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Effects of Organic Agricultural Materials and Cultivation Methods on the Control of Ginger Rhizome Rot Disease and Growth in Organic Ginger Farming

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Abstract: This study aimed to develop eco-friendly disinfection technology for ginger seed rhizomes by evaluating the effects of various organic agricultural treatments on germination rates, fresh weight, and disease resistance. The Korean native ginger variety, Bongdongjaerae, and the Chinese variety, Laiwu xiao, were treated with lime–sulfur mixtures, antifungal bacterial isolates, and microalga. Results showed that the 0.4% lime–sulfur treatment achieved the highest germination rate of 89.0% for domestic ginger grown under a single-bed cultivation. The combined treatment with *Bacillus velezensis* strains GT227 and GT234 and *Chlorella fusca* (CHK0058) significantly increased the fresh weight, highlighting its potential to enhance ginger growth under organic farming conditions. Single-bed cultivation yielded better results compared to flat-bed cultivation, showing higher fresh weights and lower infection rates. Overall, organic treatments, particularly the combination of CHK0058, GT227, and GT234, proved effective in enhancing ginger growth and reducing disease incidence, highlighting the potential for sustainable agricultural practices in ginger cultivation.

Keywords: *Zingiber officinale* Roscoe; rhizome rot; cultural practices; antifungal bacteria; microalga

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1. Introduction

Ginger (*Zingiber officinale* Roscoe) is a perennial herb notable for its extensive cultivation and significant medicinal, nutritional, and ethnomedical benefits across the globe [1–5]. In Korea, ginger represents a highly profitable crop with a profit of 52.5% across ten regions, a value-added rate of 68.4%, and a commercialization rate of 96.7% [6,7].

Despite typically being grown in tropical climates, ginger is cultivated as an annual in Korea because the cold winter temperatures prevent the plants from surviving through the winter, with planting occurring in spring and harvesting in autumn [8]. Key domestic cultivation regions include Wanju in North Jeolla Province [9] and Seosan and Taean in South Chungcheong Province [10,11]. Recently, cultivation has expanded to Andong, Gyeongsangbuk-do, with a cultivation area of 1991 hectares and an annual production of 22,137 tons in 2022 [7].

In addition to its significance in the Korean agricultural sector, ginger holds substantial importance in the global market. In 2021, global ginger production reached approximately 4 million tons, with India and China being the leading producers, together accounting for over half of the world's ginger supply [12]. The global market value of ginger exceeded USD 3 billion in 2022, driven by rising demand in various industries, including food, pharmaceuticals, and cosmetics. Understanding the dynamics of both local and global markets underscores the relevance of developing sustainable cultivation techniques to enhance ginger production and profitability [13].

Ginger faces susceptibility to ten distinct plant diseases [14], including rhizome rot (caused by *Pythium myriotylum*), bacterial wilt (*Ralstonia solanacearum*), and Fusarium wilt (*Fusarium oxysporum*), with rhizome rot being a significant issue characterized by decay in the underground parts of the plant [15]. In Korea, ginger rhizome rot primarily results from pathogens such as *Pythium zingiberum* [16], *Pythium myriotylum* [17,18], and *Fusarium oxysporum* f. sp. *zingiberi* [18]. Additionally, bacterial root rot is induced by *Erwinia carotovora* subsp. *carotovora*, *Pseudomonas marginalis* pv. *marginalis*, and *Ralstonia solanacearum* [19–22].

Economic damage from ginger root rot is significant, with thresholds for economic damage and control set at 4.1% and 3.3%, respectively [23]. These pathogens, notably *P. myriotylum* and *F. oxysporum* f. sp. *zingiberi*, also impact other major ginger-producing countries [24,25]. Conventional and organic cultivation methods, including chemical pesticide applications, struggle to manage rhizome rot effectively, necessitating seed rhizome disinfection and multiple chemical treatments during the growing season [26].

Integrated disease management (IDM) approaches, including the use of resistant varieties [27,28], soil health management [29,30], biological control agents [31–34], and physiological methods [35,36] are recommended for effective rhizome rot control.

Research indicates that cultivation practices as well as soil temperature greatly influence the occurrence of rhizome rot [37,38]; therefore, managing the physical and chemical properties of the soil is crucial. Previous studies have highlighted the importance of cultivation practices such as ridge type [39] and organic amendments [40] in managing rhizome rot. Single ridges and the application of organic treatments were found to reduce disease incidence and improve yield [41]. Proper irrigation management and drainage systems to prevent excess moisture can inhibit pathogen growth [27]. Additionally, pre-treatment of ginger seeds, such as heat treatment at 47 °C for 30 min, is effective in eliminating pathogens before planting [35].

Sulfur, historically utilized for pest control since the 1800s, remains a widely used non-selective agent for various crops [42,43]. In Korea, powdered sulfur has been beneficial in enhancing the quality of fruits, vegetables, and garlic while controlling soil-borne diseases [44,45]. Liquid sulfur has demonstrated effectiveness against tomato powdery mildew [46], gray mold [47], citron black spot [48], and pear black spot [49].

Chlorella species have been shown to significantly promote plant growth by producing bioactive compounds that enhance various physiological parameters. Studies using Chlorella species like *Chlorella vulgaris* [50] and *Chlorella pyrenoidosa* [51] demonstrated improvements in shoot length, leaf size, fresh weight, and overall biomass when applied to crops such as *Medicago truncatula* [52,53]. These microalgae act as biostimulants, improving nutrient uptake and enhancing photosynthesis. In addition, microalgae improve soil fertility and promote plant growth through the production of growth-promoting substances. The combination of microalgae with beneficial bacteria has led to synergistic effects, enhancing overall crop health and yield [52,54,55].

Compost tea, derived from fully composted organic material and aerated to extract nutrients and beneficial microorganisms, offers a dual benefit of nutrient management and disease control [56,57]. The efficacy of compost tea depends on the type of organic compost and production method used [57–59].

The purpose of this study was to explore the effectiveness of various organic agricultural materials and cultivation methods in controlling ginger rhizome rot disease and enhancing the growth of organic ginger. We investigated the impact of eco-friendly disinfection technology, ginger varieties, lime–sulfur mixture, and antifungal bacterial isolates and chlorella applications with the aim of providing insights that could improve disease management practices and promote sustainable agricultural techniques for organic ginger cultivation.

2. Materials and Methods

2.1. Plant Materials

To investigate the effects of organic agricultural materials and cultivation methods on the control of ginger rhizome rot disease and the growth of organic ginger, we used a Korean native ginger variety, Bongdongjaerae, and one imported Chinese variety, Laiwu xiao. The Korean variety, Bongdongjaerae, was sourced directly from ginger farms in Bongdong, North Jeolla Province, which is recognized as one of the major ginger-producing regions. The Chinese variety, Laiwu xiao was obtained from a specialized ginger import company, grown in Shandong Province in 2022, and imported following quarantine procedures. The two tested ginger varieties Bongdongjaerae and Laiwu xiao were treated with 0.4% ($v \cdot v^{-1}$) lime–sulfur mixture for two hours before sowing, air-dried, and then sown in the test fields on 15 April 2022.

2.2. Preparation of Ginger Cultivation Field

Ginger cultivation and nutrient management followed the standard practices commonly used by farmers. To study the effects of bed width on the occurrence of ginger rhizome rot and plant growth, a ginger cultivation field was tilled twice with a rotary tiller. Then, using a bed former, beds were shaped into two types, flat type and single type, with the width and height of 90 × 20 cm and 60 × 20 cm, respectively. The experiment was conducted by covering the beds with straw instead of black plastic mulch.

2.3. Culture and Treatment of the Microalga and Antimicrobial Microorganisms

We used *Bacillus velezensis* isolates GT234 and GT227, derived from tomato rhizosphere soil, as biocontrol agents against six kinds of normal plant pathogens: *Fusarium oxysporum*, *Pythium ultimum*, *Rhizoctonia solani*, *Phytophthora capsici*, *Sclerotinia sclerotiorum,* and *Botrytis cinerea*. *Chlorella fusca* CHK0058, a microalga with plant-growth-promoting and disease-suppressing properties, was also used [60]. The two tested biocontrol agents, GT234 and GT227, were cultured in 1 L sterilized Erlenmeyer flasks containing 500 mL TSB (Tryptic soy broth, Difco Lab, Ltd., NJ, USA). The cultures were incubated at 28 °C in the dark and shaken at 250 rpm for 5 days. Once the concentration of the culture solution reached 10^9 cfu·mL^{-1}, it was diluted 100-fold with water, and 50 mL of the 0.1% diluted culture solution of GT234 and GT227 was applied to each ginger plant by drenching. The chlorella culture solution was prepared by adding 5 mL of a chlorella-specific culture medium (F & B Nature Co. Ltd., Chengju, Republic of Korea) to 8 L of commercial mineral water in a 10 L container, inoculating with CHK0058, and incubating under 3000 lux light at 28–30 °C, with air blown over it at 5 L·min^{-1}. After 5 to 7 days, the culture reached a concentration of 1.5×10^7 cells·mL^{-1} and was diluted to 0.4% for irrigation treatment. Control groups were sprayed and irrigated with water, and treatments were applied at two-week intervals using a high-pressure sprayer.

2.4. Organic Agricultural Materials

2.4.1. Lime–Sulfur Mixture

The lime–sulfur mixture (LSM) used was a 25% (w/v) solution, self-manufactured in the laboratory with 25 kg·100 L^{-1} sulfur powder (99%, Miwon Chemical Co. Ltd., Ulsan, Republic of Korea) and 12.5 kg·100 L^{-1} quicklime powder (95%, Baek Kwang Mineral Products Co. Ltd., Eumseong, Republic of Korea) following the method developed by the National Agricultural Research Institute [61]. The LSM solutions were diluted to 0.4% and 1.0% ($v \cdot v^{-1}$) with water and were applied to each ginger plant at two-week intervals using a high-pressure sprayer. LSM was used for ginger rhizome disinfection and as a soil-borne disease-control material in this study.

2.4.2. Compost Tea

Compost tea (CT) was prepared by placing 200 g of fully decomposed organic compost into a nylon net, submerging it in 20 L of water, and fermenting it aerobically for two days using a household air pump and bubble machine [61]. The compost tea was used immediately after preparation, diluted 25-fold for foliar application and 50-fold for soil drenching, with 100 mL of CT solution distributed around the roots of each ginger plant at two-week intervals. CT was utilized in the trials to determine effective organic agricultural materials for promoting ginger plant growth.

2.4.3. Essential Oils

Karanja and Neem oils were purchased from specialized reagent companies, with concentrations of the active ingredients Karanjin and Azadirachtin above 10,000 ppm·mL^{1}. Emulsifiers were prepared by sequentially mixing 0.3% ($v{\cdot}v^{-1}$) canola oil and 0.01% ($v{\cdot}v^{-1}$) egg yolk, homogenizing with a high-speed grinder, and then adding Karanja and Neem oils to a concentration of 3.0% ($v{\cdot}v^{-1}$). The essential oil mixture was stored at 4 °C [61,62]. Karanja and Neem oils were used in this experiment to manage insect pests on ginger while minimizing the impact on other treatments; therefore, no separate data were recorded.

2.5. Eco-Friendly Disinfection Methods for Ginger Rhizome

The lime–sulfur mixture was tested at concentrations of 0.4% ($v{\cdot}v^{-1}$) and 1.0% ($v{\cdot}v^{-1}$) for two hours. A total of 20 kg of healthy ginger rhizomes were randomly selected, placed in household mesh bags, and treated in three replicates for each concentration and different durations [63]. Considering the characteristics of ginger rhizomes, the mesh bags containing the rhizomes were shaken every 30 min during the immersion treatment in each LSM solution to ensure proper mixing. The emergence rate and disease incidence due to ginger seed disinfection were investigated through visual inspection and measurement, with 50 plants per treatment group and three repetitions. Early-stage infections were considered to have originated from the ginger rhizome, while late-stage infections were regarded as soil-borne infections.

2.6. Estimation of Control Effect of Ginger Rhizome Rot

To evaluate the control of ginger rhizome rot based on the use of antimicrobial microorganisms, microalga, organic farming materials, and bed types, the occurrence of ginger rhizome rot was visually inspected with 20 plants per treatment, replicated three times. Infected plants were disinfected with 75% ethanol for 3 min, then washed twice with sterile distilled water in the laboratory. The samples were placed on sterile filter paper and air-dried for 30 min on a clean bench. They were then transferred to WA medium (20 g agar, 1 L distilled water) and incubated in a 25 °C incubator to isolate the pathogen. The pathogens were purified, and the causal organism was identified through microscopic observation. The control value for each treatment was calculated using the following arithmetic formula:

$$\text{Control value }(\%) = \frac{(\text{Disease incidence rate of the treatment} - \text{Disease incidence rate of control})}{\text{Disease incidence rate of control}} \times 100$$

The disease incidence scale of ginger rhizome rot from 0 to 9 is commonly used to represent varying levels of disease severity. The typical breakdown of disease incidence in such scales is as follows:

0: no disease symptoms;
1: less than 5% of the plant affected;
3: 6–25% of the plant showing symptoms;
5: 26–50% of rhizome rot;
7: 51–75% of rhizome rot;
9: more than 75% of rhizome rot.

2.7. Experimental Data Collection and Statistical Analysis

The experiment was designed to assess the effects of the aforementioned treatments on both the control of ginger rhizome rot and growth of organic ginger. Each treatment was applied at two-week intervals, with data collected on the emergence rate of seedlings, disease incidence, plant growth parameters (plant height and fresh weight). All experimental data were collected in triplicate and analyzed using the SAS program for Windows (ver.

9.2_PC32, SAS Institute Inc., Cary, NC, USA). Significance testing between treatments was performed using Duncan's multiple range test at a 5% significance level.

3. Results

3.1. Evaluation of Lime–Sulfur Mixture Contents for Disinfection of Ginger Rhizome Seeds

To develop eco-friendly disinfection technology for ginger seed rhizomes, the effects of treating domestic ginger, Bongdongjaerae, and Chinese imported ginger, Laiwu xiao, with 0.4% and 1.0% LSM solution on seedling emergence rates were investigated. After 80 days, the domestic ginger, Bongdongjaerae, treated with 0.4% LSM solution, had the highest seedling emergence rate at 89.0 ± 3.0%, while the Chinese variety, Laiwu xiao, had a seedling emergence rate of 81.4 ± 1.8% (Figure 1). Comparing the average seedling emergence rates by variety, the domestic ginger, Bongdongjaerae, had an average rate of 81.8 ± 7.1%, which was 5.4% higher than the average rate of the Chinese variety Laiwu xiao of 76.4 ± 5.2% (Figure 1).

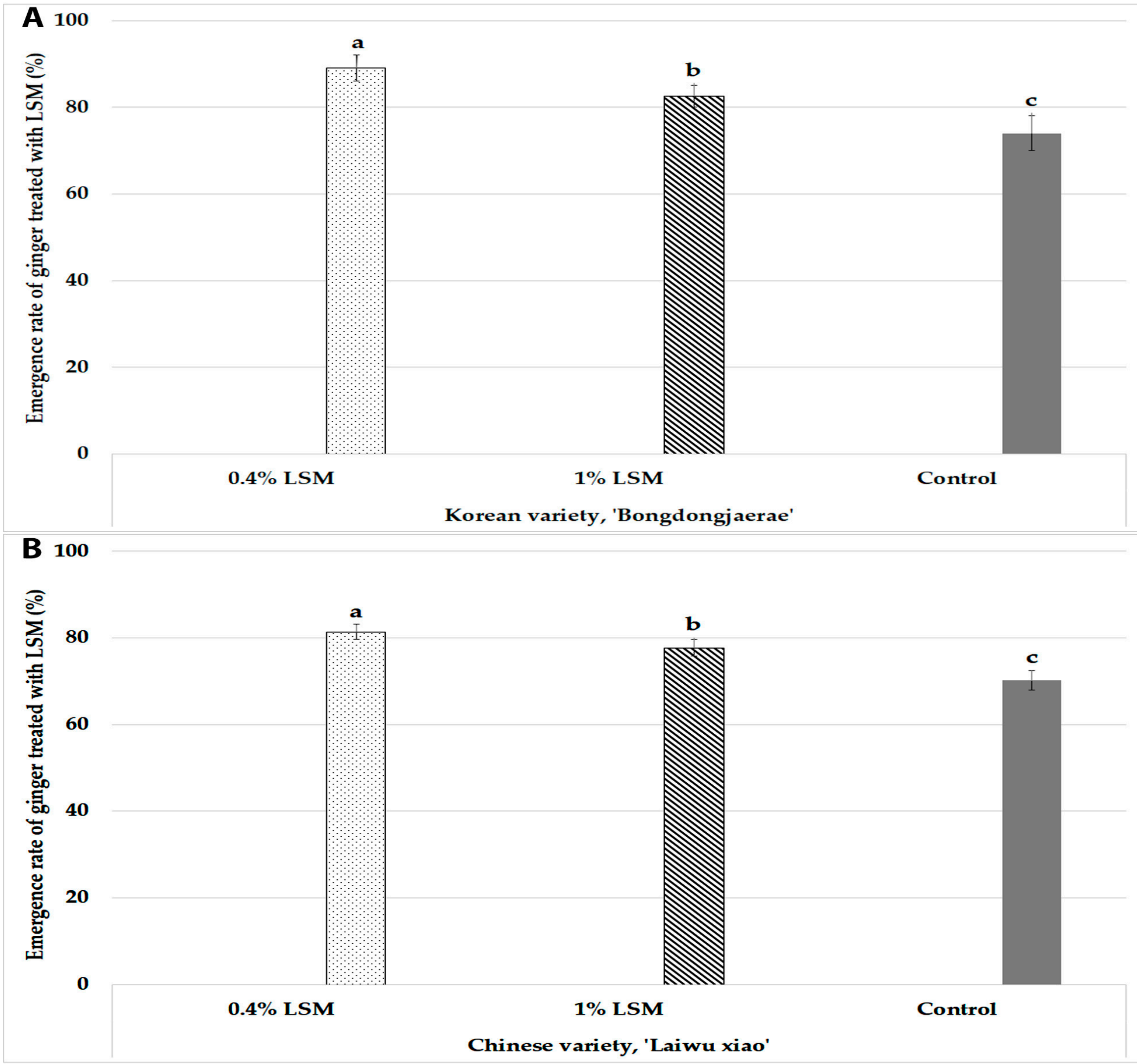

Figure 1. Comparison of emergence rates of Korean variety, Bongdongjaerae (**A**), and imported Chinese variety, Laiwu xiao (**B**), organic ginger rhizome seeds treated with organic agricultural material or 0.4% or 1.0% lime–sulfur mixture (LSM) in an organic field. The bars represent the emergence rates, and lower case letters on the bars indicate significantly differences compared to the untreated control at the $p < 0.01$.

3.2. Comparison of Emergence Rates and Fresh Weight of Organic Ginger Rhizome Seeds Treated with Antifungal Bacterial Isolates and Microalga

After 80 days of treatment, the control group (CK) that received only water had the lowest emergence rate at 85.6%. Treatment with 0.1% GT234 improved the emergence rate to 90.2%, while 0.1% GT227 resulted in a slightly higher rate of 91.2%. The highest emergence rate was achieved with 0.2% CHK0058, which reached 100%. The combination of 0.1% GT234 and CHK0058 led to a 92.2% emergence rate, higher than GT234 alone but lower than 0.2% CHK0058 alone. The combination of 0.1% GT227 and 0.2% CHK0058 showed an emergence rate of 95.2%, significantly better than the control and single 0.1% GT227 treatment but even lower than 0.2% CHK0058 alone. Overall, the seedling emergence rates increased by 5.4% to 16.8% compared to the untreated control for both single and combined treatments (Table 1).

Table 1. Effects of single and combined treatments usingantifungal bacterial isolates, *Bacillus velezensis* GT234 and GT227, and biostimulant microgreen alga, *Chlorella fusca* CHK0058, on the emergence rate and fresh weight of Korean ginger variety, Bongdongjaerae.

Treatment [(a)]	Korean Ginger Variety, Bongdongjaerae	
	Emergence Rate (% ± SD)	Fresh Weight of Rhizome (g/Plant ± SD)
CK	85.6 ± 15.2 e	310.0 ± 8.4 f
0.1% GT234	90.2 ± 4.2 d	350.1 ± 6.2 e
0.1% GT227	91.2 ± 3.6 c	363.2 ± 5.3 d
0.2% CHK0058	100 ± 0 a	388.2 ± 4.2 c
0.1% GT234 + 0.2% CHK0058	92.2 ± 2.3 c	394.8 ± 4.8 b
0.1% GT227+ CHK0058	95.2 ± 5.4 b	405.2 ± 5.2 a

[(a)] CK, untreated control with only water; GT234 + CHK0058, combined treatment of *Bacillus velezensis* GT234 and *Chlorella fusca* CHK0058; GT227 + CHK0058, combined treatment of *Bacillus velezensis* GT227 and *Chlorella fusca* CHK0058. Data with in a column followed by the same letter are not significantly different compared to the untreated control at the $p < 0.05$.

At the harvest stage, the control group had the lowest fresh weight of rhizomes at 310.0 g/plant. Treatment with 0.1% GT234 increased the fresh weight to 350.1 g/plant, while 0.1% GT227 further increased it to 363.2 g/plant. The 0.2% CHK0058 treatment significantly increased the rhizome fresh weight to 388.2 g/plant. The combined treatment of 0.1% GT234 and 0.2% CHK0058 resulted in 394.8 g/plant, outperforming either treatment alone. The highest fresh weight was observed with the combined treatment of 0.1% GT227 and CHK0058, resulting in 405.2 g/plant, significantly outperforming all other treatments. All treatments increased the fresh weight of ginger rhizomes by 12.9% to 30.7% compared to the control, with the order of increase being 0.1% GT227 + 0.2% CHK0058 > 0.1% GT234 + CHK0058 > 0.2% CHK0058 > 0.1% GT227 > 0.1% GT234 (Table 1).

B. velezensis GT234, GT227, and *C. fusca* CHK0058 were all identified as effective organic agricultural materials for increasing both the seedling emergence rate and fresh weight of organic ginger (Table 1).

3.3. Comparison of Ginger Yield by Ridge Width (Single Row, Flat Row) and Organic Agricultural Material Treatment

In Table 2, the highest fresh weight was observed in the 0.2% CHK0058 treatment, with the single-bed configuration yielding 363.3 g and the flat-bed yielding 290.2 g. The second-highest fresh weight was achieved with the 4% compost tea treatment in the single-bed configuration (337.0 g). Comparing ridge widths, single-bed cultivation yielded a higher average fresh weight (296.3 ± 39.9 g) compared to flat-bed cultivation (258.9 ± 30.3 g), indicating a 37.4 g increase per 10 plants.

Table 2. Effects of various treatment on the fresh weight of ginger in flat and single cultivation bed of Korean ginger variety, Bongdongjaerae.

Treatment [(a)]	Average Fresh Weight of Ginger (g/10 Plants)	
	Flat–Bed	Single–Bed
0.1% GT234	250.7 ± 15.5 c	270.0 ± 14.2 d
0.1% GT227	283.3 ± 18.2 b	263.3 ± 13.2 e
0.2% CHK0058	290.2 ± 10.2 a	363.3 ± 9.5 a
4% CT	286.7 ± 10.4 b	337.0 ± 8.5 b
0.4% LSM	232.4 ± 11.2 d	287.7 ± 7.4 c
CK	210.0 ± 14.2 e	256.7 ± 13.2 f
Max	290.2	363.3
Min	232.4	263.3
Mean	258.9 ± 30.3	296.3 ± 39.9

[(a)] CK, untreated control with only water; GT234 and GT227, antifungal bacterial isolates *Bacillus velezensis* GT234 and GT227; CHK0058, biostimulant microalga *Chlorella fusca* CHK0058; CT, compost tea; LSM, lime–sulfur mixture. Data with in a column followed by the same letter are not significantly different compared to the untreated control at the $p < 0.05$.

The 0.1% GT227 treatment yielded 283.3 g in the flat bed and 263.3 g in the single bed. The lowest yield was observed in the untreated control, with 210.0 g for the flat bed and 256.7 g for the single bed. Generally, the single-bed configuration produced higher yields across all treatments.

Comparing the average fresh weight per 10 plants by treatment, the 0.2% CHK0058 treatment showed the highest average fresh weight among the five types of organic materials. In flat-bed cultivation, treatments increased the fresh weight by 22.4 to 80.2 g compared to the control, while in single-bed cultivation, the increase ranged from 6.6 to 106.6 g.

In flat-bed cultivation, the treatments increased fresh weight in the order of 0.2% CHK0058 > 4% CT > 0.1% GT227 > 0.1% GT234 > 0.4% LSM. In single-bed cultivation, the order was 0.2% CHK0058 > 4% CT > 0.1% GT234 > 0.1% GT227 > 0.4% LSM (Table 2).

3.4. Growth Promotion Effects of Organic Ginger by Soil Treatment with Organic Agricultural Material

The combined treatment of *B. velezensis* (AFB2-2 and GT234) and *C. fusca* (CHK0058) produced the tallest plants across both varieties and ridge configurations. The 0.4% LSM and 0.1% AFB2-2 + 0.1% GT234 treatments also significantly improved plant height compared to the control.

When measuring plant height after soil drenching with four types of organic materials, the Korean ginger variety, Bongdongjaerae, consistently exhibited greater plant height than the Chinese ginger variety, Laiwu xiao. Bongdongjaerae showed average height increases of 29 to 31 cm, while Laiwu xiao showed increases of 23 to 30 cm, depending on the treatment (Table 3).

Overall, the Korean ginger variety, Bongdongjaerae, had greater plant height across all treatments and ridge configurations, with the flat-ridge configuration resulting in taller plants compared to the single-ridge configuration for both varieties. Among the treatments, the combined treatments of 0.1% AFB2-2, 0.1% GT234, and 0.2% CHK0058 led to the most significant increase in plant height, followed by 0.4% LSM and 0.1% AFB2-2 + 0.1% GT234 alone. All treatments showed significantly greater above-ground growth compared to the control, with the combined microbial agent and chlorella showing the best results (Table 3).

Table 3. Growth promotion effects of organic ginger by soil treatment with organic agricultural materials.

Treatments [(a)]	Plant Height of Ginger (cm)			
	Flat Ridge		Single Ridge	
	Chinese Variety, Laiwu Xiao	Korean Variety, Bongdongjaerae	Chinese Variety, Laiwu Xiao	Korean Variety, Bongdongjaerae
0.4% LSM	29	31	24	29
0.1% GT227 + 0.1% GT234	26	30	23	29
0.1% GT227 + 0.1% GT234 + 0.2% CF	30	31	25	31
CK	17	27	20	25

[(a)] CK, untreated control with only water; LSM, lime–sulfur mixture; AFB2-2 + GT234, combined treatment of *Bacillus velezensis* GT227 and GT234; GT227 + GT234 + CF, combined treatment of GT227 + GT234 and *Chlorella fusca* CHK0058.

3.5. Comparison of Organic Ginger Rhizome Rot Infection Rates by Ginger Variety, Ridge Width, and Organic Agricultural Material Treatment

When comparing infection rates of organic ginger rhizome rot by ginger variety, ridge width, and organic material treatment, single-ridge cultivation generally had lower infection rates compared to flat-ridge cultivation.

In flat-ridge cultivation, the domestic ginger variety, Bongdongjaerae had an average infection rate of 19.4%, while the Chinese variety, Laiwu xiao had an average infection rate of 31.6%. The infection rates for the Chinese variety, Laiwu xiao were 24.4% (0.4% LSM), 30.0% (0.1% GT227 + 0.1% GT234), 20.0% (0.1% GT227 + 0.1% GT234 + 0.2% CHK0058), and 52.0% (control). For the Korean variety, Bongdongjaerae, the rates were 15.0% (0.4% LSM), 22.4% (0.1% GT227 + 0.1% GT234), 10.0% (0.1% GT227 + 0.1% GT234 + 0.2% CHK0058), and 30.2% (control) (Table 4).

Table 4. Effect of ginger variety, ridge width, and organic agricultural material treatment on organic ginger rhizome rot infection rates.

Treatments [(a)]	Ridge Type [(b)]	Disease Incidence of Rhizome Rot (%)		Control Value (%)	
		Chinese Variety, Laiwu Xiao	Korean Variety, Bongdongjaerae	Chinese Variety, Laiwu Xiao	Korean Variety, Bongdongjaerae
0.4% LSM	Flat	24.4	15.0	53.1	50.3
	Single	19.0	0	55.2	100.0
0.1% GT227 + 0.1% GT234	Flat	30.0	22.4	42.3	25.8
	Single	25.0	12.5	41.0	32.4
0.1% GT227 + 0.1% GT234 + 0.2% CHK0058	Flat	20.0	10.0	61.5	66.9
	Single	15.0	0	64.6	100.0
CK	Flat	52.0	30.2	-	-
	Single	42.4	18.5	-	-
Mean	Flat	31.6	19.4	52.3	47.7
	Single	25.4	7.8	53.6	77.5
LSD 0.05	Flat	0.04	0.04	0.03	0.02
	Single	0.03	0.02	0.02	0.01

[(a)] CK, untreated control with only water; LSM, lime–sulfur mixture; AFB2-2 + GT234, combined treatment of *Bacillus velezensis* AFB2-2 and GT234; AFB2-2 + GT234 + Ch, combined treatment of AFB2-2 + GT234 and *Chlorella fusca* CHK0058. [(b)] Flat-ridge type and single-ridge type had width and height of 90 × 20 cm and 60 × 20 cm, respectively.

In single-ridge cultivation, the Korean variety, Bongdongjaerae had an average infection rate of 7.8%, while the Chinese variety, Laiwu xiao had 25.4%. The infection rates for the Chinese variety, Laiwu xiao were 19.0% (0.4% LSM), 25.0% (0.1% GT227 + 0.1% GT234), 15.0% (0.1% GT227 + 0.1% GT234 + 0.2% CHK0058), and 42.4% (control). For the Korean variety, Bongdongjaerae, the rates were 0% (0.4% LSM), 12.5% (0.1% GT227 + 0.1% GT234), 0% (0.1% GT227 + 0.1% GT234 + 0.2% CHK0058), and 18.5% (control) (Table 4).

Overall, the combined treatment of *B. velezensis* (GT227 and GT234) and *C. fusca* (CHK0058) was most effective in reducing rhizome rot infection rates for both varieties and ridge configurations. The Korean variety, Bongdongjaerae, consistently exhibited lower infection rates across all treatments compared to the Chinese variety, Laiwu xiao. Single-ridge configurations generally resulted in lower infection rates than flat-ridge configurations, suggesting a more favorable environment for reducing rhizome rot (Table 4).

3.6. Distribution of Pathogens by Ginger Variety, Ridge Width, and Organic Agricultural Material Treatment

In an organic ginger field, pathogen distribution was assessed by isolating pathogens from infected plants during different growth stages of Chinese variety, 'Laiwu xiao', and Korean variety, Bongdongjaerae.

In the flat-ridge type, the Chinese variety, Laiwu xiao exhibited a disease incidence score of 4.3 ± 0.5 during the early stage, increasing to 8.2 ± 0.8 by the harvest stage. The Korean variety, Bongdongjaerae, showed no signs of disease (0 ± 0) in the early stage but recorded a lower incidence score of 3.8 ± 1.1 at harvest. For the single-ridge type, the Chinese variety, Laiwu xiao had a disease incidence score of 2.2 ± 0.6 in the early stage, rising to 4.5 ± 0.7 by harvest. The Korean variety, Bongdongjaerae remained disease-free (0 ± 0) in the early stage, with a slight increase to 2.2 ± 0.4 at harvest. In the flat-ridge type with the Chinese variety, Laiwu xiao, *Pythium* sp. isolation was 70 ± 9.4% in the early stage, decreasing to 65 ± 7.1% by harvest. *Fusarium* sp. isolation was 20 ± 8.2% in the early stage and 19.5 ± 8.6% at harvest. *Ralstonia* sp. isolation rates increased from 10 ± 3.3% in the early stage to 15 ± 4.7% at harvest (Table 5). For the flat-ridge type with the Korean variety, Bongdongjaerae, no pathogens were isolated in the early stage. At harvest, *Pythium* sp. was isolated at 70 ± 8.2%; *Fusarium* sp. at 25 ± 4.7%; and *Ralstonia* sp. at 5 ± 0.8%.

Table 5. Contribution of plant pathogens isolated from infested ginger rhizome according to the early (August) and harvest (October) stage of ginger cultivation in Jeonju in 2023.

Type of Ridge [(a)]	Variety	Disease Incidence (0–9) [(b)]		Percentage of Isolated Pathogens (%)					
				Pythium sp.		*Fusarium* sp.		*Ralstonia* sp.	
		Early	Harvest	Early	Harvest	Early	Harvest	Early	Harvest
Flat	Chinese variety, 'Laiwu xiao'	4.3 ± 0.5	8.2 ± 0.8	70 ± 9.4	65 ± 7.1	20 ± 8.2	19.5 ± 8.6	10 ± 3.3	15 ± 4.7
	Korean variety, 'Bongdongjaerae'	0 ± 0	3.8 ± 1.1	0 ± 0	70 ± 8.2	0 ± 0	25 ± 4.7	0 ± 0	5.0 ± 0.8
Single	Chinese variety, 'Laiwu xiao'	2.2 ± 0.6	4.5 ± 0.7	80 ± 8.2	50 ± 9.4	20.0 ± 8.2	32 ± 7.9	0 ± 0	18 ± 9.5
	Korean variety, 'Bongdongjaerae'	0 ± 0	2.2 ± 0.4	0 ± 0	7512.7±	0 ± 0	19.5 ± 6.0	0 ± 0	5 ± 1.5

[(a)] Flat-type and single-type beds had width and height of 90 × 20 cm and 60 × 20 cm, respectively. [(b)] The disease incidence scale of ginger rhizome rot (0–9)—0: no disease symptoms; 1: less than 5%; 3: 6–25%; 5: 26–50%; 7: 51–75%; 9: more than 75% of rhizome rot.

In the single-ridge type with the Chinese variety, Laiwu xiao, *Pythium* sp. was isolated at 80 ± 8.2% in the early stage, decreasing to 50 ± 9.4% by harvest. *Fusarium* sp. showed an isolation rate of 20 ± 8.2% in the early stage and 32 ± 7.9% at harvest. *Ralstonia* sp. was not isolated in the early stage but had an isolation rate of 18 ± 9.5% at harvest (Table 5). For the single-ridge type with the Korean variety, Bongdongjaerae, no pathogens were isolated in the early stage. At harvest, *Pythium* sp. had an isolation rate of 75 ± 12.7%; *Fusarium* sp. had an isolation rate of 19.5 ± 6.0%; and *Ralstonia* sp. had an isolation rate of 5 ± 1.5%.

3.7. Comparison of Ginger Yield by Variety and Organic Agricultural Material Treatment

The control treatment yielded 802.5 g for the Chinese variety, Laiwu xiao, and 1443.8 g for the Korean variety, Bongdongjaerae (Figure 2). With the 0.4% lime–sulfur mixture, yields increased to 1651.3 g (a 105.8% increase) for the Chinese variety, Laiwu xiao, and 2677.5 g (an 85.4% increase) for the Korean variety, Bongdongjaerae. The combined *B. velezensis* GT227 and GT234 treatment resulted in yields of 1622.5 g (a 102.1% increase) for the Chinese variety, Laiwu xiao, and 2345.0 g (a 62.4% increase) for the Korean variety, Bongdongjaerae. The highest yields were obtained with the combined treatment of GT227, GT234, and *C. fusca* CHK0058, producing 1893.8 g (a 136.0% increase) for the Chinese variety, Laiwu xiao, and 2831.3 g (a 96.1% increase) for the Korean variety, Bongdongjaerae (Figure 2).

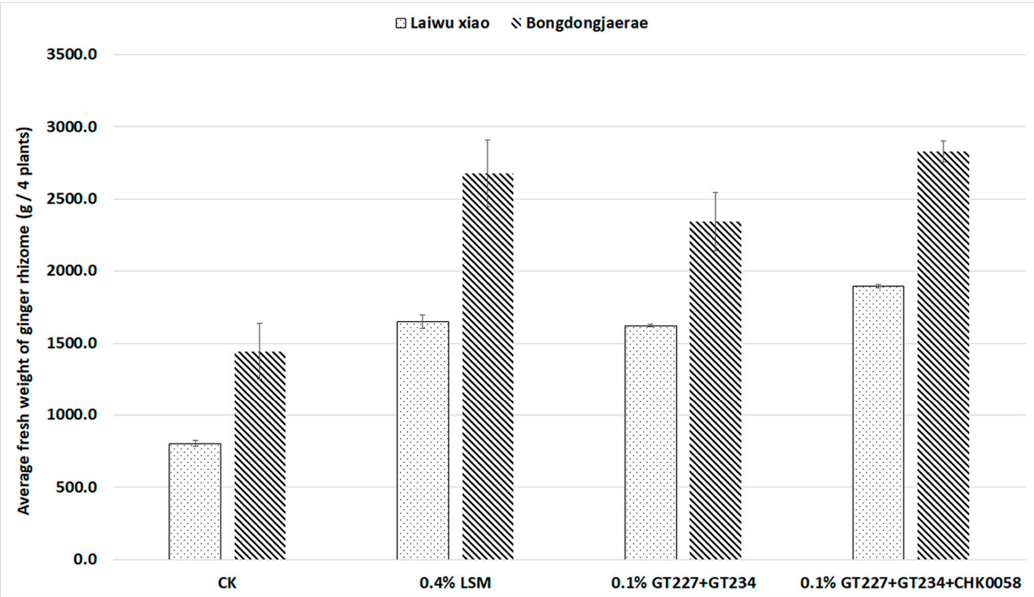

Figure 2. Comparison of fresh weight of ginger with ginger varieties treated with organic agricultural materials. LSM, lime–sulfur mixture; GT227 + GT234, combined treatment of *Bacillus velezensis* GT227 and GT234; GT227 + GT234 + CHK0058, combined treatment of GT227 + GT234 and *Chlorella fusca* CHK00058.

4. Discussion

This study successfully demonstrated the potential of eco-friendly disinfection treatments for ginger seed rhizomes, particularly through the use of lime–sulfur mixtures and microbial agents. The 0.4% lime–sulfur treatment significantly enhanced germination rates, while the combination of *Bacillus velezensis* strains and *Chlorella fusca* showed promising results in increasing fresh weight and reducing disease incidence. These findings support the viability of organic treatments for improving ginger growth and highlight the potential for integrating sustainable practices in ginger cultivation.

Both 0.4% and 1.0% LSM significantly increased ginger emergence rates, with 1.0% LSM being more effective in both Bongdongjaerae and Laiwu xiao, suggesting a dose-dependent response. Bongdongjaerae showed greater improvement, likely due to genetic differences. Wang et al. [64] also found that 1.0% LSM significantly increased emergence rates, aligning with our findings. In contrast, Zhang et al. [65] observed that sulfur treatments, while improving soil health, did not enhance emergence and sometimes caused phytotoxicity.

Treatments with *Bacillus velezensis* (GT234 and GT227) and *Chlorella fusca* (CHK0058) significantly improved emergence rates and fresh weight in Bongdongjaerae ginger. The combination of GT227 and CHK0058 showed the best results. Solomon et al. [52] found similar effects with *Bacillus subtilis* and *Chlorella vulgaris*. Other research supports the synergistic effect of combining bacteria and algae for improved crop performance [62,66,67].

Johnson et al. [68] found that *Bacillus* alone improved ginger growth but algal extracts did not significantly enhance results and sometimes caused phytotoxicity. Zhang et al. [69] noted that the benefits of biostimulants varied by soil type, with high-clay soils showing less improvement. These studies suggest the effectiveness of treatments depends on strains, environmental conditions, and soil composition.

The highest fresh weight was seen in the 0.2% *Chlorella fusca* CHK0058 treatment, especially in single-bed configurations. Kang et al. [55] similarly found that raised beds increased ginger yields, especially with *Chlorella vulgaris*. The combination of *Bacillus* and *Chlorella* enhanced both emergence and rhizome weight.

Our data show that *Bacillus velezensis* GT234 and GT227 and *Chlorella fusca* CHK0058 treatments significantly improved plant height, especially in Bongdongjaerae. The flat-ridge configuration supported better plant growth, aligning with previous studies that highlight the benefits of combining microbial treatments and optimal ridge configurations for maximizing yield [70–72].

Sharma et al. [70] and Patil et al. [71] found that wider ridges significantly improved ginger yield and quality, similar to our results. Single-bed cultivation acted like a wider ridge, providing better soil aeration and moisture retention, improving ginger growth.

Our results showed lower infection rates in single-ridge configurations. Patil et al. [71] and Kumar et al. [35] found that raised beds significantly reduced disease rates. In contrast, Zang et al. [69] reported that organic treatments were less effective in high-clay soils, emphasizing the need for customized applications.

This study found *Pythium* sp. was the dominant pathogen during the harvest stage in both varieties, with *Fusarium* sp. and *Ralstonia* sp. present but at lower rates. Studies by Islam et al. [41] and Singh [73] support the dominance of *Pythium* sp. in rhizome rot. Regional variations in pathogen prevalence suggest the need for tailored disease management strategies.

Behera et al. [74] found that seed treatment and application of *Trichoderma* spp. were suitable for the effective biological control of *Pythium* soft rot in ginger.

Their findings were consistent across both Chinese and Korean ginger varieties, supporting the dominance of *Pythium* sp. observed in our study. Islam et al. [75] investigated ginger rhizome rot in tropical climates and found that *Pythium* sp. was responsible for the majority of wilt cases, with a similar pathogen distribution pattern: *Pythium* sp. (60–70%), *Fusarium* sp. (20–25%), and *Ralstonia* sp. (10–15%). These results corroborate the prevalence of *Pythium* sp. as the dominant pathogen in ginger cultivation.

While our study aligns with several reports, there are notable studies with differing results, particularly concerning the prevalence of other pathogens. Shanmugam et al. [76] demonstrated that a mixture of *Bacillus subtilis* (S2BC-1) and *Burkholderia cepacia* (TEPF-Sungal) achieved the highest rhizome production (85.2%) and significantly reduced yellows and rhizome rot incidence (87.8% and 88.4%) in a greenhouse, enhancing defense enzyme activity. Field trials showed the strain mixture reduced disease incidence by 50.5%, comparable to a fungicide mixture.

This contrasts with our findings, where *Pythium* sp. was the dominant pathogen. The difference could be attributed to regional climatic variations and the different ginger varieties used in their study. Metthews et al. [77] investigated the minimum spore density required for infection in the dominant Australian ginger cultivar, Canton. Inoculation with varying spore densities (10^1 to 10^7 microconidia per gram of soil) showed that disease severity increased with higher inoculum levels. The minimum threshold for plant infection was found to be 10^1 microconidia per gram of soil.

Kifelow et al. [78] reported that ginger is a vital crop for small-scale farmers in Ethiopia, with up to 85% of farmers and 35% of arable land dedicated to its production. However, bacterial wilt epidemics in 2011 and 2012 caused severe losses, with the incidence reaching up to 100% in some areas. This finding is in stark contrast to our results, suggesting that local environmental factors and soil conditions might play significant roles in pathogen prevalence.

Our findings align with studies like Chang et al. [79], which showed that lime–sulfur treatments effectively enhanced yields. The combination of *Bacillus* and *Chlorella* strains further improved yields and reduced pathogen pressure, as supported by Mahapatra et al. [80] and Zhang et al. [69].

The substantial yield increases observed with lime–sulfur mixture, *Bacillus*, and *Chlorella* suggest their potential as powerful tools for organic farming. Future research should focus on understanding how these treatments interact with soil microbiomes and affect plant health in the long term.

5. Conclusions

This study shows that a 1.0% lime–sulfur mixture (LSM) effectively enhances the emergence rates of organic ginger rhizome seeds, providing an eco-friendly solution for improving crop establishment and productivity in organic ginger cultivation. Further research could examine the long-term effects of LSM on ginger growth, yield, and soil health. The combined use of *Bacillus velezensis* GT234 and GT227 with *Chlorella fusca* CHK0058 significantly improves the emergence rate and fresh weight of Korean native ginger variety, Bongdongjaerea, with the combination of GT227 and CHK0058 being particularly effective due to their synergistic effects. The use of biostimulants such as *C. fusca*, *B. velezensis*, and compost tea enhances ginger yields, with single-bed configurations recommended for optimal growth. Future research should investigate the mechanisms behind these treatments and their long-term effects on soil health and crop productivity. This study also emphasizes the importance of bed configuration and organic materials in optimizing ginger growth, with wider or raised beds improving soil conditions and root development. The synergistic effects of biocontrol agents and biostimulants can significantly enhance ginger yield and growth, supporting plant health and disease resistance, particularly with single-ridge configurations. The results also indicate that the disease incidence is higher at harvest compared to in the early stage, with the Chinese variety, Laiwu xiao being more susceptible to rhizome rot than Bongdongjaerea. *Pythium* sp. is the most prevalent pathogen, especially at harvest, with *Fusarium* sp. and *Ralstonia* sp. varying by ridge type and ginger variety. The Korean native ginger variety, Bongdong and the single-ridge type effectively reduce disease incidence, particularly during the early stages. The combination of GT227, GT234, and CHK0058 significantly increased yields for both ginger varieties, with the Korean native ginger variety, Bongdongjaerea showing better responsiveness. These findings highlight the potential of specific beneficial microorganisms and chlorella to improve ginger yield, offering valuable insights for optimizing organic ginger cultivation practices. Further research should refine these treatments and explore their applicability in different conditions and varieties.

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