Drechsler* [11] and *P. aphanidermatum Fitzpatrick* [12], came from several nations, including Taiwan, India [13], Malaysia, the United States, Japan, Fiji, and Australia [14]. In addition to *Pythium*, *Fusarium* is yet another significant fungus that has been linked to ginger soft rot. *Fusarium* comes in a variety of species, but *F. oxysporum.* sp. *zingiberi* has become the most prevalent species and is mostly responsible for the significant decline in ginger yield caused by decomposing ginger rhizomes [15]. Altogether, the cultivation of ginger has been severely impacted by the two fungi listed previously, culminating in considerable financial loss. Consequently, it is vital to control ginger's soft rot. While there are several commercial antifungals in the business to manage those fungi, using them can have harmful effects on the ecosystem.

Additionally, repeated application of synthetic antifungal agents has led to the development of fungicide resilience in fungal infections and diminished soil quality [16]. In substitution for synthetic fungicides, the use of several biological control, including *T. harzianum* and plant isolates, are thought to be environmentally benign and sustainable [17,18]. Furthermore, it has been shown that applying holistic control techniques to the management of soft rot is relatively efficient. There is an urgent demand to research and create fresh strategies for the quick and efficient control of soft rot of ginger considering the magnitude of the illness and financial damage. Given that different nanoparticles have diverse antifungal properties, it is thought that nanotechnology can be extremely important in the treatment of such illnesses. Soft rot of ginger causes a significant impact on the pharmaceutical and phytochemical value of the crops. The premature loss of crops and damage during storage leads to a significant reduction in the yield of numerous components of ginger having prominent pharmaceutical values. Effective management of the pathogen is necessary to maintain and improve the value of ginger both financially and pharmaceutically. This review focuses on various strategies to treat the soft rot of

(a)

Fig. 1a. Major Ginger producing countries (https://www.atlasbig.com/en-in/countries-by-ginger-production, Accessed on 03/07/2023).



(b)

Fig. 1b. Major ginger growing states of India (Source- National Horticulture Board 2021–22).

ginger disease.

2. Chemistry and pharmacology of ginger

The principal bioactive compounds present in ginger's rhizome can be generally categorized into non-volatile and volatile phenolic chemicals, the majority of whom have unpleasant characteristics (Fig. 2). It is commonly accepted that the chemicals from these categories, particularly the non-volatile spicy phenolics, are responsible for the ginger rhizome's pharmacologic impact. The main kind of gingerols and their derivative products, such as gingerdiols, are analogous phenolic alkanones found in healthy rhizomes. The main component of these substances is 6-gingerol, whereas 8- and 10-gingerol exist in lesser quantities [19–23]. Most of the volatile oil's constituents are mono- and sesquiterpenes, including terpenes, camphene, curcumene, beta-phellandrene, cineole, terpineol, geranyl acetate, borneol, linalool, geraniol, limonene as well as alpha-zingiberene (30–70%), beta-sesquiphellandrene. The main aroma-contributing constituent, zingiberol, along with zingiberene, diarylheptanoids, vitamins, gingediol, and phytosterols have also been discovered in the oleoresin [24].

By reducing body fat and enhancing soft lean mass, ginger can enhance body composition. Ginger extract protects against obesity brought on by high-fat diets. By preventing its hydrolysis, the aquatic extract of *Z. officinale* known as Roscoe may reduce the gastrointestinal uptake of ingested fat. As a result, ginger appears to enhance body balance by altering liver enzymes, decreasing the uptake of fat, boosting the beta-oxidation of lipids, and raising calorie expenditure [25]. Ginger has a potent analgesic effect that frequently results from COX-1 antagonism. Aspirin is less effective than gingerol and its derivatives, particularly paradol, at inhibiting COX-1 [26]. Ginger is among the plants that are most frequently used to alleviate morning sickness and vomiting during pregnancy [27]. The shogaols, gingerols, and galanolactone of ginger are assumed to be the constituents of ginger that are accountable for the antiemetic effect, while the precise mode of operation of ginger on vomiting and nausea is yet unknown [28]. Other pharmacological roles of ginger are listed in the table below (Table 1 and Figs. 3 and 4).

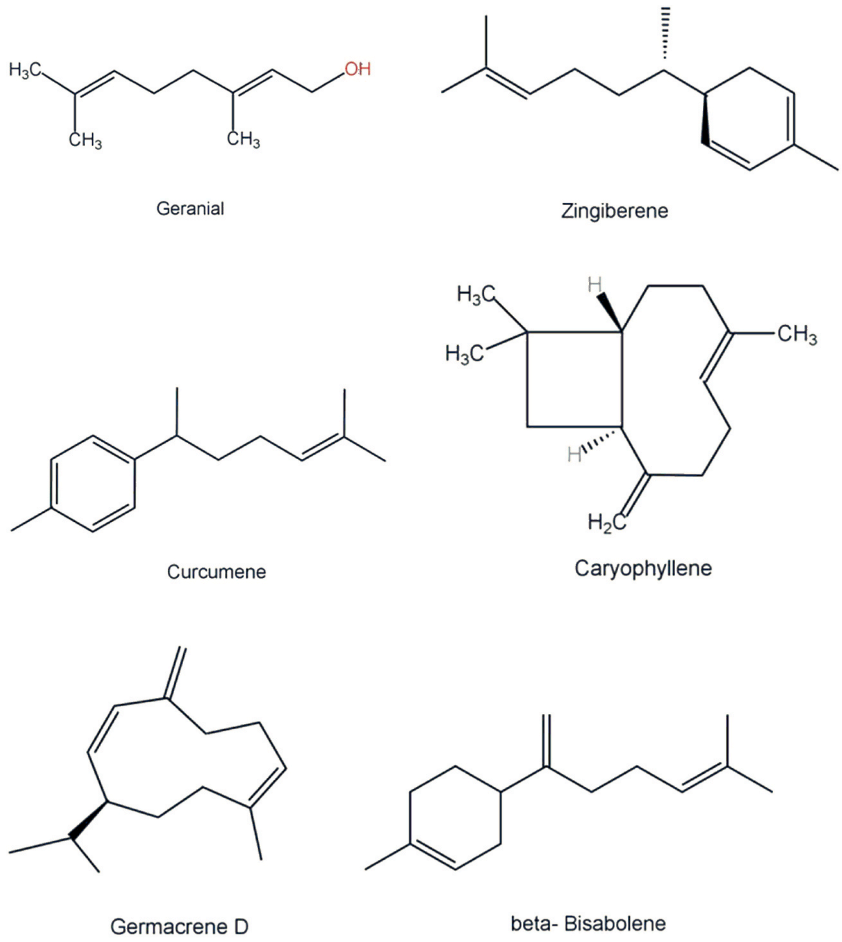


Fig. 2a. Important bioactive compounds of *Zingiber officinale.*

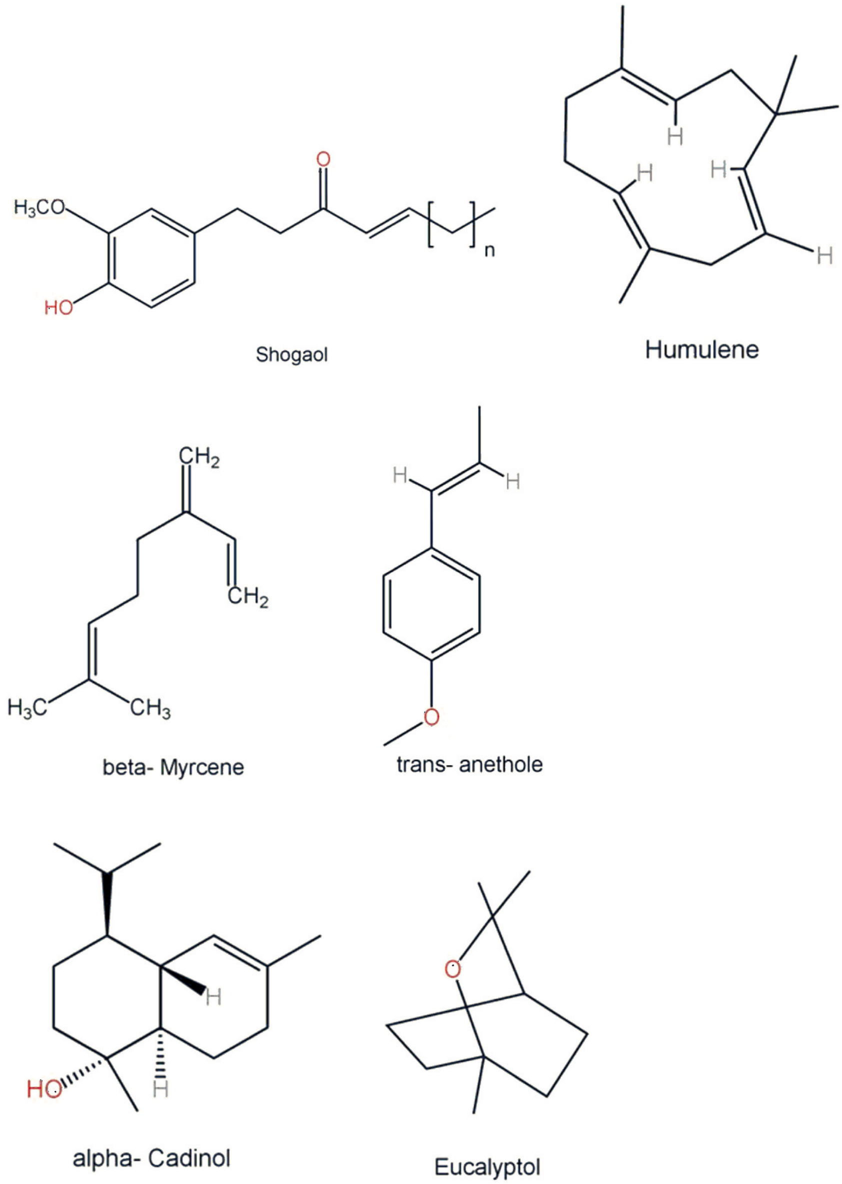


Fig. 2b. Important bioactive compounds of *Zingiber officinale*.

3. Impact of soft rot disease on the production of ginger

The soft rot microorganisms can afflict hosts at any phase of development, including post-harvest storing, wherein development from dormant infectious agents can result in significant damage. The majority of *Pythium* species thrive in the ground when soil temperatures are elevated and wetness levels are close to or above saturation [14]. Around the summers of 2007–2008, these circumstances happened in Queensland, Australia, the province that produces ginger, and they led to a 5–30% reduction of premature ginger in certain contaminated farms [14]. Such losses were also reported in various other countries including India, Fiji, Taiwan, Korea, Japan, etc.

All such significant damages have typically happened in seasons with suitable climates for disease proliferation. *Pythium* spp. has a significant negative influence on preservation as well; losses between 24 and 50% were recorded, while levels sometimes surpassed 90% in India [9,29].

4. Morphology of *Pythium* spp.

The *Pythium longisporangium* specimen exhibits morphology that is characteristic of a *Pythium* family. It is an oomycete that grows

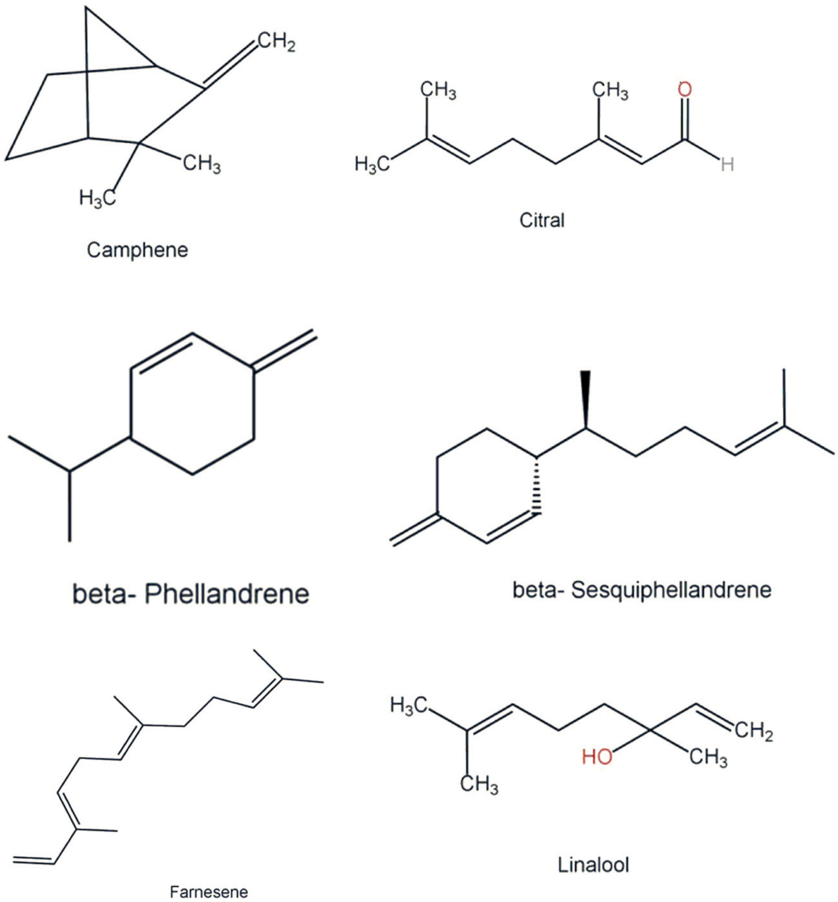


Fig. 2c. Important bioactive compounds of *Zingiber officinale.*

slowly and has a huge, globe-to-cylinder-shaped sporophyte, sleek-walled oogonia, and primarily hypogynous antheridia [30].

5. Life cycle of *Pythium* spp.

Pythium persists as oospores, hyphae, and sporangia in the ground. The fungi can persist as oospores in unfavorable moisture in the ground and temperatures for a long period. Oospores can create sporophytes or a germ tract to invade the plants effectively. The mobile component of the fungi, known as zoospores, is produced by the sporangia. Before encysting and producing a germ tube that can spread illness, the zoospores float along for a short amount of time. Comparable to oospores, sporophytes that have formed on crop tissues possess the ability to sprout both directly and via producing zoospores (Fig. 5). When contaminated waste is moved to uninfected regions and the ground is sufficiently moist for the zoospores to float easily, the disease is disseminated [31].

6. Symptoms of soft rot disease

For a timely intervention to decrease yield loss, prompt identification of soft rot disease is crucial. For cultivators, the illness is primarily recognized by signs that are visible above the soil, such as withering and yellowing. Soft rot initially manifests as wet, brown blisters above the ground sections at the rhizome-stem junction, or "collars." The branch and rots then collapse as a result of such lesions growing larger and coalescing [9]. The very first signs of a baseline illness on leaflets are a yellowing of the apex of mature leaves, followed by discoloration that progressively spreads across the border to affect the whole of the leaf blades and then the sheathing. New leaflets begin to acquire an equivalent symptomatic development as affected leaves shrivel and exhibit necrotic signs, and so forth till the plants as a whole perish [32]. After this, sick branches can sometimes be readily pulled away since there won't be any mechanical support holding them to the root systems [9]. The ginger crops might live, but they may stay unproductive and dwarfed if the illness is not extensive [33]. Root systems from sick crops have a brown, wet, decaying appearance and therefore will eventually decompose [9]. The illness's signs could be confused with those of either microbial withering produced by *R. solanacearum* or *Fusarium* yellows, which are both induced by the fungus *F. oxysporum f.* sp. *zingiberi*. But a deeper look at the characteristics ought to make the three illnesses distinct.

Table 1
Chemistry and Pharmaceutical value of ginger.

S. No.	Chemical compounds	Chemical compounds identification techniques	Pharmaceutical value	References
1	Geranial	Gas chromatography-mass spectrometry	Anti-bacterial, antifungal, antioxidant	[134–136]
2	Eucalyptol	Gas chromatography-olfactometry	Anti-bacterial	[134]
3	α-zingiberene	Gas chromatography-mass spectrometry	Anti-bacterial, antifungal, antioxidant, anti-inflammatory	[134–138]
4	ar-curcumene		Anti-bacterial, antifungal, 5antioxidant, Anti-i6nflammatory	[134–138]
5	β-bisabolene		Anti-bacterial, antifungal,	[135]
6	β-sesquiphellandrene		Anti-bacterial, antifungal,	[135,136]
7	Germacrene-D		Anti-bacterial, antifungal,	[135]
8	Camphene		Antifungal, antioxidant, cytotoxic	[137,139]
9	β-phellandrene		Antifungal, antioxidant	[137]
10	caryophyllene	Raman spectroscopy and principal component analysis	Antibacterial, antioxidant	[136]
11	α-farnesene	Gas chromatography-mass spectrometry	Antibacterial, antioxidant	[136]
12	6,9,9-tetramethyl-2,6,10-cycloundecatrien1-one		Antimicrobial	[140]
13	b-myrcene	Gas chromatography-mass spectrometry	Anti-inflammatory, Larvicidal, and repellant	[138,141]
14	Citral	High speed liquid chromatography	Anti-inflammatory, cytotoxic	[138,139]
15	α-cadinol	Gas chromatography-mass spectrometry	Larvicidal and repellant	[141]
16	α-humulene		Antimicrobial	[142]
17	Linalool	Nuclear magnetic resonance spectroscopy & Gas chromatography-mass spectrometry	Cytotoxic	[139]
18	*Trans*-anethole	Gas chromatography-mass spectrometry	Antibacterial	[143]
19	6-shogaol	Liquid Chromatography-Mass Spectrometry/Mass Spectrometry	Antioxidant	[144]

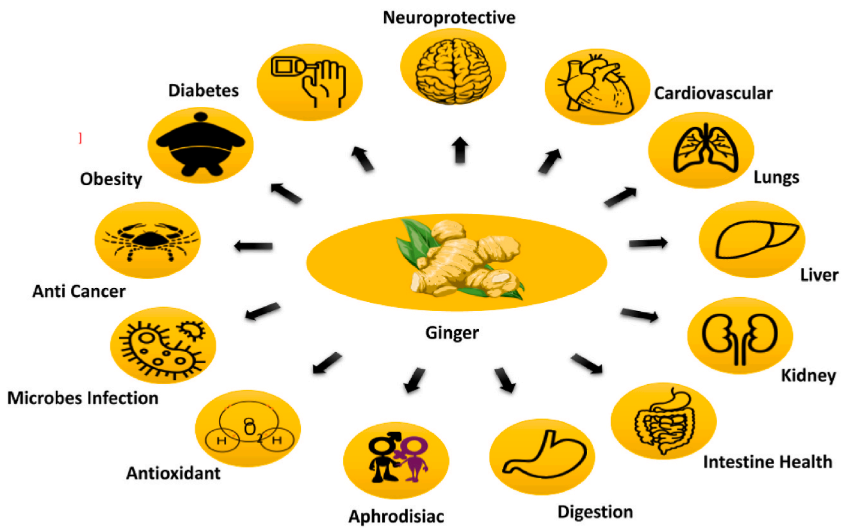


Fig. 3. Modern clinical and pharmacological activities of *Zingiber officinale*.

7. Management of soft rot of ginger

For the control of diseases, there are several classical approaches, including cultural procedures, along with biological and chemical substances (Table 2). The use of these techniques in ginger farms aids in illness management and limits the spread of fungus-causing infections [1,8,34]. It has been shown that managing soft rot with a single traditional strategy is challenging. Hence, it has been discovered that combining many methods was more effective in controlling this illness [1,35].

7.1. Physical methods

A crucial aspect in reducing the risk of infection by *Pythium* spp. is choosing healthy, illness-free seedlings [35]. There are several methods of seed management, such as germ enrichment, seed disinfestations, & germ sterilization, to produce seedlings of excellent quality. All of the aforementioned methods show promise in the treatment of pathogens without endangering embryos or the chance of

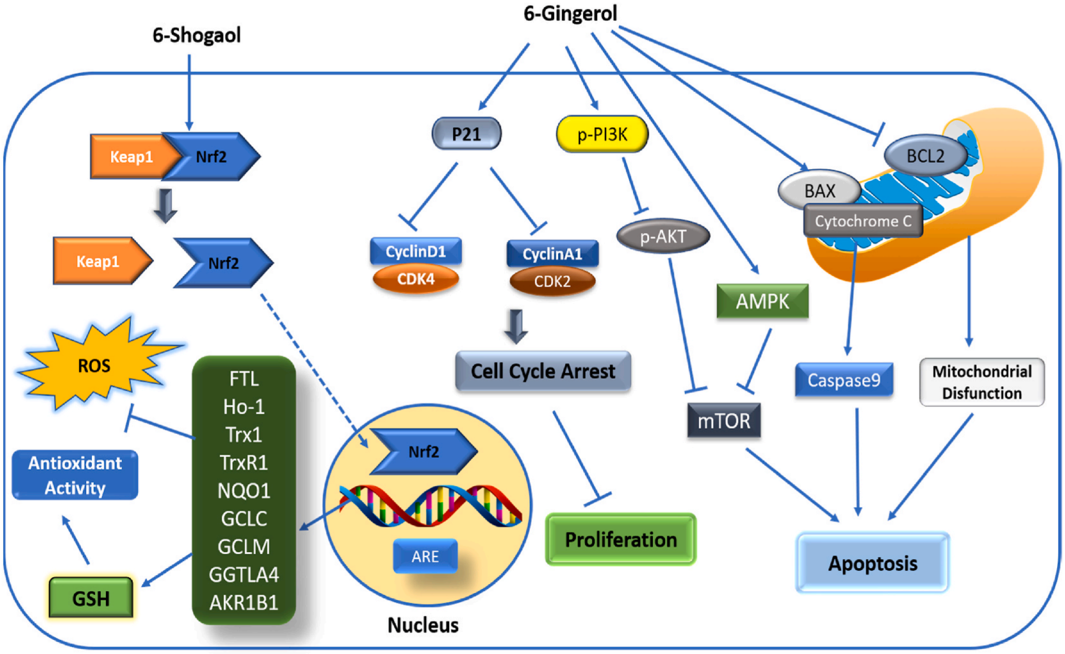


Fig. 4. Molecular targets of 6-Shogaol and 6- Gingerol (Phytoconstituents of *Zingiber officinale)*.

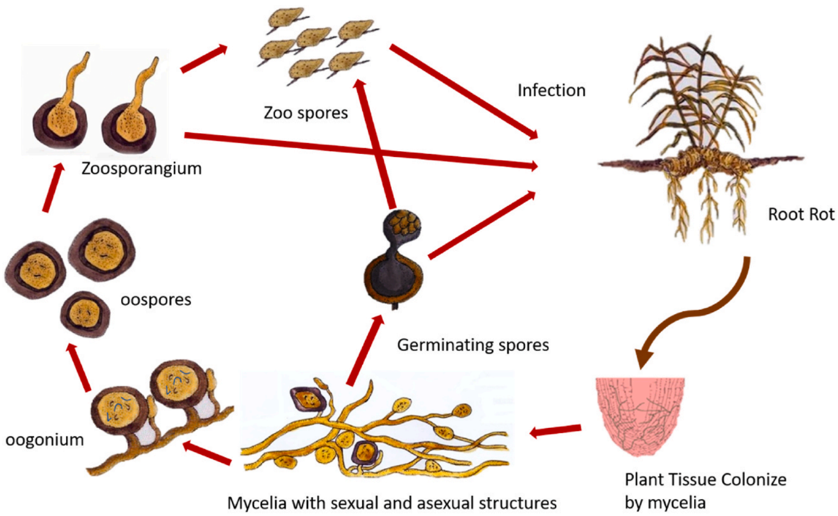


Fig. 5. Disease cycle of *Pythium* spp.

viability of seeds [34].

If a certain plant or some alternative crop that serves as a target for a specific microorganism is grown each year, the microbe's predominance in the land also contributes to the onset of illnesses. In this situation, it is necessary to grow a wide range of crops; therefore, crop variation or rotations might be a useful strategy to prevent the resurgence of pathogens during successive harvests. Since maize and paddy are tolerable to ginger microorganisms, it was proposed that they may be employed as substitute crops once ginger was grown within the same farm [36].

One other strategy for enhanced harvest security in traditional farming techniques is the use of inhibitory soils for virulent diseases. According to Lee et al. [37], grounds with greater clay contents and low pH levels are better suited for growing ginger than inductive soils because they inhibit the development of *P. zingiberum* as well as *F. oxysporum f.* sp. zingiberi.

A further crucial method for destroying soil germs and promoting the development and viability of crops is land solarization. Microbes, other parasites, and weeds are reduced when the soil that has been wrapped with plastic is heated by sun radiation during the summertime for one to two months. In conjunction with soil solarization, using biocontrol substances promotes crop development

Table 2
Biological control agents and pathogen.

Biological control agents	Pathogens	References
Fungi		
Trichoderma hamatum	*Pythium* ultimum	[63,64,145]
T. harzianum	*Pythium* spp.	
T. viride	*Fusarium oxysporum* f. sp. *zingiberi*	
Gliocladium virens		
T. harzianum		
T. harzianum		
T. viride		
T. virens		
T. koningii		
Trichoderma harzianum strain T-22.	Soil borne pathogens	[146,147]
Gliocladium virens	*Pythium ultimum.*	
Trichoderma spp.	*Fusarium* sp.	[148]
Gliocladium virens	*Pythium* ultimum	[149]
Trichoderma harzianum	*Pythium* spp. *Fusarium* spp.	[41,65,150,151]
T. Viridie	*Pythium aphanidermatum*	
T. harzianum	*Pythium aphanidermatum*	
T. harzianum	*Fusarium oxysporum* and *Pythium* sp.	
Trichoderma viride	*Fusarium oxysporum* f.sp *zingiberi*	[150]
T. harzianum		
T. koningii		
T. virens		
Rhizopycnis vagum	*P. myriotylum*	[152]
Colletotrichum trunctatum	*Fusarium oxysporum*	[153,154]
	Scleorotinia sclerotiorum	
F. oxysporum	*Fusarium oxysporum*	[155]
Trichoderma sp	*M. roreri*	[156]
Avremonium sp.	*Fusarium oxysporum,*	[157]
	F. albedinis	
Bacteria		
Pseudomonas fluorescens.	*Pythium ultimum*	[158,159]
P. chlororaphis	*Fusarium oxysporum* f. sp. *radicis-lycopersici*	
P. aeruginosa	*Fusarium oxysporum* f. sp. *ciceris*	
P. putida	*&*	
P. aurantiaca	*Pythium splendens*	
Burkholderia cepacian	*Fusarium oxysporum*	
R. leguminosarum	*Pythium ultimum*	
	Pythium sp. "group G″ strain LRC 2105	
Pseudomonas fluorescens	*Pythium myriotylum*	[160]
Bacilluspolymixa		
B. lentus		
Enterobacter agglomerans		
Glomus sp.		
Rhizobium japonicum	*Fusarium solani*	[161,162]
Pseudomonas fluorescens	*Pythium ultimum*	[163]
Bacillus mycoides	*Pythium aphanidermatum*	[164]
Bacillus subtilis	*Pythium ultimum,*	[165]
	Fusarium solani	
Alcaligenes sp.	*Pythium myriotylum*	[166]
Bacillus cereus		
Bacillus thuringiensis		
Bacillus vietnamensis	*Pythium myriotylum*	[166]
Bacillus BH072	*Bacillus BH072*	[83]
B. amyloliquefaciens Q-12	*B. amyloliquefaciens Q-12*	
B. amyloliquefaciens NK10.B	*B. amyloliquefaciens NK10.B*	
Bacillus strains EU07, QST713 and FZB24	*Fusarium oxysporum*	[80]
Bacillus amyloliquefaciens	*B. cactivora*	[82]
Bacillus sp.	*Pythium myriotylum.*	[167]
Bacillus subtilis strain M4	*Pythium ultimum*	[85]
Bacillus spp.	*Fusarium oxysporum*	[84]
Pseudomonas aeruginosa	*P. myriotylum*	[168]
Actinomycetes		
Streptomyces janthinus,	*Pythium coloratum*	[169]
S. cinerochromogenes		
Actinamadura ruhra,		

(*continued on next page*)

Table 2 (*continued*)

Biological control agents	Pathogens	References
Actinnplanes philippinensis, *Micromonospora carbonaceae* *Streptosporangium albidum*		
Streptomyces rubrolavendulae S4	*Pythium aphanidermatum*	[170]
Nocardiopsis spp. ZoA 1, KC188323	*Pythium myriotylum*	[171]
Management of soft rot disease in ginger using plants extract.		
Jacaranda mimosifolia, *Moringa oleifera* *Polyalthia longifolia* *Terminalia arjuna* *Lawsonia inermis* *Aegle marmelos* *Nigella sativa* *Azadirachta indica*	*Pythium aphanidermatum*	[4]
Zingiber zerumbet (wild ginger)	*Pythium myriotylum*	[17]
Allum sativa *Aloe barbandensis* *Cassia fistula* *Lantana camara*	*F. solani* *P. aphanidermatum*	[172]
Allium cepa *Ocimum sanctum* *Tagetes erecta* *Mentha arvensis*	*P. aphanidermatum*	[173]
Piper betle *Vitex negundo* *Eucalyptus globulus* *A. Sativum*	*P. aphanidermatum*	[174]
Schima wallichii *Tagetes erecta* *Lantana camara* *Ocimum sanctum*	*P. aphanidermatum*	[173]
Artemesia vulgaris Linn + *Urtica dioica* + *Zanthoxylum armatum DC* + *Allium cepa* L. + *Allium sativum* L. + *Nicotiana tabacum* + *Capsicum annuum* L. + Jeevatu *Azadiricta indica* *Agave americana*	*Pythium* spp. *Fusarium* spp. *Fusarium oxysoprum* f. sp. *zingiberi* *Pythium aphanidermatum*	[91]
Acorus calamus *Allamanda cathertica* *Lasia spinosa* *Laurus nobilis*	*Pythium aphanidermatum*	[92]
Alamonda leaf extract	*Fusarium oxysporum*	[93]
Artocarpus lakoocha *Hemedesmus indicus* *Elaegnus kologa Schlecht* *Polyalthia longifolia* *Croton roxburghii Balak.*	*P. aphanidermatum* *F. oxysporum*	[94]

and inhibits the spread of a range of illnesses. The cheap and prolonged advantages of soil solarization make it among the best methods for conservatories, greenhouses, flower gardens, and landscapes [38].

Additionally, adding silicon (Si) to the ground is said to promote vegetation development while inhibiting the proliferation of *P. aphanidermatum*. As soon as infection signs start to manifest in the fields, regular phyto-sanitation is advised to stop the condition's transmission to other healthier crops. To prevent the spread of microbes to healthier crops, it is crucial to locate infected crops, destroy them, and then sanitize the instruments employed for phyto-sanitation.

7.2. Chemical methods

All around the world, several antifungal agents are frequently used to manage post-harvest infections in ginger. Since *Pythium* spp. can persist in the land for extended periods after being incorporated, managing soft rot is much more challenging. Numerous synthetic antifungals were found and are currently in common use all over the globe. Mancozeb, copper oxychloride, Ziram, propineb, and Guazatine, are among the crucial antifungal agents. These antifungals are thought to be among the most efficient at preventing soft rot.

Metalaxyl is also among the most often applied synthetic antifungal agents. This fungicide can be applied to the land or employed as a drench independently or in conjunction with various antifungal agents to effectively prevent soft rot brought on by *Pythium* [39,40]. In a field that was inherently polluted with *P. aphanidermatum*, Singh et al. [41] conducted comparison research on the seedling treatments with Ridomil MZ and warm water and they found that the intervention with Ridomil MZ increased root survivability by 30%. Furthermore, Smith and Abbas [42] suggested that antifungals such as metalaxyl, fludioxonil, Ridomil, and Proplant significantly aid in the control of soft-rot brought on by *P. myriotylum* in a potted trial rather than just carbendazim seedling therapy.

Additional fungicidal substances such as zineb, thiram, captafol, phenylmercuric acetate, methyl bromide, copper oxide, mercuric chloride, and mancozeb have also been shown to be efficacious towards several *Pythium* organisms [43]. Metalaxyl was found to be significantly effective in controlling rhizome-rot, according to Dohroo et al. [44]. Comparable to this, treating ginger soft rot with a combination of metalaxyl & captafol and soaking the soil and seed efficiently managed the problem [45].

When Srivastava [46] applied zineb or mancozeb to the ground after treating the rhizomes with carbendazim and mixing Thiodan grit into the ground to prevent pest infestation, he successfully managed the soft-rot of ginger in Sikkim. In their research, Gautam and Mainali [47] showed that the mixture of insecticides Carbendazim 50 DF, Mancozeb 80 WP, and Chlorpyrifos 20 EC was much more potent towards rhizome flies and soft rot.

7.3. Biological methods

Currently, environmentally benign infection control techniques are used. There is a rising concern across the globe over the usage of dangerous antifungal agents in farming. Consequently, developments in farming towards better durability over the last 20 years have contributed to an upsurge in awareness about the risks connected with the application of artificial insecticides and the usage of biological products to manage plant infections. Biocontrol is the lowering of an organism's capacity to cause illness or the concentration of its bacterial culture, whether it is done organically while it is alive or by deliberately introducing antagonists into the ecosystem [48,49]. By using modern biology as well as genetics-related techniques, it was feasible to evaluate the function of bacterial inoculum in real habitats to an extent that was hitherto impossible, leading to fresh discoveries into the fundamental processes of how biocontrol products work [50].

Currently, a wide range of microorganisms, primarily fungi, and bacteria have been identified that fight off significant agroecological insects and illnesses. These comprise *Trichoderma* spp. [34,51], *Pseudomonas*, *Bacillus*, *Streptomyces* [52–56], mycoparasitic *Verticillium* species [57], and *Lecanicillium* species [58], among others. Scientists from all over the world are paying close emphasis to fungal organisms towards plant diseases as prospective biological control tools in various plants. *Trichoderma/Hypocrea* is among the highly researched fungi species [34,57,59].

7.3.1. Fungi as a biological control agent

Biological control treatments may also cause physiologic changes in plants, like the development of phytohormones or the overly sensitive reaction, or the creation of chitinase and glucanase, which activate the plant's protective mechanisms [60]. Since *Pythium* pathogens can immediately infect seeds or roots and have the potential to produce long-lasting root rots, the biocontrol of these species is quite challenging. Despite these limitations, antagonistic fungi, microbes, and actinomycetes were successful in controlling several significant disorders [34,60].

Numerous *Pythium* species can be controlled using fungal endophytes *Trichoderma* as a biological control agent. *Trichoderma* engages in several noteworthy functions, including the formation of substances that degrade cell walls, indole acetic acid and cyanide, phosphate solubility, and others. These processes play a significant role in the cellular wall degradation of *Pythium* spp. Oomycetes [61,62]. The treatment of *P. aphanidermatum*-caused soft-rot sickness in turmeric plants was previously described by Vinayarani and Prakash. According to the research, fungal endophytes *T. harzianum* significantly inhibited the development of the mycelium that is responsible for the turmeric rhizome-rot infection [62]. An antagonistic response was seen in *in vitro* testing utilizing *T. viride, T. hamatum*, and *T. harzianum* towards *P. aphanidermatum, F. solani, and F. equiseti* [63–67]. After *T. viride and T. harzianum* were treated to the ground in conjunction with sawdust, a significant reduction of soft-rot disease was observed in agricultural conditions [68].

When *T. harzianum* was administered to soil together with neem oil cakes, it was found that *P. aphanidermatum*, which causes soft rot of ginger, was effectively controlled [69]. After utilizing biological control agents, the possible reduction of proliferation of *Fusarium oxysporum* and *P. aphanidermatum* inducing yellows and soft rot of ginger was noted [1,41,69]. Ram et al. [70] showed how various biological control organisms, such as *T. virens, T. harzinum,* and *T. aureoviride*, can prevent ginger soft rot. According to reports, the colony abundance of all *F. solani* and *P. aphanidermatum* was greatly diminished by all of the aforementioned biological control treatments. According to Ginting et al. [71], *F. oxysporum*, a phytopathogenic fungus, can be effectively controlled by the fungal endophytes *C. gloeosporioides*. Table 2 shows list of various antagonist fungi used as biocontrol agent to manage *Pythium* and *Fusarium* spp. in ginger and other crops.

7.3.2. Mechanism of action of Trichoderma species

Trichoderma species exhibit antifungal activities by various mechanisms which include competition for nutrients, activation of resistance by plants, induction of defense mechanisms, enzymes that degrade cell walls, etc. Relative to competing species, *Trichoderma* has a greater ability to transport and absorb soil minerals. *Trichoderma's* capacity to produce Adenosine Triphosphate from the breakdown of various carbohydrates, including those formed from polysaccharides commonly found in fungal habitats, underpins the effective utilization of accessible resources [72]. Before stimulating crop, development and providing disease defense, *Trichoderma* species must infiltrate crop roots. Colonization denotes the capacity to cling to and detect crop roots, infiltrate the crop, and endure toxic compounds generated by the crops in reaction to the intrusion by an external entity, regardless of whether it is pathogenic. *Trichoderma* variants typically improve root proliferation and expansion, crop yield, tolerance to abiotic stressors, and nutrient absorption and utilization through root colonizing [73].

In trials conducted in conservatories, plant seedlings that had formerly been exposed to *Trichoderma* germs produced a significant rise in production [72]. Traditionally thought to have an inhibitory action on the invading microorganism, *Trichoderma* variants can defend crops from root infections [72]. Transgenic plants that were extremely adaptable to or entirely impervious to the foliar microbes *Alternaria solani*, and *B. cinerea* as well as the land microbe *Rhizoctonia solani* were produced when the chitinase Chit42 from *T. harzianum* was expressed in tobacco plants [74]. An adequate reaction to every specific pH state is one of the strategies used by *Trichoderma* variants to accomplish colonization and infection suppression in a variable pH environment. *T. harzianum* isolates that regulate environmental pH stringently maintain ideal levels for their endogenous secretory enzymes [75].

7.3.3. Bacteria and actinomycetes

The bacteria's capacity to create significant byproducts such as lipopeptides, which have substantial fungicidal action, makes them extremely useful as biological control tools [76,77]. Luminous *Pseudomonas*, *Streptomyces*, and *Bacillus* spp. gained the most emphasis amongst bacterium and actinomycetes since they are simple to culture on a mass scale and may be used to treat both ground and seedlings.

Previously, Zouari et al. [78] revealed that *Bacillus amyloliquefaciens* variant CEIZ-11 showed a wide spectrum of fungicidal activity against a variety of crop infections, particularly *P. aphanidermatum*. According to earlier research [79], *Bacillus* species can manufacture a variety of antimicrobial drugs in a strain-specific way. In research by Rao [80], the secretion of lysogenic enzymes, hydrolases, and proteolytic enzymes by the *Bacillus* strains EU07, QST713, and FZB24 was examined for its suppressive action on *Fusarium*. There are preceding findings on the identification and separation of *Bacillus* sp., which defends alfalfa plants from *Phytophthora megasperma*-caused seedling sickness [81].

It has been demonstrated that the antifungal abilities of the *Bacillus amyloliquefaciens* strain can suppress Bipolaris stem rotting brought upon by *B. cactivora* [82]. A unique bacteria called BH072 *B. amyloliquefaciens*, which was derived from nectar, demonstrated potent fungicidal action against many fungi in one investigation [83]. In their work, Sarwar et al. [84] found that the biosurfactant of *Bacillus* species showed effective efficacy vs several plant pathogens, such as *F. oxysporum*, which induces rot disease, and *Fusarium moniliforme*, which originates the paddy bakanae infection, among others. Ongena et al. [85] provided evidence for the protective effects of bioactive peptides released by *B. subtilis* variant M4 versus *Pythium ultimum*-induced dampening of bean seeds [86]. Table 2 shows list of various bacterial strains used as biocontrol agent to manage *Pythium* and *Fusarium* spp. in ginger and other crops.

7.3.4. Plants extracts

The regulation of plant infections brought on by *Pythium* spp. can be done in an economical and environmentally friendly manner by using diverse flora as biocontrol agents. *Usnea pictoides* was found to have antagonistic action towards the ginger soft-rot disease-causing *P. aphanidermatum*, according to Vinayaka et al. [87]. Iranian plant methanolic and water extracts have been shown to have fungicidal action toward *Pythium* sp [88]. Neem and other limonoids, according to Dohroo and Gupta [89], too were highly successful in controlling a variety of plant diseases. Additionally, Neem leaves were found to have certain sulfurous substances that had fungicidal capabilities, according to Pant et al. [90]. Acharya et al. [91] reported the activity of various plant extracts such as *Arthemesia vulgaris Linn, Urtica dioica, Nicotiana tabacum,* and *Capsicum annuum Linn* against *Pythium* and *Fusarium* species that cause soft rot of ginger. In another study, Kumar et al. [92] demonstrated the antifungal activity of extracts of *Acorus calamus, Allamanda cathertica, Lasia spinosa,* and *Laurus nobilis* against *Pythium aphanidermatum* that causes ginger soft rot disease. The antifungal activity of extracts of Alamonda leaves against rhizome rot causative agent *F. oxysporum* was reported by Hasnat et., al [93].

Rakesh and co-workers reported the antifungal activity of extracts of *Artocarpus lakoocha, Hemedesmus indicus, Elaegnus kologa Schlecht, Polyalthia longifolia* and *Croton roxburghii Balak* against *P. aphanidermatum* and *F. oxysporum* that causes ginger soft rot disease [94]. The assessment of plant varieties' resistance to the rot-causing fungus *P. aphanidermatum* was also studied in the past in various experimental and conservatory settings [95]. Several phytoconstituents are fungitoxic to *P. aphanidermatum,* which was collected from a ginger sample with rhizome rot, according to research by Haouala et al. and Suleiman and Emua [96,97]. Table 2 shows list of some plant extracts which are used to manage soft rot disease in ginger.

7.3.5. Nanotechnology based management

When it comes to managing phytopathogens, nanotechnology has numerous perks over traditional chemical solutions that are known to be ecotoxic. By strategically delivering pharmacological substances, nanoparticles in farming seek to minimize the number of toxic substances applied [98]. Nanoparticles (NPs) have the potential to both alleviate current effects and substantially accelerate the paradigm shift in agricultural output [99]. NPs are used to stimulate plant growth as well as to inhibit the expansion of diseases [100]. The farming sector uses nano biosensors to combat several plant diseases [101]. It is advantageous in many different ways; for instance, the use of nanocapsules in plant illnesses and pest control. The control of ginger soft rot by nanotechnology-based methods is urgently needed.

Nanotechnology's market worth as fungicide and crop growth stimulants has recently increased dramatically. Nanomaterials let farmers distribute micronutrients in a regulated manner with the least amount of nutritional loss possible [102,103]. The nanomaterials have the potential to administer active chemicals or minerals in a precise fashion, making them an excellent fungicide distribution mechanism in farming. They also have compact sizes, vast surfaces, improved durability, and better accessibility to crops [104–107]. According to reports, synthetic fungicides can also attack non-target lifeforms and have detrimental impacts on all ecological living beings. Thus, using these synthetic insecticides can irrationally increase risk and disrupt ecological integrity, especially concerning threatened and vulnerable species. As a result, various strategies are being developed by research organizations to treat fungal diseases without any negative consequences [107].

One of the finest options for battling fungi infections is the creation of multimodal nanoparticle complexes, which contain many active chemicals [108]. The application of nanotechnology to treat the fungi-caused soft rot ailment in ginger is not documented in the official literature. Nevertheless, there have been reports of utilizing nanomaterials to treat *Pythium* sp. and *Fusarium* sp. derived from various crops. Copper sulfide nanoparticles have been shown by Chakraborty et al. to have suppressive action toward *Fusarium* sp [109]. Silver nanoparticles (AgNPs) have been widely advocated for use in managing plant infectious fungi, but sadly, they have received less attention in the control of illnesses caused by *Pythium* species and *Fusarium* species, which cause wilts and soft rot, respectively [110,111].

The study conducted to control white rot disease in onion and garlic using AgNPs, biologically synthesized by *F. oxysporum*. The biosynthesized AgNPs at various concentrations showed a promising antifungal activity against the linear growth, mycelial biomass and scelerotial germination of *S. cepivora* isolates. Therefore, AgNPs can be used as nanofungicide against white rot disease and as nanofertilizers for onion and garlic productions [112–114].

7.3.6. Challenges for application of nanotechnology to control fungal pathogen

In this age of scientific discovery, new ideas and applications for human and environmental well-being emerge every decade. Nanotechnology also comforts this decade and its advantages make it essential in agriculture. Despite its use in agriculture, some challenges remain. Nanohybrid materials regulate fungi. Silver, gold, copper, iron, graphene, silica, chitosan, and other organic molecules are used to make composites or nano-hybrids. Nanohybrid synthesis requires expensive chemicals, reagents, and energy. Thus, nanohybrids may be effective against phytopathogens, but they may infiltrate the plant system or accumulate in its vegetative sections when applied in the field. Before developing nano-formulations for antibacterial/fungicidal applications, it is necessary to comprehend the effect of nanoparticles on crop plants. Numerous researchers have hypothesized that nanoparticles may impede plant growth and development [115].

NPs interaction with soil pollutants including metals and organic molecules can alter bioconcentration or inherent toxicity, which can harm plants. NP-contaminant combinations may cause unexpected hazardous consequences via multiple pathways that influence chemical availability, absorption, and metabolic processes involved in detoxification and degradation. The mechanisms of the NP-contaminant interaction on joint toxicity are unclear [116].

Qian et al., reported the adverse effects of copper oxide nanoparticles (CuO NPs) treatment on wheat seedlings due to a combination of CuO NPs and released Cu^{2+}. Its treatment significantly reduced wheat root and shoot biomass by 35.8% and 15.8%, respectively [117]. Effect of different concentrations of AgNPs were investigated in *Trigonella foenum-graecum*. The highest amount of trigonelline (TG) and nicotinic acid (NT) contents were obtained in 10 mg/L of AgNPs. Treatments with an AgNPs concentration higher than 10 mg/L led to reduced growth, biomass, chlorophyll, protein, TG and NA contents [118]. NPs exposure to plants causes ROS, lipid peroxidation, redox homeostasis disruption, DNA, and membrane damage. It causes oxidative stress, plant growth disruption, and genotoxicity. Despite the many benefits of NPs for agriculture, investigating the hazards of nanotoxicity from NPs in food for human consumption is necessary because engineered and inadvertent NPs can create future health issues. Thus, future study must clarify NPs characteristics to assure safe use in agriculture, one of the key food sources for humans [119].

8. Traditional vs modern strategies

8.1. Cultural strategies

Cultural methods such as crop rotation, tillage, organic modification, drainage, and quarantine are frequently used to reduce PSR and prevent the propagation of *Pythium* spp. to uninfected farms. By adding more organic matter to the soil, these approaches aim to 1) increase soil condition and hence create a more diversified and disease-suppressive soil biota, and 2) restrict Pythium spp. inside the affected region and prevent the spread to uninfected areas. Crop rotation may not always be an effective strategy to manage *Pythium* spp. on ginger because the majority of the Pythium spp. that were identified on ginger is also virulent on a broad spectrum of hosts. Harvey and Lawrence [120], however, thought that rotations of crops could change *Pythium* spp. populations, arguing that every plant would be related to a certain *Pythium* Spp. and that probable inoculum could be decreased to some degree in areas with yearly rotations. According to Urrea et al. [121], the diversity of *Pythium* spp. is significantly dependent on the rotation of host crops that are vulnerable to the fungus, and it is low in monoculture systems. As a result, pathogenic Pythium spp. multiplied and took over under mono-cropping regimes [122]. Stirling et al. [123] found that methods to retain the existence of antagonist soil microbes were less efficient in controlling the pathogen if factors for *P. myriotylum* proliferation were perfect, such as high temperatures and saturated soils.

For effective ginger farming and PSR management, tillage techniques that minimize soil disturbance ought to be taken into consideration. According to Rames et al. [124], minimum tillage resulted in soils with larger microbial numbers than the standard tillage technique; nevertheless, the grounds also seemed to set hard, and ginger establishment and growth were poor after direct mechanical drilling of the seed.

Pythium spp. release zoospores that can swim and disperse in free water, hence Smith and Abbas [42] hypothesized that effective water drainage is crucial for PSR management. Drain breaks that are carefully positioned throughout the field can stop the spread of zoospores by catching them in surface water flowing along beds and interrow. In addition, Kim et al. [125] demonstrated that when compared to a control, unridged field, the frequency of PSR was reduced by almost 70% in fields with thin ridge farming. Given that the yield was only half as the control, this method was thought to be unfeasible.

8.2. Modern strategies

Ginger germplasm does not yet contain any sources of resistance to this disease [126]. Ginger is entirely sterile and can only be propagated vegetatively by utilizing a rhizome. The use of any traditional method for promoting disease resistance in ginger is hampered by total sterility and the low heterogeneity for disease resistance, demanding the employment of transgenic technology for plant modification. Previous research suggested that *Zingiber. zerumbet*, an uncultivated variant of cultivated ginger, could contribute to the genetic enhancement of ginger by providing soft rot resistance [127]. According to the gene-for-gene paradigm, the ability to recognize a particular pathogen is controlled by plant-encoded disease resistance (R) gene products. Upon recognizing a pathogen-encoded elicitor, these gene products initiate downstream signal transduction cascades, which then quickly mobilize defenses to stop pathogen growth [128,129]. Nair et al. [130] noticed a connection between the wild taxa's resistance to *P. aphanidermatum* infections and ZzR1 expression. Given that mandatory vegetative propagation prevents genetic improvement in ginger cultivars, this is a significant genomic resource for the progression of tolerance to *P. aphanidermatum*. The economic significance of soft rot infection and the ecological effects of chemical management methods make it imperative to understand the molecular basis of resistance mechanisms.

9. Host plant resistance

The microorganisms that cause soft rot could still cause plant mortality or at the very least reduced yields, even though it is possible to control it to a certain degree using chemical, biological, and nanotechnology means. Although creating a *Pythium*-resistant variation will be preferable, neither of the palatable ginger cultivars now in existence is immune to harmful pathogens [130]. Senapati and Sugata [131] screened 134 ginger variants that were accessible in Koraput, India, and discovered one variety that was resilient to *P. aphanidermatum* as well as eight others that had modest tolerance. However, the findings were not shared by other investigators across the nation, leading to the conclusion that the resilient cultivar in this instance was likely a regionally distinctive response against *P. aphanidermatum*. Thus, efforts to create a ginger variety with soft rot resistance persist.

10. Comparison between various management strategies

Farmers and agriculturists should learn healthy, non-toxic, effective, and eco-friendly strategies (green strategies) for controlling fungal diseases in plants in order to protect human and animal health and soil biodiversity. For the control of plant fungal diseases, these strategies must be implemented in vivo. Physical treatments (heat, irradiation, PL, plasma) are also commonly applied to sanitize food packaging, reducing the risk of spoilage during storage and transport [132]. Physical treatments prevent chemical residues from adhering to produce. UV light may stimulate plant defence systems in fresh fruits and vegetables, in addition to killing microorganisms [133]. In comparison to chemical treatments, potential drawbacks of physical methods are that they do not remove dirt and plant debris and that they may lead to physical (*e.g.* thermal) damage to the produce. Additionally, regulations for chemical treatments are tightening to limit the accumulation of fungicides and of disinfection by-products in food produce, in irrigation, processing water and in the environment. New technologies for fungal control are also necessitated by the emergence of resistance. Existing fungicides can be enhanced by exploiting synergies between chemical agents, thereby reducing chemical consumption. Current crop management strategies should be strengthened by identifying novel synergies and commercialising existing synergistic combinations. Biocontrol and methods of stimulating plant defence can reduce food spoilage and crop disease, while films and coatings can protect fruit from mechanical damage and be adapted to enhance the delivery of other control measures. On contrary Bacillus spp. (B. cereus) as biocontrol agent its enterotoxigenic virulence factors in infant formula and ready to use baby food was investigated because it is considered as the more harmful one in lower numbers 133.

11. Conclusion

Ginger is one of the medicinally important commercial crops, cultivating throughout the world for various purposes having global market of US$190 million. But, on the other hand, there are number of pest & diseases which causes deterioration of this highly important industrial crop. Soft rot disease is one of an important disease caused by *Pythium* and *Fusarium* spp., responsible for quantitative and qualitative losses of ginger.

The current review focused on various aspects of the soft rot disease, its etiology and the management practices including physical, chemical, biological methods and nanotechnological approaches as well as their '*pros and cons*'. Although, application of physical methods of disease control is ecofriendly in nature but it is costly and time consuming. Similarly, chemical methods/fungicides have been proven to be promising in controlling soft rot disease of ginger but they have several side effects. Nanotechnology has also been providing the significant opportunities to treat phytopathogens by avoiding excess use of chemical fungicides, herbicides, and fertilizers but it requires expensive chemicals, reagents and needs extensive experimental trials for evaluation of toxicity to beneficial microbes, animals, human beings and environment. However, biological management is the only method that could be used as an effective source of fungicides/bioagent(s) of eco-friendly in nature for the soft rot disease control. Literature also revealed that there are number of commercial fungicides/bioagents are available in the market viz., *Trichoderma Tricoderma. Harzianum, T. viride, T. virens,T. koningii* as well as *Pseudomonas fluorescens Bacillus subtilis, Streptomyces rubrolavendulae;* that could not only be used as an effective fungicide but also having the edge over synthetics.

Besides this, findings of the present review could also be used as a base line for budding researcher, plant pathologist and policy makers; who are working in the area of pest & disease management.

Author contribution statement

All authors listed have significantly contributed to the development and the writing of this article.

Data availability statement

Data included in article/supplementary material/referenced in article.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper

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