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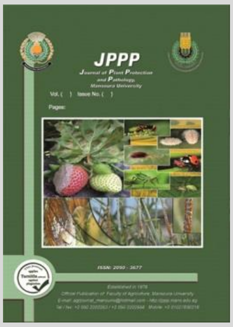
Comparative Effectiveness of Organic, Biological, and Chemical Methods for Managing White Rot in Garlic (*Allium sativum* L.)

Karima G. Helmy[1]; Noura M. Taha[2] and Aya H. Abo-Zaid[1*]

[1]Plant Pathology Dept., Fac. of Agric., Ain Shams University, Egypt.
[2]Horticulture Department, Faculty of Agriculture, Ain Shams University, Egypt



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ABSTRACT

White rot disease, caused by *Sclerotium cepivorum*, severely affects garlic yields in Egypt. Aim of study assessed 27 fungal isolates from various Egyptian governorates, revealing pathogenicity variability with disease severity from 28.60% (Qalyubia) to 82.47% (Sharqia). Greenhouse tests showed all treatments reduced disease severity. In Balady, bougainvillea extract and Folicure had the lowest severity (36.00%, 59.09% efficacy), while *Bacillus thuringiensis* and salicylic acid significantly enhanced plant weight (8.6–8.63 g; >128% increase) and bulb diameter (up to 2.03 cm; 84.55% increase). In Sids-40 cultivar, Folicure (24.00%, 66.67% efficacy) and bougainvillea extract (28.00%, 61.11%) were most effective, and KH_2PO_4 improved plant weight (16.5–17.5 g; ~98-110% increase) and bulb diameter (up to 2.87 cm; 125.98% increase).Notably, Balady cultivar showed higher average disease severity (45.93%) than Sids-40 (41.19%), with Sids-40 exhibiting superior growth, including greater height (42.37 vs. 40.26 cm), fresh weight (14.31 vs. 7.3 g), and bulb diameter (2.69 vs. 1.80 cm). Field trials confirmed these findings; untreated controls had 65.2% disease severity and 3.1 kg/plot yield. Folicure reduced severity (19.5%, 70.1% efficacy), while KH_2PO_4 and salicylic acid led to significant yield increases (11.9 and 11.1 kg/plot; up to 280.2–253.7% increase). Overall, KH_2PO_4, salicylic acid, and selected biocontrol agents effectively suppressed white rot and enhanced garlic growth, suggesting a sustainable alternative to chemical fungicides

Keywords: *Sclerotium cepivorum*, Biocontrol, Salicylic acid, sodium bicarbonate, Potassium phosphate.

INTRODUCTION

Garlic (*Allium sativum* L.) is a widely cultivated crop with significant culinary and medicinal value, attributed to its bioactive constituents such as allicin, flavonoids, and organosulfur compounds (Subroto *et al*., 2021; El-Saadony *et al*., 2024). In Egypt, garlic is a key component of winter vegetable production, contributing substantially to both domestic consumption and export markets (Hanna and Mohammed, 2023).

White rot, caused by *Sclerotium cepivorum* Berk., poses a major threat to garlic cultivation, particularly under cool and moist conditions. The pathogen persists in soil through sclerotia, which germinates in response to Allium root exudates, rendering eradication challenging (Pinto *et al*., 2000; Siyoum and Yesuf, 2013).

Conventional management strategies, including chemical fungicides and crop rotation, have shown limited long-term efficacy and raise environmental and health concerns (Rhouma, 2025). Consequently, research has shifted toward sustainable alternatives. Biocontrol agents such as *Trichoderma harzianum* and *B. thuringiensis* exhibit antagonistic activity against *S. cepivorum via* mycoparasitism, competition, and antifungal metabolite production (Elshahawy *et al*., 2019; Saikia, 2023; Singh *et al*., 2024; Zawawy *et al*., 2025). Additionally, systemic acquired resistance (SAR) inducers including salicylic acid, sodium bicarbonate, and potassium phosphates have demonstrated potential in enhancing plant defense mechanisms (Elshahid *et al*., 2022; Lyousfi *et al*., 2022; Geng *et al*., 2025).

Organic amendments such as vermicompost and botanical extracts (e.g., *Bougainvillea glabra*) have further shown efficacy in suppressing white rot while improving soil fertility and microbial diversity (Abolmaaty and Fawaz, 2016; Abo-Zaid, 2020; Nayak *et al*., 2024; Zulfi *et al*., 2024).

This study investigates the comparative effectiveness of biological, chemical, and botanical treatments in managing white rot under artificial greenhouses conditions and naturally infested field conditions. It also evaluates their impact on vegetative growth and yield of two garlic cultivars (Balady and Sids-40), with the aim of identifying sustainable approaches for integrated disease management.

MATERIALS AND METHODS

Plant Material

Two garlic (*A. sativum* L.) cultivars, Balady and Sids-40, were obtained from the Horticulture Research Institute, Agricultural Research Center, Giza, Egypt. These cultivars were selected for their relevance to local agricultural practices and susceptibility to white rot disease.

Isolation and Identification of *S. cepivorum*

Garlic and onion plants exhibiting white rot symptoms were collected from various governorates across Egypt. Fungal isolates were identified based on morphological characteristics, following the descriptions provided by Rahman *et al*. (2020). Cultural, microscopic, and phytopathological examinations were conducted following the protocol described by Bipinbhai (2021), confirming that all 27 isolates belonged to *S. cepivorum*.

Preparation and Application of Treatments

Seven treatments were evaluated for their effects on garlic growth and disease suppression.

- **Salicylic Acid (SA)**

Salicylic acid ($C_7H_6O_3$), a phenolic compound known for its role in systemic acquired resistance, was applied at a

[*] Corresponding author.
E-mail address: ayaabo-zaid@agr.asu.edu.eg
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concentration of 100 ppm (Saputra *et al*., 2022). To prepare the solution, exactly 0.1 g of salicylic acid was first dissolved in a small volume of Ethanol 95% to facilitate solubility. The solution was then diluted with distilled water to a final volume of 1 L, resulting in a final concentration of 100 mg/L. Cloves were soaked prior to sowing, and foliar application was performed post-germination (Thomson *et al*., 2017).

- **Sodium Bicarbonate ($NaHCO_3$)**

Sodium bicarbonate was applied as a foliar spray at 5 g/L. The solution was freshly prepared with distilled water before each application. Cloves were soaked before sowing, and post-germination spraying was conducted using a hand sprayer until full foliage coverage (Abed and Farhan, 2023).

- **Potassium Dihydrogen Phosphate (KH_2PO_4, PDP)**

PDP was prepared at 100 mM in sterile distilled water and used as a foliar spray. Application was performed with a knapsack sprayer during early morning hours to minimize evaporation, following the method of El-Mohamedy *et al.* (2014).

- ***Bougainvillea Blossoms* Extract**

Fresh *Bougainvillea blossoms* (50 g) were washed, shade-dried, and crushed. The material was soaked in 500 mL distilled water for 48 hours at room temperature in a conical flask, with periodic shaking. The extract was filtered and concentrated under reduced pressure using a rotary evaporator to obtain the crude extract (Abarca-Vargas and Petricevich, 2018). A 5% solution was used for treatment, as described above (Ebrahim and Helmy, 2016).

- ***T. harzianum***

Soil samples from the garlic rhizosphere were used to isolate *T. harzianum* on Potato Dextrose Agar (PDA), following Kamel *et al*. (2017). Pure cultures were obtained through repeated sub-culturing. Identification was based on colony morphology and microscopic features, using the keys of Gams and Bissett (2002); Siddiquee *et al*. (2009), Sharma and Singh (2014). Seven-day-old PDA cultures were used to prepare spore suspensions. Spores were scraped into 10 mL sterile distilled water / Petri dish, transferred to a sterile beaker, and homogenized. Spore concentration was adjusted to 1×10^8 spores/mL using a hemocytometer. This suspension was used for seed soaking and foliar application (Udoh and Olufolaji, 2021).

- ***B. thuringiensis***

B. thuringiensis was isolated from garlic rhizosphere soil in Giza Governorate. Identification followed standard microbiological methods (Thiery and Franchon, 1997; El-Ghiet *et al*., 2023). A bacterial suspension was prepared in nutrient broth and adjusted to 1×10^7 CFU/mL Cloves were soaked before sowing, and the treatment was applied *via* soil drenching post-germination (Dehkian *et al*., 2024).

- **Folicure Fungicide (Tebuconazole 25% EC)**

Folicure, a systemic fungicide containing 25% Tebuconazole (EC), was obtained from the Ministry of Agriculture, Egypt. It was applied as a foliar spray at the manufacturer-recommended dose until full leaf coverage. This treatment served as the chemical control standard.

Greenhouse Experiments

Pathogenicity Testing and Isolate Selection

The pathogenicity of twenty-seven *S. cepivorum* isolates against garlic (*Allium sativum* L.) cultivar Sids-40 was evaluated under greenhouse conditions. Inocula were prepared by culturing each isolate on sterilized barley grains medium for three weeks at 20°C, following the method described by Van der Meer *et al.* (1983). The inoculum was then incorporated into sterilized pots (15 cm diameter) containing a sterilized sand–clay soil mixture (1:1, v/v) at a rate of 2% (w/w), seven days prior to planting (Amin *et al*., 2016).

Five pots were assigned to each isolate, with two garlic cloves sown per pot. The pots were arranged in a completely randomized block design. Disease severity was subsequently assessed, and the most virulent isolate of *S. cepivorum* was selected for subsequent experiments.

Disease severity was evaluated using the scale described by Cimen *et al*. (2010):

- 0 = Healthy plant
- 1 = Bulb covered with fungal mycelium, no visible decay
- 2 = 1–25% bulb rot
- 3 = 26–50% bulb rot
- 4 = 51–75% bulb rot
- 5 = 76–100% bulb rot

Severity scores were converted to percentage values using the formula:

Disease Severity (%) = (Σ(score × number of plants at each score) / (maximum score × total number of plants)) × 100

Greenhouse Evaluation of different Treatments on Disease Severity and Vegetative Growth of Garlic Cultivars (Balady and Sids-40).

Pot experiments were conducted in the greenhouses of the Plant Pathology Department, Faculty of Agriculture, Ain Shams University, to evaluate the effects of the tested treatments. Plastic pots (30 cm in diameter) were filled with a sterilized sand–clay soil mixture (1:1, v/v) and artificially infested with *S. cepivorum* inoculum at a rate of 2% (w/w) seven days before planting (Amin *et al*., 2016).

Each treatment and control were replicated in five pots. Four cloves from each of the two garlic cultivars (Balady and Sids-40) were planted per pot after treatment application. Disease severity was assessed following the methodology described earlier and treatment efficiency was calculated as:

Efficiency (%) = (A - B) / A) × 100

Where:

A = Disease severity (%) in untreated control
B = Disease severity (%) in treated plants

At the end of the experiment, ten plants per treatment were randomly sampled to measure:

- Plant height (cm)
- Plant weight (g)
- Bulb diameter (cm)

Percentage increase over the untreated control (infested soil without treatment) was calculated using:

Increase (%) = (Treated value - Control value) / Control value) × 100

Comparative Analysis of Garlic Cultivars under Greenhouse Conditions

To evaluate the relative susceptibility and agronomic performance of the two garlic cultivars (Balady and Sids-40) under natural infection with *S. cepivorum*, disease severity and selected growth parameters were statistically analyzed. A comparative bar chart was generated to illustrate differences between cultivars in terms of disease severity (%), plant height (cm), fresh weight (g), and bulb diameter (cm). The chart was prepared using [Microsoft Excel/Origin/GraphPad Prism] software, where mean values were plotted with standard error bars to represent data variability. Significant differences between means were identified using Duncan's multiple range test (p ≤ 0.05), and distinct letters above the bars denote statistically significant variations.

Field Experiment

Field Evaluation of Treatments on Disease Severity and Vegetative Growth of Garlic Sids-40 Cultivar under natural infection

Afield trial was conducted over two consecutive growing seasons in naturally infested soil at Giza Governorate to evaluate the efficacy of selected treatments on disease severity in garlic cv. Sids-40. Experimental procedures followed those of the greenhouse study, adapted for field conditions. Garlic cloves were planted 10 cm apart on both sides of each row. Each plot measured 10.5 m² (14 m × 0.75 m). The experiment was arranged in a split-plot design with three replicates within a randomized complete block layout. Disease severity was assessed using the same methodology as described for the greenhouse experiment. At harvest, ten plants per treatment were randomly selected to measure yield (kg/plot), plant height (cm), and bulb weight (g/plant). Percentage increases were calculated relative to the untreated control (infested soil without treatment), following the same procedure used in the greenhouse study.

Statistical Analysis

Data was analyzed using analysis of variance (ANOVA) via the General Linear Model (GLM) procedure (SAS Institute, 2012). Mean comparisons were performed using Duncan's multiple range test (Duncan, 1955).

RESULTS AND DISCUSSION

RESULTES

1. Greenhouse experiments

Pathogenicity Testing and Isolate Selection

Twenty-seven isolates of *S. cepivorum* were isolated from infected plants of garlic and onion collected from Giza, Sharqia, Mansoura and Qalyubia governorates are shown in Fig. (1 and 2). The isolated fungi were identified, and Pathogenicity tests were carried out to investigate the virulence of different fungal isolates on garlic plants (Sids-40). The evaluation of *S. cepivorum* isolates obtained from different Egyptian governorates demonstrated a wide range of disease severity levels on onion plants, highlighting significant variability in pathogenic potential among the isolates.

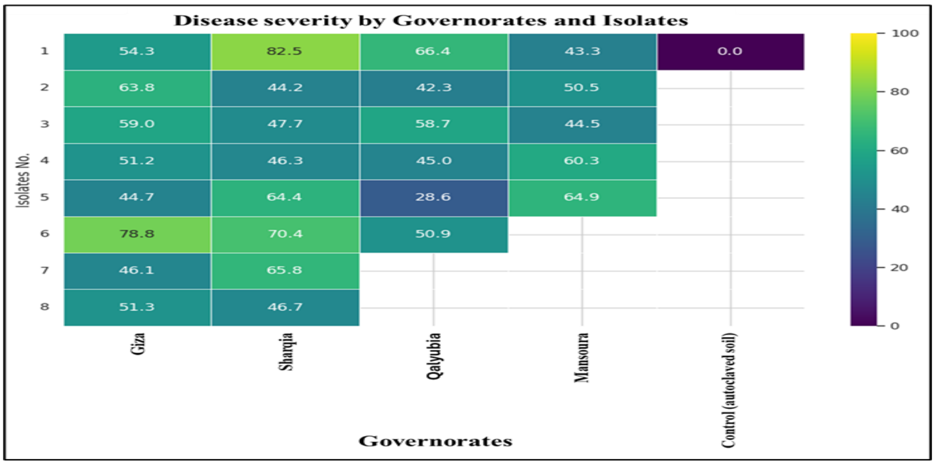

Fig. 1. Pathogenicity of different S. cepivorum isolates on garlic plants (Balady cultivar) *recorded as disease severity.

***. Data presented as the means of three replicates ± SD. Different letters refer to significant difference (P ≤ 0.05). L.S.D. at 0.05%**

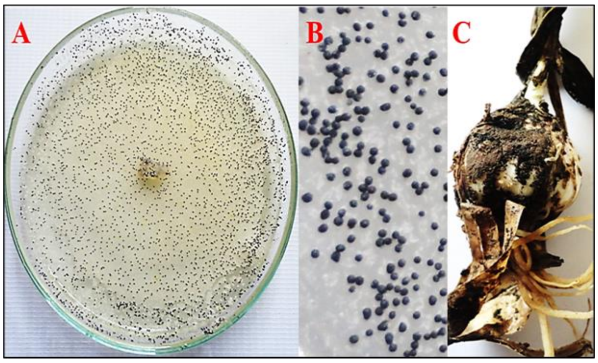

Fig. 2. Pathogenicity test of a *S. cepivorum* isolate on garlic plant (cv. Balady). (A: *S. cepivorum* on PDA medium, B: Sclerotium, C: White rot on garlic).

In Sharqia, isolate no. 1 exhibited the highest disease severity among all tested isolates, reaching 82.47%, indicating an extremely virulent strain. Other isolates from this governorate also caused relatively high infection rates, particularly isolates no. 6 and 7, which recorded 70.37% and 65.80%, respectively. The remaining isolates showed intermediate severity values ranging between 44.20% and 47.70%.

Isolates collected from Giza presented variable pathogenicity. Isolate no. 6 caused 78.80% disease severity, making it the most aggressive in that region. Moderate levels were observed with isolates no. 2 (63.77%) and no. 3 (58.97%). The lowest severity in Giza was recorded by isolate no. 5 (44.70%).

Only one isolate was tested from Mansoura, which resulted in 43.27% disease severity, suggesting relatively low aggressiveness compared to isolation from other governorates.

In Qalyubia, the pathogenic potential ranged widely among isolates. Isolate no. 1 showed a high severity value (66.40%), while isolate no. 5 recorded the lowest disease severity across all tested isolates at 28.60%. Other isolates from this region fell within a moderate range, between 42.33% and 60.29%.

The control treatment, where sterile autoclaved soil was used without inoculation, showed no disease symptoms (0.0%), confirming that the observed disease development in the other treatments was attributed solely to the tested fungal isolates.

Greenhouse Evaluation of Treatments on Disease Severity and Vegetative Growth of Garlic Cultivars

On Balady Cultivar:

Data presented in Table (1) demonstrate that all tested treatments significantly reduced white rot disease severity and enhanced the growth performance of Balady garlic under greenhouse conditions compared with the infested control. The infested control exhibited the highest disease severity (88.00%), with the lowest plant height (24.67cm), plant weight (3.77g), and bulb diameter (1.10 cm).

In contrast, all tested treatments significantly lowered disease severity compared with the infested control. The lowest severity was recorded with bougainvillea extract and Folicure, both at 36.00%, corresponding to an efficiency of 59.09% respectively. Salicylic acid and *T. harzianum* also achieved notable reductions (40.00%), with efficiencies of 54.55%. The highest disease severity among the treatments was associated with *B. thuringiensis* and $NaHCO_3$ (44.00%), giving efficiencies of 50.00 % (Fig. 3).

Regarding growth parameters, the non-infested control (autoclaved soil) exhibited the maximum plant height (47.00 cm) and the lowest disease severity (0.00%). Among the treatments, bougainvillea extract resulted in the tallest plants (45.33 cm), followed by KH_2PO_4 (44.67 cm) and *T. harzianum* (43.00 cm). In terms of plant weight, *B. thuringiensis* (8.63 g) and salicylic acid (8.60 g) recorded the highest values, corresponding to increases of 128.91% and 128.12%, respectively, compared to the infested control. Similarly, salicylic acid significantly increased bulb diameter (2.03 cm), representing an 84.55% improvement, followed by *B. thuringiensis* (2.00 cm; 81.82%) and bougainvillea extract or *T. harzianum* (1.93 cm; 75.45%).

Overall, all treatments significantly improved plant growth compared with the infested control, with salicylic acid, *B. thuringiensis*, and bougainvillea extract showing the most consistent effects in enhancing both growth parameters and bulb diameters.

Table 1. Effect of different treatments on white rot disease severity, Plant weight (gm), Plant height (cm), Bulb diameter (cm), and their Increases (%) of Balady garlic cultivar under greenhouse conditions.

Treatments	Disease Severity (%)	Efficiency (%)	Plant height (cm)	Increases (%)	Plant weight (gm)	Increases (%)	Bulb diam.(cm)	Increases (%)
Salicylic acid	$40.00^{CB}\pm2.30$	54.55	$40.00^{DC}\pm1.52$	62.14	$8.60^{A}\pm0.15$	128.12	$2.03^{A}\pm0.08$	84.55
$NaHCO_3$	$44.00^{B}\pm2.30$	50.00	$39.33^{DC}\pm1.20$	59.42	$8.37^{BA}\pm0.24$	122.02	$1.87^{BA}\pm0.08$	70.00
KH_2PO_4	$42.67^{CB}\pm3.52$	51.51	$44.67^{BA}\pm1.45$	81.07	$7.63^{BA}\pm0.18$	102.39	$1.90^{BA}\pm0.05$	72.73
Bougainvillea extract	$36.00^{C}\pm2.30$	59.09	$45.33^{BA}\pm1.45$	83.75	$7.67^{BA}\pm0.17$	103.45	$1.93^{BA}\pm0.08$	75.45
Trichoderma harzianum	$40.00^{CB}\pm2.30$	54.55	$43.00^{BC}\pm0.57$	74.30	$8.23^{BA}\pm0.37$	118.30	$1.93^{BA}\pm0.08$	75.45
Bacillus thuringiensis	$44.00^{B}\pm1.15$	50.00	$39.67^{DC}\pm1.45$	60.80	$8.63^{A}\pm0.60$	128.91	$2.00^{BA}\pm0.05$	81.82
Folicure	$36.00^{C}\pm2.30$	59.09	$38.67^{D}\pm0.88$	56.75	$7.27^{B}\pm0.61$	92.84	$1.73^{B}\pm0.08$	57.27
Control autoclaved soil	$0.00^{D}\pm3.50$	100.0	$47.00^{A}\pm0.57$	90.51	$5.77^{C}\pm0.53$	53.05	$1.77B^{A}\pm0.08$	60.9
Control infested	$88.00^{A}\pm2.30$	0.0	$24.67^{E}\pm0.88$	0.00	$3.77^{D}\pm0.24$	0.00	$1.10^{C}\pm0.011$	0.0

Data presented as the means of three replicates ± SD. Different letters refer to significant difference (P ≤ 0.05). L.S.D. at 0.05%

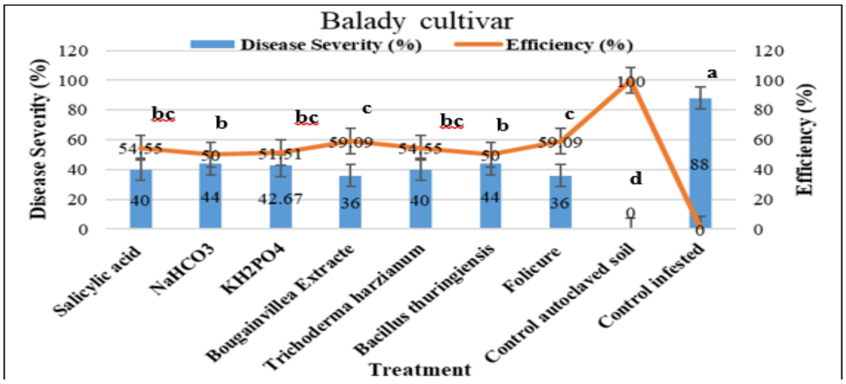

Fig. 3. Effect of different treatments on disease severity and efficiency (%) of garlic Balady cultivar.

Results in Fig. (4) refer to a very strong negative correlation of -1.00 between Disease Severity (%) and Efficiency (%). This is a crucial finding, indicating a direct inverse relationship: as the disease becomes more severe, the treatment's efficiency drops proportionally. Efficiency (%) shows a strong positive correlation with several key growth indicators. Correlates at +0.88 with both Plant height (cm) and Plant weight increase (%). This clearly suggests that more effective treatments lead to better overall plant development.

Different growth metrics are also strongly correlated with each other. For instance, there's a very strong positive correlation of +0.93 between Plant weight (gm) and Bulb diam. (cm), indicating that heavier plants tend to have larger bulbs. Similarly, plant height (cm) and Bulb diam. (cm) have a strong correlation of +0.81.

Correlation analysis statistically confirms that successful disease control, as measured by high efficiency, is directly linked to improved plant growth. The data also highlights the interdependence of plant growth parameters, showing that a favorable change in one metric is often accompanied by similar improvements in others. This matrix provides solid evidence that the most effective treatments are those that not only suppress the disease but also holistically enhance the plant's health and development.

On Sids-40 Cultivar:

Data in Table (2) demonstrate that all applied treatments significantly reduced white rot disease severity and enhanced growth performance of the Sids-40 garlic cultivar compared with the infested control. The highest disease severity was recorded in the infested control (72.00%), which was associated with the lowest plant height (23.00 cm), plant weight (8.33 g), and bulb diameter (1.27 cm). In contrast, Folicure provided the greatest reduction in disease severity (24.00%), with an efficiency of 66.67%, followed by bougainvillea extract (28.00%; 61.11% efficiency). Salicylic acid (33.33%) and *T. harzianum* (34.67%) were also effective, with efficiencies of 53.71% and 51.85%, respectively. The least effective treatments were $NaHCO_3$ (46.67%; 35.18% efficiency) and *B. thuringiensis* (44.00%; 38.89% efficiency) (Fig. 5).

Regarding plant growth, the tallest plants were observed with KH_2PO_4 and Folicure (47.00 cm), followed by bougainvillea extract (46.33 cm). Plant weight was maximized with bougainvillea extract (17.50 g; 110.08% increase) and KH_2PO_4 (16.50 g; 98.08% increase), while *T. harzianum* also promoted considerable increases (16.40 g; 96.88%). Bulb diameter was significantly improved by all treatments compared with the infested control, with values ranging between 2.60 and 2.87 cm, corresponding to increases of 104.72% to 125.98%.

Overall, data in Table (2) confirm that Folicure and bougainvillea extract were the most effective treatments against white rot in the Sids-40 cultivar, as they achieved the lowest disease severity and the greatest enhancements in plant growth and bulb development.

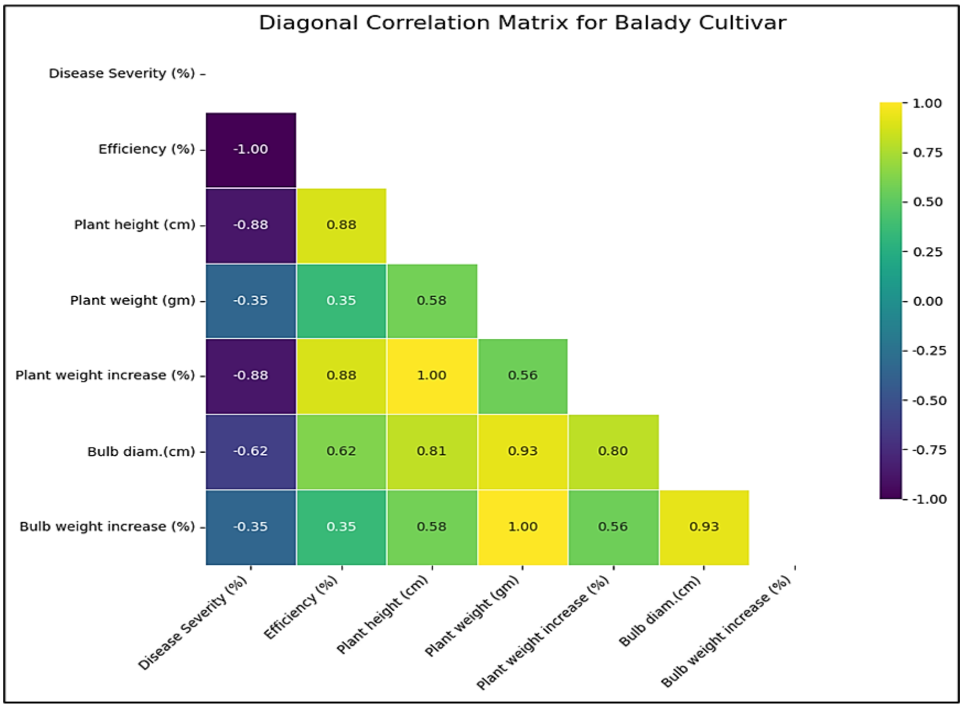

Fig. 4. Diagonal correlation matrix illustrates a scientific analysis of the linear relationships between various variables for Balady Cultivar. The values range from -1 (a perfect negative correlation) to +1 (a perfect positive correlation), with 0 indicating no linear relationship

Table 2. Effect of different treatments on white rot disease severity Plant weight (gm), Plant height (cm), Bulb diameter (cm), and their Increases (%) of Sids-40 garlic cultivar under greenhouse conditions.

Treatments	Disease Severity (%)	Efficiency (%)	Plant height (cm)	Increases (%)	Plant weight (gm)	Increases (%)	Bulb diam. (cm)	Increases (%)
Salicylic acid	$33.33^{CD}\pm1.33$	53.71	$44.67^{BA}\pm1.20$	94.22	$14.33^{BC}\pm0.12$	72.03	$2.87^{A}\pm0.08$	125.98
$NaHCO_3$	$46.67^{B}\pm1.33$	35.18	$44.67^{BA}\pm0.88$	94.22	$12.167^{C}\pm0.60$	46.10	$2.60^{A}\pm0.11$	104.72
KH_2PO_4	$40.00^{CB}\pm2.30$	44.44	$47.00^{A}\pm0.57$	104.35	$16.50^{BA}\pm0.86$	98.08	$2.80^{A}\pm0.05$	120.47
Bougainvillea Extracte	$28.00^{ED}\pm2.30$	61.11	$46.33^{BA}\pm0.88$	101.44	$17.50^{A}\pm0.28$	110.08	$2.73^{A}\pm0.08$	114.96
Trichoderma harzianum	$34.67^{CD}\pm1.33$	51.85	$40.67^{C}\pm0.88$	76.83	$16.40^{BA}\pm0.37$	96.88	$2.80^{A}\pm0.05$	120.47
Bacillus thuringiensis	$44.00^{B}\pm1.45$	38.89	$43.33^{BC}\pm1.20$	88.39	$15.40^{BA}\pm0.73$	84.87	$2.73^{A}\pm0.08$	114.96
Folicure	$24.00^{E}\pm2.30$	66.67	$47.00^{A}\pm1.15$	104.35	$14.07^{BC}\pm1.30$	68.91	$2.67^{A}\pm0.12$	110.24
Control autoclaved soil	$0.00^{F}\pm1.52$	100.00	$44.67^{BA}\pm1.45$	94.22	$14.13^{BC}\pm0.69$	69.63	$2.70^{A}\pm0.05$	112.60
Control infested	$72.00^{A}\pm2.30$	0.00	$23.00^{D}\pm1.15$	0.00	$8.33^{D}\pm0.44$	0.0	$1.27^{B}\pm0.08$	0.0

Data presented as the means of three replicates ± SD. Different letters refer to significant difference ($P \leq 0.05$). L.S.D. at 0.05%

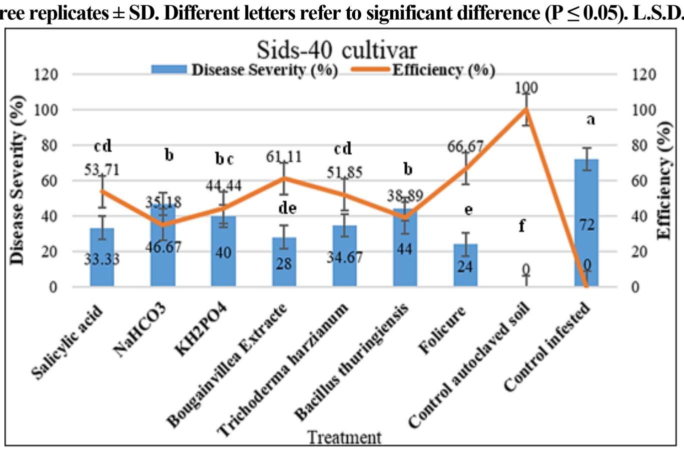

Fig. 5. Effect of different treatments on disease severity and efficiency (%) of garlic Sids-40 cultivar.

Results in Fig. (6) refer to a very strong negative correlation of -1.00 between Disease Severity (%) and Efficiency (%). This is a crucial finding, indicating a direct inverse relationship: as the disease becomes more severe, the treatment's efficiency drops proportionally. Disease Severity (%) increases all other measured variables: Efficiency (%), Plant height (cm), Plant weight (g), Plant weight increase (%), Bulb diam.(cm), and Bulb weight increase (%) tend to decrease. This is indicated by the strong negative correlations in the first column (1.00 with Efficiency (%), r=−0.70 with Plant weight increase (%)). These results are expected, as higher disease severity would negatively impact plant health and productivity. Bulb weight increase (%) has a robust positive correlation with Bulb diam. (cm)' (r=0.94), 'Plant weight increase (%)' (r=0.92), and 'Plant weight (gm)' (r=0.92). This suggests that as the plant's overall weight and size increase, the bulb's weight and diameter also increase proportionally. Plant weight increase (%). This clearly suggests that more effective treatments lead to better overall plant development.

Comparative Analysis of Garlic Cultivars under Greenhouse Conditions

Data in Fig. (7) illustrate a comparative analysis between the two garlic cultivars, Balady and Sids-40, revealed significant differences across all measured parameters under greenhouse conditions. The disease severity was markedly higher in the Balady cultivar (45.93%) compared to the Sids-40 cultivar (41.19%). Despite both cultivars being affected, Sids-40 exhibited a lower percentage, indicating a relatively higher tolerance to the disease.

Regarding plant height, Sids-40 outperformed Balady, reaching an average of 42.37 cm versus 40.26 cm, respectively. The difference was statistically significant, reflecting the better vegetative growth of the Sids-40 cultivar. In terms of plant weight, Sids-40 showed a substantial advantage, recording an average fresh weight of 14.31 g, which was more than double the weight observed in Balady (7.3 g). This suggests enhanced biomass accumulation in Sids-40 under the same growing conditions.

Similarly, the bulb diameter was larger in Sids-40 (2.69 cm) than in Balady (1.80 cm), indicating improved bulb development and a potential increase in marketable yield. These results collectively indicate that the Sids-40 cultivar exhibits superior growth performance and greater resilience to disease compared to the Balady cultivar under controlled greenhouse conditions.

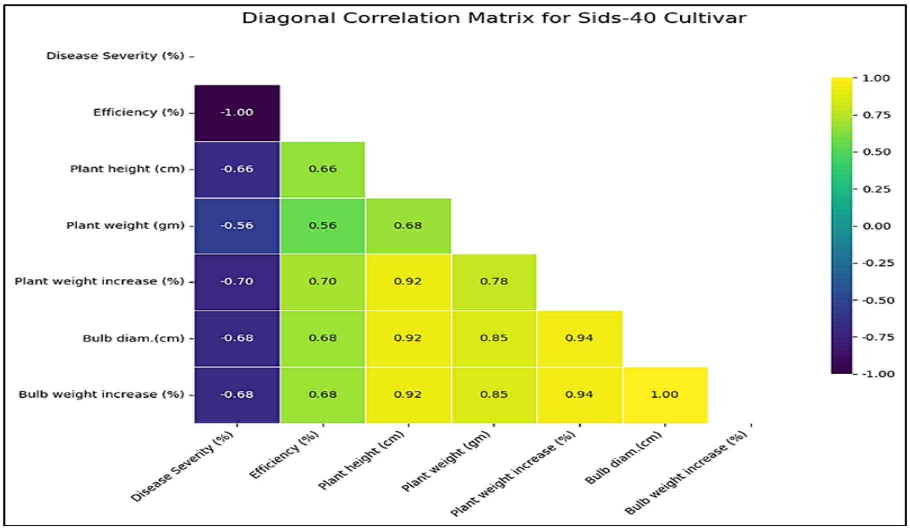

Fig. 6. Diagonal correlation matrix illustrates a scientific analysis of the linear relationships between various variables for Sids-40 Cultivar. The values range from -1 (a perfect negative correlation) to +1 (a perfect positive correlation), with 0 indicating no linear relationship.

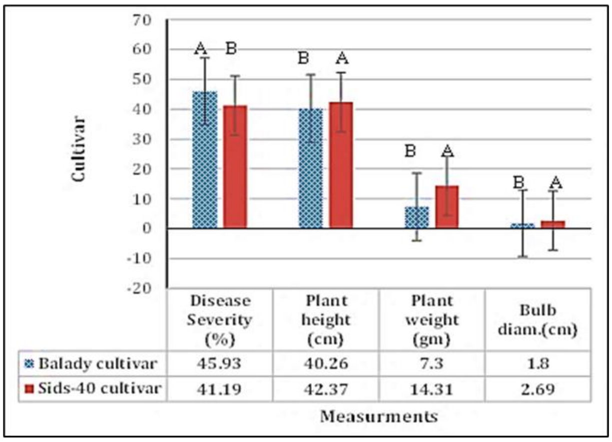

Fig.7. Comparative Evaluation of Balady and Sids-40 Garlic Cultivars in Response to Different Treatments on Disease Severity and Vegetative Growth Parameters under greenhouse conditions.

2. Field Experiment

Field Evaluation of Treatments on Disease Severity and Vegetative Growth of Garlic Sids-40 Cultivar under natural infection

Data in Table (3) show that all tested treatments significantly reduced white rot disease severity and improved yield and growth traits of the Sids-40 garlic cultivar under natural field infection compared with the untreated control. The highest disease severity was recorded in the untreated control (65.2%), which was associated with the lowest yield (3.1 kg/plot), plant height (21.3 cm), and bulb weight (23.3 g). Among the treatments, Folicure provided the greatest reduction in disease severity (19.5%), corresponding to 70.1% efficiency. This was followed by KH_2PO_4 (24.7%; 62.1% efficiency), *T. harzianum* (29.5%; 54.8%), and salicylic acid (31.9%; 51.1%). The least effective treatments were $NaHCO_3$ (42.8%; 34.3%), *B. thuringiensis* (37.1%; 43.1%), and bougainvillea extract (36.6%; 43.8%). With respect to yield, the highest values were recorded with

KH_2PO_4 (11.9 kg/plot; 280.2% increase), followed by salicylic acid and *T. harzianum* (11.1 kg/plot; 253.7–255.6% increase). Bougainvillea extract also improved yield to 9.2 kg/plot (192.9% increase), while $NaHCO_3$ and *B. thuringiensis* resulted in moderate increases (6.3 and 8.2 kg/plot). Folicure, despite being the most effective in reducing disease severity, achieved the lowest yield among the treatments (6.0 kg/plot; 92.7% increase). In terms of plant height, $NaHCO_3$ recorded the tallest plants (50.1 cm; 135.5% increase), followed by KH_2PO_4 and salicylic acid (48.4 cm; 127.4–127.6% increase). B. thuringiensis produced intermediate values (46.1 cm; 116.9%), while Folicure-treated plants were the shortest (38.2 cm; 79.6%).

For bulb weight, the heaviest bulbs were obtained with KH_2PO_4 (100.4 g; 331.5% increase), followed by *T. harzianum* (89.3 g; 283.9%) and salicylic acid (87.1 g; 274.3%). Bougainvillea extract also promoted considerable increases (72.1 g; 209.9%), while $NaHCO_3$ and *B. thuringiensis* recorded moderate effects (58.2 and 63.1 g). The lowest bulb weight among treatments was found with Folicure (45.5 g; 95.4%) (Fig. 8). Overall, Table (3) indicates that KH_2PO_4 and salicylic acid were the most promising treatments under field conditions, as they effectively combined reduced disease severity with substantial improvements in yield and bulb weight, whereas Folicure, although highly effective in disease suppression, showed limited impact on yield and plant growth.

Table 3. Effect of different treatments on white rot disease severity, yield (kg/plot), Plant height (cm), Bulb diameter (cm), and their Increases (%) of Sids-40 garlic cultivar under natural infection in Field conditions.

Treatments	Disease Severity (%)	Efficiency (%)	Yield (kg/plot)	Increases (%)	Plant height (cm)	Increases (%)	Bulb weight (gm)	Increases (%)
Salicylic acid	$31.9^{DC} \pm 2.06$	51.1	$11.1^{A} \pm 0.44$	253.7	$48.4^{B} \pm 0.44$	127.4	$87.1^{B} \pm 4.07$	274.3
$NaHCO_3$	$42.8^{B} \pm 1.64$	34.3	$6.3^{D} \pm 0.20$	101.3	$50.1^{A} \pm 0.77$	135.5	$58.2^{D} \pm 1.28$	150.2
KH_2PO_4	$24.7^{FE} \pm 1.26$	62.1	$11.9^{A} \pm 0.10$	280.2	$48.4^{B} \pm 0.52$	127.6	$100.4^{A} \pm 2.43$	331.5
Bougainvillea Extracte	$36.6^{C} \pm 1.23$	43.8	$9.2^{B} \pm 0.33$	192.9	$48.4^{B} \pm 0.44$	127.7	$72.1^{C} \pm 1.15$	209.9
Trichoderma harzianum	$29.5^{DE} \pm 1.26$	54.8	$11.1^{A} \pm 0.46$	255.6	$47.6^{CB} \pm 0.55$	123.8	$89.3^{B} \pm 2.70$	283.9
Bacillus thuringiensis	$37.1^{C} \pm 2.97$	43.1	$8.2^{C} \pm 0.44$	161.0	$46.1^{CD} \pm 0.18$	116.9	$63.1^{D} \pm 1.53$	171.2
Folicure	$19.5^{F} \pm 1.26$	70.1	$6.0^{D} \pm 0.08$	92.7	$38.2^{E} \pm 0.49$	79.6	$45.5^{E} \pm 2.94$	95.4
Control untreated	$65.2^{A} \pm 2.63$	0.00	$3.1^{E} \pm 0.18$	0.00	$21.3^{F} \pm 0.43$	0.00	$23.3^{F} \pm 0.74$	0.00

Data presented as the means of three replicates ± SD. Different letters refer to significant difference ($P \leq 0.05$). L.S.D. at 0.05%

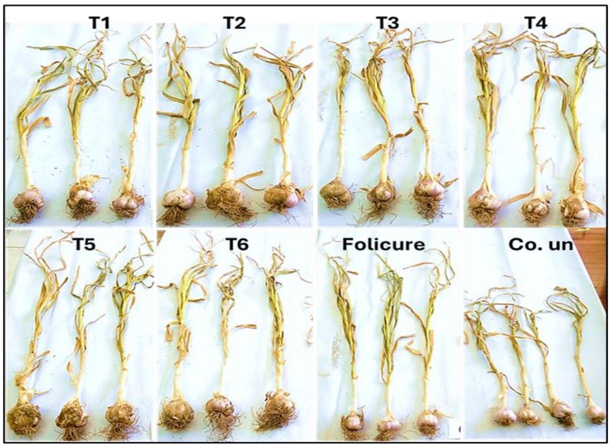

Fig. 8. Effect of different treatments on white rot disease in Field conditions.

The correlation matrix shown in Fig. (9) provides a scientific analysis of the linear relationships between various variables for the 'Balady Cultivar'. The results show a clear and expected pattern: there are strong negative correlations between disease severity and all other plant growth and yield parameters. This confirms the fundamental scientific principle that as disease progression increases, plant health and productivity are negatively impacted. A correlation value close to -1.00 would signify that disease is the primary limiting factor for this cultivar. Conversely, the matrix also reveals strong positive correlations among the growth and yield variables themselves, such as bulb weight and plant height. These findings suggest that these parameters can serve as reliable indicators of overall yield, providing valuable data-driven insights for guiding cultivation practices and breeding programs aimed at improving the 'Balady Cultivar's productivity.

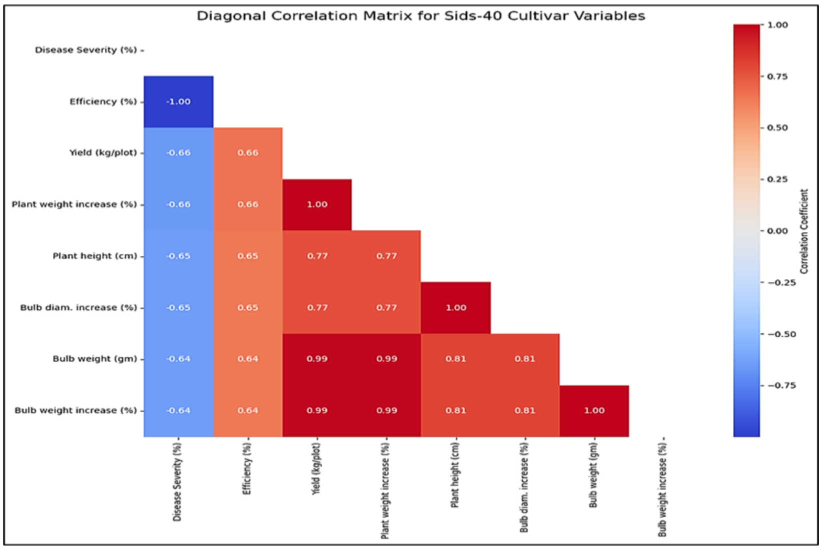

Fig. 9. Diagonal correlation matrix illustrates a scientific analysis of the linear relationships between various variables for Balady Cultivar. The values range from -1 (a perfect negative correlation) to +1 (a perfect positive correlation), with 0 indicating no linear relationship.

Discussion

The isolation and identification of *S. cepivorum* from garlic and onion plants collected across four Egyptian governorates revealed considerable pathogenic variability among the obtained isolates. Such intraspecific variation in virulence is a cocmon feature of soil-borne fungal pathogens and has been extensively documented in previous literature (Haq *et al*., 2003; Mahmoud *et al*., 2021). The findings from the pathogenicity tests on the Balady garlic cultivar clearly demonstrate that the degree of white rot severity caused by *S. cepivorum* is significantly influenced by the genetic and environmental background of the isolate.

In this study, isolate No.1 from Sharqia exhibited the highest disease severity (82.47%), making it the most aggressive among all tested isolates. Similar observations were reported by Borah *et al*. (2024), who noted that *S. cepivorum* populations can possess highly virulent strains capable of causing up to 100% mortality in susceptible Allium crops under conducive conditions. The aggressive behavior of this isolate may be attributed to its higher sclerotia viability and possibly elevated enzymatic activity (especially pectinases and cellulases), which facilitate host tissue penetration (Albert *et al*., 2022).

Isolate No.6 from Giza followed in aggressiveness (78.80%) and again reflects the diversity in virulence even within isolates from a single geographical location. This pattern is supported by Sallam *et al*. (2009), who suggested that differences in aggressiveness are likely associated with local selection pressures, such as cropping history, microclimate, and soil microbiota composition.

Interestingly, isolate No.5 from Qalyubia demonstrated the lowest disease severity (28.60%), indicating weak pathogenic potential. This could be due to several reasons, including genetic drift, lower sclerotia germination rates, or antagonism by native soil microbes (Narváez and Marroquín, 2022). The moderate disease severity levels observed among other isolates (ranging from 42.33% to 66.40%) are consistent with prior studies that found a spectrum of virulence across *S. cepivorum* isolates from different agroecological zones (Mahmoud *et al*., 2021).

Overall, the wide variation in disease severity among isolates underscores the importance of using the most virulent isolate (in this case, isolate No.1 from Sharqia) for further screening of control strategies under greenhouse and field conditions.

The present study revealed that all tested treatments significantly reduced white rot disease severity in both Balady and Sids-40 garlic cultivars compared to the infested control, though the magnitude of suppression varied by treatment and cultivar. This supports prior evidence that integrated approaches involving chemical, botanical, and biological agents can be effective in managing *S .cepivorum* infections under greenhouse conditions (Ndifon, 2024).

Among all treatments, Folicure (tebuconazole) and *Bougainvillea* leaf extract demonstrated the most substantial disease suppression in both cultivars. These findings align with those of Stewart and McLean (2006) and Morsy *et al*. (2021), who reported the efficacy of systemic fungicides like tebuconazole in inhibiting sclerotia germination and mycelial growth of *S. cepivorum*. Similarly, the antifungal properties of plant extracts, including polyphenols and flavonoids, have been documented to interfere with fungal cell wall integrity and spore viability (Singh, 2024).

Salicylic acid (SA) also showed promising results in disease mitigation, particularly in the Sids-40 cultivar. SA is known to be a key phytohormone in systemic acquired resistance (SAR), priming plants to respond more efficiently to pathogen attacks by upregulating pathogenesis-related (PR) proteins and antioxidant enzymes (Elshahid *et al*., 2022). The higher responsiveness observed in Sids-40 may be attributed to its inherent capacity to activate these defense pathways more robustly, indicating possible genetic resistance or higher inducibility, as suggested by Roychowdhury *et al*. (2024).

Biological control using *T. harzianum* also achieved moderate disease suppression. This biocontrol agent has been widely reported to antagonize soil-borne pathogens through mycoparasitism, competition for nutrients and space, and production of antifungal metabolites (Singh *et al*., 2024; Zawawy *et al*., 2025). However, its relative efficacy appeared lower than chemical or botanical treatments, possibly due to environmental constraints or microbial competition in the rhizosphere.

Interestingly, *B. thuringiensis* and sodium bicarbonate ($NaHCO_3$) were less effective, particularly in Balady. While *Bacillus spp.* is known for producing lipopeptides and volatile compounds that inhibit fungal growth (Saikia, 2023), Similarly, $NaHCO_3$ exerts antifungal activity primarily by altering pH and ionic balance, but its effects are typically transient and dose-sensitive (Imhacmed and Alhdad, 2022; Elenany *et al*., 2024).

The differential responses between cultivars are noteworthy. Sids-40 consistently exhibited lower disease severity and higher treatment responsiveness across all tested agents. This suggests cultivar-specific variation in susceptibility or defense mechanisms, which have been previously reported in *Allium* crops (Gurjar, 2022).

The current findings revealed that all tested treatments significantly enhanced plant height in both Allium sativum cultivars (Balady and Sids-40) compared to the infected control. These results suggest that the applied agents not only suppressed disease symptoms but also promoted vegetative growth. Similar conclusions were drawn by Mohy *et al*. (2024), who observed improved plant vigor and height following the application of biocontrol and organic compounds in garlic fields infested with *S. cepivorum*.

In the Balady cultivar, the untreated healthy control naturally exhibited the highest plant height (47.00 cm), reflecting optimal growth conditions. Interestingly, *Bougainvillea* extract, KH_2PO_4, and *T. harzianum* were among the most effective treatments, increasing plant height by 83.75–90.51% over the infected control. The role of *T. harzianum* in enhancing plant growth has been well documented, as it improves nutrient availability and induces systemic resistance (Sun *et al*., 2025). KH_2PO_4, as a source of phosphorus and potassium, is vital for cell elongation and energy transfer, which explains its efficacy in promoting shoot growth under stress conditions (Geng *et al*., 2025).

Bougainvillea extract also showed promising results, likely due to its phenolic content and potential antifungal properties (Abo-Zaid *et al*., 2025). Meanwhile, salicylic acid and sodium bicarbonate provided moderate enhancement in plant height. These compounds are known to activate plant defense responses and stabilize physiological processes under biotic stress (Zulfi *et al*., 2024).

In the Sids-40 cultivar, the response was even more pronounced. Treatments with KH_2PO_4 and Folicur resulted in the highest recorded plant height (47.00 cm, 104.35% increase), followed closely by *Bougainvillea* extract and *B. thuringiensis*. The remarkable effect of *B. thuringiensis* may be attributed to its ability to produce plant growth-promoting substances and indirectly inhibit fungal pathogens through antibiosis and competition (Bakr *et al*., 2025). Folicur, a systemic fungicide, likely contributed by reducing disease pressure and facilitating normal physiological growth.

The consistency of salicylic acid and sodium bicarbonate in both cultivars indicates their broad-spectrum efficacy. This aligns with the findings of Nawarathna and Eeswara (2025), who reported that such treatments could enhance growth and resistance in garlic under stress conditions.

The data presented clearly indicate that all applied treatments significantly enhanced garlic plant weight in both Balady and Sids-40 cultivars under greenhouse conditions, compared to the untreated infested control. This improvement can be attributed to the ability of these treatments to either suppress pathogen activity or promote plant growth through various physiological or biochemical mechanisms.

Among the biological treatments, *B. thuringiensis* showed a notable effect in the Balady cultivar, achieving the highest plant weight (8.63 g, 128.91%). This may be related to its known role in inducing systemic resistance and producing metabolites with antifungal activity (Du and Li, 2024). In Sids-40, however, the most effective treatment was Bougainvillea extract, which achieved the highest plant weight (17.50 g, 110.08%). This result suggests that the extract may contain bioactive compounds capable of enhancing plant growth and suppressing soil-borne pathogens such as *Rhizoctonia solani*, in agreement with the findings of Abo-Zaid (2020) and Zulfi *et al*. (2024), who reported that plant-based extracts improve plant health under biotic stress.

The application of KH_2PO_4 was also highly effective in both cultivars, especially in Sids-40 (16.50 g, 98.08%). Phosphorus and potassium are critical nutrients for root development and energy transfer, and foliar application of KH_2PO_4 has been shown to enhance nutrient uptake and disease tolerance (Geng *et al*., 2025 and Sun *et al*., 2025). Moreover, *T. harzianum*, a well-known biocontrol agent, resulted in high plant weights in both cultivars, consistent with its documented roles in mycoparasitism, competition, and production of growth-promoting hormones (Zawawy *et al*., 2025).

The effect of salicylic acid was also evident, especially in the Balady cultivar, where it significantly increased plant weight by 128.12%. Salicylic acid is known to activate plant defense responses and modulate physiological processes related to growth (Elshahid *et al*., 2022). Similarly, $NaHCO_3$ contributed to increased plant weight, possibly by modifying soil pH and inhibiting pathogen development (Lyousfi *et al*., 2022).

Interestingly, the chemical fungicide Folicure resulted in the lowest plant weight among the treatments in both cultivars, although it still significantly outperformed the infected control. This could reflect the suppressive action of the fungicide on the pathogen but a lack of direct growth-promoting effects, which are characteristic of biological and organic treatments (Amin and Ahmed, 2023). Furthermore, the autoclaved soil control yielded moderate plant weights in both cultivars, likely due to the reduction in pathogen inoculum but also the absence of beneficial microbial activity.

The data obtained clearly demonstrate that the application of various treatments significantly enhanced the bulb diameter of garlic in both Balady and Sids-40 cultivars under greenhouse conditions. This increase in bulb girth suggests a positive physiological response to the applied compounds, especially in mitigating the effects of white rot disease caused by *S. cepivorum*.

In the Balady cultivar, the application of salicylic acid (SA) led to the highest increase in bulb diameter (2.03 cm; +84.55%). Salicylic acid is well-documented for its role in inducing systemic acquired resistance (SAR) and promoting vegetative and reproductive growth in several crops under biotic stress (Elshahid *et al*., 2022 and Roychowdhury *et al*., 2024). Its capacity to activate defense-related pathways, reduce oxidative damage, and enhance photosynthetic efficiency might explain the significant increase observed in bulb diameter.

Likewise, *B. thuringiensis* (2.00 cm) and *T. harzianum* (1.93 cm) also showed notable improvements. Both are renowned biological control agents (BCAs) with dual functions: antagonistic activity against soil-borne pathogens and plant growth promotion (Saikia 2023; Singh *et al*., 2024; Zawawy *et al*., 2025). The mechanisms underlying this improvement may involve production of phytohormones (e.g., auxins), siderophores, and lytic enzymes, which indirectly contribute to enhanced nutrient uptake and cell expansion in developing bulbs.

Bougainvillea extract produced a similar increase to *T. harzianum*, which is likely attributed to its phytochemical profile, rich in phenolics and flavonoids (Abo-Zaid, 2020 and Zulfi, *et al*., 2024). Such compounds can play antioxidant and antimicrobial roles, thus alleviate stress and allow plants to allocate more resources to storage organ development.

In contrast, Folicur (tebuconazole) resulted in the lowest bulb diameter increase among the treatments (1.73 cm; 57.27%). Though effective as a fungicide, Folicur lacks plant growth-promoting traits and may suppress beneficial rhizosphere microbes, thus reducing indirect growth stimulation (Amin and Ahmed, 2023).

In the Sids-40 cultivar, salicylic acid again exhibited superior performance, recording the largest bulb diameter (2.87 cm; +125.98%). This cultivar-specific response suggests Sids-40 may be more responsive to SA-mediated signaling pathways under disease pressure. Supporting literature also confirms that SA application can significantly improve garlic bulb development and productivity under stress (Elshahid *et al*., 2022 and Roychowdhury *et al*., 2024).

Furthermore, KH_2PO_4 and *T. harzianum* (2.80 cm; 120.47%) also showed high efficiency in Sids-40. The role of KH_2PO_4 (a source of phosphorus and potassium) in improving bulb diameter may be linked to its involvement in root development, energy transfer (ATP), and cell expansion processes, Adequate phosphorus levels have been associated with increased assimilate transport to sink organs, such as bulbs in garlic (Geng *et al*., 2025; Sun *et al*., 2025).

Interestingly, both cultivars responded positively to the *Bougainvillea* extract, suggesting that the bioactive compounds present could be a promising organic alternative for enhancing bulb quality, though further biochemical analyses are necessary. The infested control in both cultivars exhibited the lowest bulb diameter values, affirming the deleterious effect of *S. cepivorum* infection, which disrupts water and nutrient uptake due to root decay. The untreated healthy control in Sids-40 surprisingly yielded intermediate values (2.70 cm), implying that even in the absence of disease, certain treatments can still boost productivity via enhanced nutrient use efficiency or hormonal modulation.

A comparative evaluation between two garlic cultivars, Balady and Sids-40, under greenhouse conditions, demonstrated significant genotypic differences in disease resistance and growth performance. Sids-40 exhibited lower disease severity (41.19%) than Balady (45.93%), indicating higher tolerance to *S. cepivorum*, consistent with findings by Raslan *et al*. (2015); Mohamed and Hassan (2023) and Mohy *et al*. (2024).

In addition to reduced disease symptoms, Sids-40 recorded superior plant height (42.37 cm), fresh weight, and bulb diameter (2.69 cm), compared to Balady. These enhancements are likely associated with better hormonal regulation, improved root vigor, and increased physiological resilience, as described by Raslan *et al*. (2015). The Sids-40 cultivar demonstrated greater stability in bulb weight per plant under drought and stress conditions compared to the Balady cultivar, which exhibited higher variability in bulb weight performance across different environmental conditions (Badran, 2015).

Furthermore, the enhanced bulb development aligns with prior work on carbohydrate translocation and delayed senescence facilitated by treatments such as salicylic acid and KH_2PO_4 (Hongsong *et al*., 2025). Overall, these results highlight Sids-40 as a superior cultivar under biotic stress, offering greater yield potential and disease resilience when integrated with appropriate agronomic interventions (Badran, 2015).

Under natural field infection conditions, the significant reduction in white rot severity across all tested treatments demonstrates their potential efficacy in managing *S. cepivorum* infections in the garlic cultivar Sids-40. The fungicide Folicure (tebuconazole) achieved the highest suppression of disease severity (19.50%) and exhibited an efficiency of 70.09%, consistent with its known mode of action as a triazole compound that inhibits sterol biosynthesis essential for fungal cell membrane integrity (Prathyusha *et al*., 2022). Such systemic fungicides have been widely reported to offer reliable protection against various soil-borne pathogens, particularly under high disease pressure.

Among the non-chemical alternatives, KH_2PO_4 (potassium dihydrogen phosphate) showed notable antifungal activity, reducing disease severity to 24.70%, corresponding to 62.12% efficiency. This outcome may be attributed to its dual role in enhancing plant nutrition and inducing systemic acquired resistance (SAR), through the activation of defense-related pathways involving peroxidases, phenylalanine acmonia lyase, and polyphenol oxidase, phosphate salts are also reported to disrupt pathogen colonization by modifying the ionic environment of the rhizosphere (Hamza *et al*., 2017).

T. harzianum exhibited strong biocontrol potential with 54.75% efficiency, reducing disease severity to 29.50%. Its effectiveness is well-established and attributed to several mechanisms, including direct mycoparasitism, secretion of hydrolytic enzymes (e.g., chitinases, glucanases), and competition for nutrients and space (Hugar and Nayaka, 2025). Furthermore, *T. harzianum* enhances host plant resistance by priming defense genes and improving root development, thus offering both protective and growth-promoting benefits.

Moderate control levels were observed for *B. thuringiensis* and sodium bicarbonate ($NaHCO_3$), with efficiencies of 43.10% and 34.31%, respectively. Although *B. thuringiensis* is primarily recognized for its insecticidal activity, several strains produce antifungal metabolites such as iturins and fengycins that exhibit activity against soil pathogens (Singh *et al*., 2024; Zawawy *et al*., 2025). $NaHCO_3$, meanwhile, alters pH levels in the soil, creating unfavorable conditions for fungal development and sclerotia germination (Lyousfi *et al*., 2022).

Salicylic acid, a known plant defense elicitor, achieved a 51.07% efficiency, which is in line with its reported role in activating systemic acquired resistance through the upregulation of PR proteins and antioxidant enzymes (Elshahid *et al*., 2022). However, its efficacy may depend on dosage, application timing, and plant physiological status. Bougainvillea extract showed a modest reduction in disease severity (36.63%), potentially due to the presence of secondary metabolites like flavonoids and alkaloids. Nevertheless, variability in concentration and bioavailability in soil might limit its consistent effectiveness (Zulfi *et al*., 2024).

In sucmary, although chemical fungicides such as Folicure remain the most effective under severe disease conditions, several eco-friendly alternatives—particularly KH_2PO_4 and *T. harzianum*—offer promising biocontrol efficacy. Integrating these treatments into a broader integrated disease management strategy could reduce reliance on synthetic chemicals, enhance soil health, and support long-term crop sustainability in pathogen-infested soils (Geng *et al*. 2025; Sun *et al*., 2025).

The significant variations in garlic yield among the evaluated treatments reflect the differential efficacy of each approach in mitigating the detrimental effects of *S. cepivorum*, the causal agent of white rot disease. The substantial yield increase observed in treatments such as KH_2PO_4, *T. harzianum*, and salicylic acid underscores their potential in enhancing plant health and productivity under natural disease pressure. The highest yield (11.90 kg/plot) was achieved with potassium dihydrogen phosphate (KH_2PO_4), corresponding to a 280.19% increase compared to the untreated control. This marked improvement is likely attributed to the dual role of KH_2PO_4 as a source of readily available phosphorus and potassium—both essential for root development, energy transfer, and stress tolerance (Hamza *et al*., 2017). Moreover, phosphate-based compounds are known to induce systemic resistance in plants, enhancing their ability to withstand biotic stressors such as soil-borne fungi (Chaluvaraju *et al*., 2004).

The biofungal agent *T. harzianum also* demonstrated remarkable efficacy (11.13 kg/plot; 255.59% increase), which aligns with its well-documented antagonistic behavior against soil pathogens *via* mechanisms such as mycoparasitism, enzyme secretion, and competition for space and nutrients (Hugar and Nayaka, 2025). Additionally, *Trichoderma* spp.

have been shown to stimulate plant growth directly, through the production of phytohormones and enhancement of nutrient uptake (Zin and Badaluddin, 2020).

The application of salicylic acid yielded comparably high results (11.07 kg/plot; 253.67%), which reinforces its role as a key signaling molecule in the activation of systemic acquired resistance (SAR). This defense pathway not only confers resistance against a wide range of pathogens but also leads to enhanced physiological responses, including increased photosynthetic efficiency and assimilating partitioning to storage organs like bulbs (Singh *et al*., 2023).

Moderate but noteworthy increases in yield were also observed with Bougainvillea extract (9.17 kg/plot; 192.97%) and *B. thuringiensis* (8.17 kg/plot; 161.02%). The use of plant extracts such as *Bougainvillea* has gained attention due to their richness in phenolic compounds, flavonoids, and natural antifungal agents, which may contribute to disease suppression and improved plant resilience (Nayak *et al*., 2024). Meanwhile, *B. thuringiensis*, traditionally known for its insecticidal activity, also contributes to plant health through production of antimicrobial peptides and elicitation of plant defense responses (Bakr *et al*., 2025).

In contrast, sodium bicarbonate ($NaHCO_3$) and the chemical fungicide Folicure showed the least efficacy among the tested treatments, achieving yield increases of 101.28% and 92.65%, respectively. While $NaHCO_3$ may provide temporary pathogen suppression by altering the pH of the soil microenvironment, its effects are typically short-lived and may not support long-term suppression of sclerotia in heavily infested soils (Lyousfi *et al*., 2022).

The lowest yield (3.13 kg/plot) in the infested untreated control clearly illustrates the devastating impact of white rot disease in the absence of intervention. This further supports the importance of deploying integrated disease management strategies that combine nutritional support, biocontrol, and plant defense elicitation to maintain productivity in garlic cropping systems.

The results obtained under field conditions naturally infested with *S. cepivorum* demonstrate that several treatments significantly enhanced both plant height and bulb weight of garlic cultivar Sids-40. These findings suggest the efficacy of certain organic, biological, and chemical strategies in mitigating the adverse effects of white rot disease and enhancing plant vigor.

The most striking outcome was associated with KH_2PO_4, which achieved the highest bulb weight (100.40 g), with a corresponding increase of 331.46%. This outcome underscores the importance of potassium and phosphorus in enhancing bulb development and strengthening plant tolerance to pathogen stress. Foliar application of KH_2PO_4 has been reported to improve metabolic processes, photosynthesis, and nutrient allocation, leading to better growth and yield (Hamza *et al*., 2017).

T. harzianum also exhibited excellent performance, supporting its well-established biocontrol potential. Its ability to suppress soil-borne pathogens through mechanisms such as mycoparasitism, competition for nutrients, and secretion of antifungal compounds likely contributed to the enhanced bulb weight and plant height (Hugar and Nayaka, 2025). Similarly, the notable results obtained with salicylic acid can be attributed to its role in inducing systemic acquired resistance (SAR) and modulating physiological processes involved in growth and defense (Singh *et al*., 2023).

Although $NaHCO_3$ led to the tallest plants, its impact on bulb weight was comparatively moderate. This suggests that while bicarbonate may suppress pathogen development and improve plant stature, it may not sufficiently support biomass accumulation in the bulbs. Such findings align with reports indicating that bicarbonates are more effective as surface protectants than systemic enhancers (Lyousfi *et al*., 2022).

The performance of *Bougainvillea* extracts in increasing both plant height and bulb weight reflects the potential of botanical extracts as eco-friendly alternatives for disease management. The presence of phenolic and flavonoid compounds may enhance antioxidant activity and suppress fungal pathogens, thereby indirectly boosting growth (Nayak *et al*., 2024).

Based on the cumulative results of this study, it is recocmended to adopt an integrated disease management approach for the Sids-40 garlic cultivar under field conditions naturally infested with *S. cepivorum*. The integration of bio-organic amendments (e.g., vermicompost), plant growth-promoting microorganisms (such as *T. harzianum*, *P. fluorescens*, and *Bacillus spp.*), and natural resistance inducers (e.g., salicylic acid and KH_2PO_4) has demonstrated consistent effectiveness in enhancing plant growth, increasing bulb yield, and suppressing white rot disease. These environmentally sustainable practices represent a promising alternative to sole reliance on chemical fungicides in garlic cultivation.

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مقارنة فعالية الأساليب العضوية والبيولوجية والكيميائية في إدارة تعفن الأبيض في الثوم(*Allium sativum* L.)

كريمة جابر حلمي [1] ، نورا طه [2] و آية حسام الدين أبو زيد [1]*

[1] قسم أمراض النبات ، كلية الزراعة ، جامعة عين شمس ، مصر
[2] قسم بساتين ، كلية الزراعة ، جامعة عين شمس ، مصر

الملخص

مرض العفن الأبيض، الناتج عن *Sclerotium cepivorum* ، يؤثر بشكل كبير على إنتاج الثوم في مصر. أُجريَت هذه الدراسة لتقييم ٢٧ عزلة فطرية من مختلف المحافظات المصرية، وكشفت عن تباين في القدرة المسببة للأمراض حيث تراوحت شدة المرض من ٢٨,٦٠٪ (في القليوبية) إلى ٨٢,٤٧٪ (في الشرقية). أظهرت اختبارات الدفيئة أن جميع المعالجات قللت من شدة المرض. في صنف بلدي، كان لمستخلص الجهنمية و Folicureأدنى شدة (٣٦,٠٠٪، و٥٩,٠٩٪ كفاعلية)، في حين أن *Bacillus thuringiensis* وحمض الساليسيليك عززا بشكل كبير وزن النبات (٨,٦–٨,٦٣ غرام؛ زيادة تفوق ١٢٨٪) وقطر البصلة (حتى ٢,٠٣ سم؛ زيادة قدرها ٨٤,٥٥٪). في صنفـSids-40 ، كان Folicure (٢٤,٠٠٪، و٦٦,٦٧٪ كفاعلية) ومستخلص الجهنمية (٢٨,٠٠٪، و٦١,١١٪) الأكثر فعالية، بينما حسّن KH_2PO_4 وزن النبات (١٦,٥–١٧,٥ غرام؛ زيادة حوالي ٩٨-١١٠٪) وقطر البصلة (حتى ٢,٨٧ سم؛ زيادة قدرها ١٢٥,٩٨٪). ومن الجدير بالذكر أن صنف بلدي أظهر شدة مرض أعلى (٤٥,٩٣٪) مقارنة مع(41.19%) Sids-40 ، حيث أظهر Sids-40 نموًا متفوقًا، بما في ذلك ارتفاع أكبر (٤٢,٣٧ مقابل ٤٠,٢٦ سم)، ووزن طازج (١٤,٣١ مقابل ٧,٣ غرام)، وقطر البصلة (٢,٦٩ مقابل ١,٨٠ سم). أكدت التجارب الميدانية هذه النتائج؛ فقد كانت ضوابط المعالجة غير المعالجة تعاني من شدة مرض بلغت ٦٥,٢٪ وإنتاجية ٣,١ كجم/قطعة. قلل Folicure من الشدة (١٩,٥٪، و٧٠,١٪ كفاعلية)، بينما أدت KH_2PO_4 وحمض الساليسيليك إلى زيادات كبيرة في الإنتاجية (١١,٩ و١١,١ كجم/قطعة؛ حتى ٢٨٠,٢–٢٥٣,٧٪ زيادة). بشكل عام، كانت KH_2PO_4 وحمض الساليسيليك والعوامل البيولوجية المختارة فعالة في كبح التعفن الأبيض وتعزيز نمو الثوم، مما يشير إلى بديل مستدام لمبيدات الفطريات الكيميائية.