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Integrating *Brassica* spp. Residues and Bioethanol to Mitigate Disease and Enhance Potato Seed Yield in Medium-Altitude Regions

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ABSTRACT

This study evaluated the effectiveness of *Brassica spp*. residues in suppressing potato disease symptoms and investigated bioethanol as a CO_2 supplementation strategy for potato cultivation in medium-altitude areas. From June to September 2024, this study was conducted at approximately 500 masl in Bantaeng Regency, South Sulawesi, Indonesia. This study used a split-plot design, with bioethanol concentration as the main plot (0% (control), 15%, and 30%) and Brassica waste type as the subplot (treatments included cabbage, green mustard, Chinese cabbage, and radish residues). Analysis of variance (ANOVA) was applied, followed by Tukey's test ($p < 0.05$). The results showed that Chinese cabbage roots had the highest total glucosinolate content, at 144.16 ± 3.14 µmol g^{-1} dry weight, whereas cabbage roots had the lowest content, at 13.60 ± 1.57 µmol g^{-1} dry weight. At 60 days after planting (DAP), 30 % bioethanol reduced the intensity of leaf roll/leaf curl, leaf spot, and leaf blight symptoms compared with the control. In addition, 30 % bioethanol increased internal CO_2 concentration and photosynthetic rate, and increased plant height at 75 DAP from 69.91 to 79.91 cm, tuber number from 8.30 to 9.10 tubers per plant, and tuber weight from 302.63 to 318.88 g per plant, while reducing transpiration rate. The interaction between bioethanol concentration and Brassica residue type was not significant. These findings indicate that 30 % bioethanol and *Brassica spp*. Residues can reduce disease symptoms and improve potato growth and yield under medium-altitude conditions.

Keywords: *Brassica* spp., bioethanol, medium-altitude areas, potato seeds, photosynthesis

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INTRODUCTION

Potato seed production is generally carried out in highland areas with low temperatures, approximately 17-20 °C (Aklilu et al., 2024; Philiphos & Tafesse, 2024), at elevations above 1,000 m above sea level (masl) (Mamilianti et al., 2019; Molina et al., 2022). However, potato development in highland areas faces various constraints, including soil erosion, limited land availability, and high production costs (Ademe et al., 2024). These conditions have encouraged the expansion of potato seed production into medium-altitude areas at approximately ±500 masl, where larger areas of potentially suitable land remain available.

Although promising, potato cultivation in medium-altitude areas faces serious agronomic constraints. Relatively high temperatures, ranging from approximately 29 to 37 °C, can increase leaf photorespiration, reduce photosynthetic efficiency, and ultimately inhibit tuber initiation and bulking (Bernacchi et al., 2023; Opoku et al., 2024). In addition, environmental conditions in medium-altitude areas may increase disease intensity, thereby reducing potato seed productivity and quality (Diploid, 2019; Lal et al., 2022; Upadhaya, 2018). Therefore, cultivation technologies are needed that can not only suppress potato disease symptoms but also support plant physiological efficiency under high-temperature conditions.

One potential approach is using *Brassica* spp. plant residues as natural biofumigants. *Brassica* residues, such as cabbage, mustard, and other *Brassica* species, contain bioactive compounds, particularly glucosinolates, which can be hydrolysed into compounds that are toxic to several soil-borne pathogens (Eugui et al., 2023; Santos et al., 2021). Several studies have reported that *Brassica* spp. residues and their bioactive compounds have the potential to suppress soil-borne pathogens and plant diseases, including nematodes and diseases affecting potato (Charkowski et al., 2020; Iraboneye et al., 2021; Pacifico et al., 2021; Sagar et al., 2018). Therefore, *Brassica* spp. residues represent a promising alternative for environmentally friendly disease management, reducing dependence on synthetic chemical inputs.

Improving photosynthetic efficiency is also important for potato cultivation in medium-altitude areas. High temperatures can accelerate CO_2 loss from leaf mesophyll tissues by increasing photorespiration. It reduces the photosynthetic rate and ultimately decreases crop yield (Rykaczewska, 2015). Therefore, bioethanol may serve as a supportive treatment because it can be metabolised in plant tissues to CO_2 and H_2O. It has potential in increasing internal CO_2 availability (Costa et al., 2018). Increased CO_2 in the leaf intercellular spaces may enhance Rubisco-mediated carboxylation, improving photosynthetic rate and reducing the negative effects of photorespiration (McGiffen Jr. & Manthey, 1996).

Previous studies reported *Brassica* spp. residues as biofumigants for pathogen management, while other studies have evaluated improvements of photosynthetic efficiency under high-temperature stress using physiological approaches. Based on the available

literature, studies integrating *Brassica* spp. residues as biofumigants with bioethanol and CO_2 supplementation remain limited. This strategy within a single potato cultivation system in medium-altitude areas remains very limited. This research gap is important since potato seed production in medium-altitude areas faces two major constraints: disease and heat-induced photosynthetic disruption. Therefore, this study evaluates an integrated strategy that combines *Brassica* spp. residues and bioethanol to suppress disease symptoms, support plant physiological processes, and improve the growth and yield of potato seed under medium-altitude conditions.

MATERIALS AND METHODS

Experimental Design and Treatments

This study was conducted from June to September 2024 at the experimental field of the Horticultural Seed Center, Ulu Ere District, Bantaeng Regency, South Sulawesi, Indonesia. The land is at approximately 500 masl, with an average temperature ranging from 29 °C to 37 °C and relative humidity between 80 % and 90 % (Maulidiyah et al., 2024; Rusli et al., 2021). Glucosinolate content was analysed at the Agricultural Biotechnology Laboratory, Universitas Bosowa.

The experiment used a split-plot design with two factors. The main plot consisted of bioethanol at different concentrations: no bioethanol as the control (0%) (B0), 15% bioethanol (B1), and 30% bioethanol (B2). The subplot factor consisted of four types of *Brassica* residue: cabbage residue (*Brassica oleracea*) (C), green mustard residue (*Brassica juncea* Coss.) (G), Chinese cabbage residue (*Brassica chinensis*) (H), and radish residue (*Raphanus sativus*) (R).

There were 12 treatment combinations. Each treatment combination was replicated three times, making 36 experimental units. Each experimental unit had nine plants, giving a total of 324 plants used in this study. From each experimental unit, three sample plants were randomly selected for the observations.

Implementation Stage

Planting Material and Growing Medium

The planting material used in this study consisted of certified potato seed tubers of the Granola variety. They were of the same variety, weighed about 50-60 g, were healthy, free from visible symptoms of pest and disease infestation, mechanically undamaged, and relatively uniform in size.

The plants were moved to the pots containing 5 kg of sterilised soil. The soil used in this study was collected from the topsoil layer of agricultural land surrounding the experimental site. It was sterilised to reduce initial pathogen contamination and standardise growing

medium conditions. Each pot was planted with one potato seed tuber. The plants received standard maintenance: watering, weeding, and limited pest and disease management as needed. The pest management was carried out manually, without pesticides. All maintenance practices were applied uniformly to ensure that differences in plant responses were primarily attributable to the *Brassica* residue and bioethanol treatments.

Preparation of Brassica *spp. Residues and Biofumigation*

Residues of cabbage (*Brassica oleracea*), green mustard (*B. juncea* Coss.), Chinese cabbage (*B. chinensis*) and radish (*Raphanus sativus*) were obtained from post-harvest residues collected in Gowa, Jeneponto, and Enrekang, South Sulawesi Province, Indonesia. The plant parts used for the biofumigation treatment were a mixture of roots and stems, as they are abundantly available as post-harvest residues. They may also contain bioactive compounds, particularly glucosinolates, as natural biofumigants. In this study, roots and stems were not treated as separate experimental factors but were used together as residue materials, depending on *Brassica* species.

The *Brassica* residues were rinsed, then chopped into pieces approximately 1 cm in length. A total of 150 g of fresh residue was incorporated into each pot containing 5 kg of sterilised soil, thoroughly mixed, and watered to a moist consistency. The pots were then tightly covered for two weeks to support organic matter decomposition and the release of bioactive compounds through biofumigation. After biofumigation, the pots were uncovered and left for 3-5 days before planting the potato seed tubers to reduce the possibility of phytotoxic effects on the seedlings.

Analysis of Glucosinolate Content

Glucosinolate analysis was performed on *Brassica* spp. residue tissue samples to determine total glucosinolate content. The analysed samples included cabbage roots, cabbage stems, green mustard roots, green mustard stems, Chinese cabbage roots, Chinese cabbage stems, and radish roots. The plant samples were cleaned to remove adhering soil, cut into 2 × 2 × 1 cm pieces, placed in polyethylene bags, and stored at -20 °C. The samples were then freeze-dried and ground into a fine powder.

Glucosinolate extraction was carried out according to the method of Tian et al. (2005) with modifications. A total of 0.20 g of powdered sample was placed into an extraction tube, followed by the addition of 5 mL of 80 % methanol (v/v) as the extraction solvent. The sample was homogenised for 5 min, then incubated at 70°C for 15 min to inactivate myrosinase and facilitate glucosinolate extraction. The sample was subsequently centrifuged at 4,000 rpm for 10 min, and the supernatant was collected as the extract for glucosinolate analysis. When necessary, the extract was diluted with 80 % methanol at a 1:10 (v/v) ratio prior to measurement.

Glucosinolate detection was performed using a photometry-based method according to Fenwick et al. (1983). The absorbance of the extract was measured at 405 nm. Total glucosinolate concentration was calculated using the following formula: $x = (A_{405} - 0.13) \times 272$, where A_{405} represents the absorbance value at 405 nm and x indicates the total glucosinolate concentration expressed in μmol g^{-1}. In this study, the analysis was limited to determining total glucosinolate content and did not include identifying specific glucosinolate compounds.

Bioethanol Application

Water hyacinth was used as the bioethanol source, applied at 0%, 15%, and 30% treatment levels. The 0 % treatment served as the control (no bioethanol addition), while the 15 % and 30 % treatments were applied at the same volume to ensure uniform application. All treatments were applied simultaneously in the morning to minimise the influence of daily environmental variation. Two weeks after planting (WAP), bioethanol application was conducted and repeated every two weeks until the plants reached 10 WAP. Bioethanol was applied at 10 mL per plant/pot via foliar application. Foliar application provided direct contact with the leaf surface and enhanced CO_2 availability around photosynthetic tissues.

Assessment of Disease Symptoms

Disease observations were conducted based on visible symptoms, including leaf roll/leaf curl symptoms, yellowing, wilting, leaf spot symptoms, leaf blight symptoms, and other visible damage to the plant canopy. This assessment was not intended to identify causal pathogens, but to quantify disease symptom intensity or the level of visual plant damage.

Disease symptom intensity was assessed using a scale based on the percentage of leaves showing visible symptoms or damage (Equation 1):

$$I = \frac{\Sigma(\mathrm{ni} \times \mathrm{vi})}{\mathrm{Z} \times \mathrm{N}} \times 100\% \qquad [1]$$

Explanation: (I) represents disease intensity (%), (ni) is the number of plants assigned to the i-th score category, (Vi) is the symptom score value, (N) is the total number of observed plants, and (Z) is the highest score value. Table 1 presents the symptom scoring scale used in this study.

Physiological, Growth, and Yield Observations

Physiological observations were performed at 30, 45, and 60 days after planting (DAP) using a CID-320 Portable Photosynthesis System. Physiological parameters included

Table 1
Disease symptom scoring scale for potato plants

Score	Category	Description
0	No attack	No signs of disease or damage on the plant.
1	1 - ≤ 25 % leaves yellowing/wilting	Leaves affected cover 1 to 25 % of the total leaves of the plant.
2	> 25 - ≤ 50 % leaves yellowing/wilting	Leaves affected cover more than 25 % to 50 % of the total leaves of the plant.
3	> 50 - ≤ 75 % leaves yellowing/wilting	Leaves affected cover more than 50 % to 75 % of the total leaves of the plant.
4	> 75 - 100 % leaves yellowing/wilting	Leaves affected cover more than 75 % to 100 % of the total leaves of the plant.

internal CO_2 concentration (ppm), photosynthetic rate (μmol m^{-2} s^{-1}), and transpiration rate (mmol m^{-2} s^{-1}).

Yield parameters were observed at harvest, approximately 90 days after planting (DAP). The yield parameters included the number and weight of tubers per plant. The number of tubers was determined by counting all tubers formed on each plant, whereas tuber weight per plant was obtained by weighing all tubers harvested from each plant using a digital balance and was expressed in grams per plant.

Data Analysis

Data were analysed using analysis of variance (ANOVA) in a split-plot design to determine the effects of bioethanol concentration, *Brassica* residue type, and their interaction on disease symptom intensity, physiological parameters, growth, and potato yield. Data analysis was performed using IBM SPSS Statistics version 26. When ANOVA indicated a significant effect, mean comparisons were conducted using Tukey's test at the 5 % significance level ($p < 0.05$).

RESULTS

Total Glucosinolate Content in *Brassica* spp. Samples

The total glucosinolate content in *Brassica* spp. extracts was measured photometrically at 405 nm and subsequently calculated from the resulting absorbance values. The results showed that total glucosinolate content varied considerably among *Brassica* spp. tissues, ranging from 13.60 to 144.16 μmol g^{-1} (Table 2).

Based on the statistical analysis, the total glucosinolate content differed significantly among *Brassica* spp. tissue types. Chinese cabbage root (*Brassica chinensis*) exhibited the highest total glucosinolate content, at 144.16 ± 3.14 μmol g^{-1}, whereas cabbage root (*Brassica oleracea*) showed the lowest content, at 13.60 ± 1.57 μmol g^{-1}.

Table 2
Total glucosinolate content in root and stem tissues of selected Brassica spp. residues

No.	Type of Extract	Absorbance Value at 405 nm	Glucosinolate Concentration (µmol g-1)
1.	Root of Cabbage (Brassica oleracea)	0.18 ± 0.01	13.60 ± 1.57d
2.	Stem of Cabbage (Brassica oleracea)	0.41 ± 0.01	76.16 ± 1.57c
3.	Root of Mustard Greens (Brassica juncea Coss)	0.39 ± 0.01	70.72 ± 1.57c
4.	Green mustard Stem (Brassica juncea Coss)	0.48 ± 0.01	95.20 ± 1.57b
5.	Root of Chinese Cabbage (Brassica chinensis)	0.66 ± 0.01	144.16 ± 3.14a
6.	Stem of Chinese Cabbage (Brassica chinensis)	0.49 ± 0.01	97.92 ± 3.14b
7.	Root of Radish (Raphanus sativus)	0.40 ± 0.01	73.44 ± 1.57c

Note. Values are presented as mean ± standard error (SE), n = 3. Values followed by different letters within the same column indicate significant differences according to Tukey's test at $p < 0.05$

The total glucosinolate content in Chinese cabbage root was approximately 10.6-fold higher than that in cabbage root.

Disease Symptom Intensity

The ANOVA results showed that bioethanol and plant residue treatments had significant effects on disease symptom intensity, particularly at 60 days after planting (DAP), whereas the Bioethanol × Plant Residue interaction was not significant ($p > 0.05$; Table 3). For the bioethanol treatment, the application of 30 % bioethanol (B2) resulted in the lowest transformed disease symptom intensity values at 60 DAP, namely 0.491 for leaf roll/leaf curl symptoms, 0.567 for leaf spot symptoms, and 0.544 for leaf blight symptoms. These values were lower than those observed in the control treatment (B0), which were 0.544, 0.682, and 0.845, respectively. Based on the transformed values, these reductions were equivalent to 9.74 %, 16.86 %, and 35.62 %, respectively, compared with the control.

Plant residue treatment also had a significant effect on disease symptom intensity at 60 DAP. Chinese cabbage residue (H) produced the lowest transformed disease symptom intensity values, namely 0.690 for leaf roll/leaf curl symptoms, 0.505 for leaf spot symptoms, and 0.552 for leaf blight symptoms. These values were lower than those observed in several other plant residue treatments.

Physiological Activity

Internal CO_2 Concentration

The ANOVA results showed that bioethanol concentration significantly affected the internal CO_2 concentration of potato leaves at 30, 45, and 60 days after planting (DAP), whereas plant residue treatment and the Bioethanol × Plant Residue interaction did not.

Table 3
Intensity of leaf roll, leaf spot, and leaf blight symptoms in potato plants at 30, 45, and 60 days after planting (DAP) as affected by bioethanol and plant residue treatments[1]

Treatment	Leaf Roll/Leaf Curl Symptoms5			Leaf Spot Symptoms5			Leaf Blight Symptoms5		
	30 DAP4	45 DAP	60 DAP	30 DAP	45 DAP	60 DAP	30 DAP	45 DAP	60 DAP
Bioethanol:									
B0 2	0.301 a	0.301 a	0.544 a	0.301 a	0.301 a	0.682 a	0.301 a	0.477 a	0.845 a
B1	0.301 a	0.301 a	0.505 a	0.301 a	0.301 a	0.606 ab	0.301 a	0.505 a	0.690 ab
B2	0.301 a	0.301 a	0.491 b	0.301 a	0.301 a	0.567 b	0.301 a	0.505 a	0.544 b
Plant Residue:									
C[3]	0.301 a	0.301 a	0.753 a	0.301 a	0.301 a	0.748 a	0.301 a	0.301 a	0.653 a
H	0.301 a	0.301 a	0.690 b	0.301 a	0.301 a	0.505 b	0.301 a	0.301 a	0.552 b
G	0.301 a	0.301 a	0.740 a	0.301 a	0.301 a	0.753 a	0.301 a	0.301 a	0.758 ab
R	0.301 a	0.301 a	0.727 a	0.301 a	0.301 a	0.752 a	0.301 a	0.301 a	0.674 a

Note.
[1]Data has been transformed using the logarithmic transformation log(x),
[2]B0 = 0 % Bioetanol, B1= 15 % Bioetanol, B2 = 30 % Bioetanol,
[3]C = Cabbage Residue, H = Chinese cabbage Residue, G = Green Mustard Residue, R= Radish Residue,
[4]DAP = Days After Planting,
[5]Numbers in the same column followed by different letters indicate significant differences based on Tukey's post hoc test at $\alpha = 0.05$
[6]Values followed by different letters within the same column indicate significant differences according to Tukey's test at $p < 0.05$. The Bioethanol × Plant Residue interaction was not significant based on ANOVA; therefore, only the main effects are presented. Roots and stems were not included as treatment factors in the analysis of disease symptom intensity, but were analysed separately to support the characterization of total glucosinolate content

Tukey's test showed that 30 % bioethanol (E2) resulted in a higher internal CO_2 concentration than the control (E0), although it was not significantly different from 15 % bioethanol (E1) at some observation times (Figure 1A). Numerically, *Chinese cabbage* residue showed a relatively higher mean internal CO_2 concentration than several other plant residues; however, these differences were not statistically significant (Figure 1B).

Photosynthetic Rate

The ANOVA results showed that bioethanol concentration had a significant effect on the photosynthetic rate of potato plants, whereas plant residue treatment and the Bioethanol × Plant Residue interaction did not show significant effects. Based on Tukey's test, the 30 % bioethanol treatment (B2) resulted in a higher photosynthetic rate than the control (B0), although at some observation times its value was not significantly different from that of the 15 % bioethanol treatment (B1) (Figure 2A).

Plant residue treatment had no significant effect on the photosynthetic rate (Figure 2B). Numerically, Chinese cabbage residue showed a relatively higher mean photosynthetic

rate than several other residue treatments; however, these differences were not statistically significant.

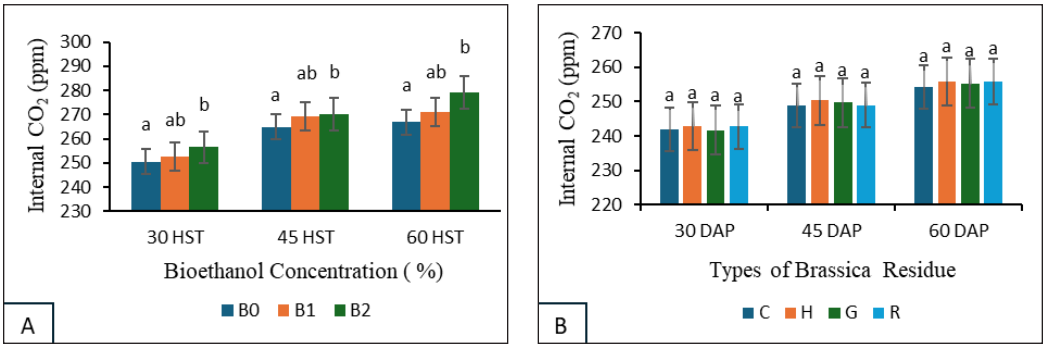

Figure 1. Internal CO_2 concentration (ppm) in potato leaves under different bioethanol concentrations (A) and plant residue treatments (B) at 30, 45, and 60 Days After Planting (DAP); B0 = 0 %, B1 = 15 %, B2 = 30 %; C = *Brassica oleracea*, H = *Brassica chinensis*, G = *Brassica juncea* Coss, R = *Raphanus sativus*

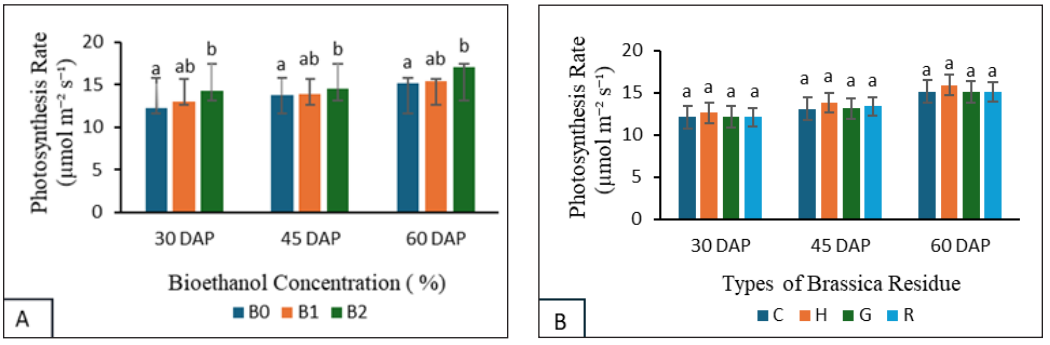

Figure 2. Photosynthesis rate (µmol m^{-2} s^{-1}) in potato plants under bioethanol treatments (A) and plant residue treatments (B) at 30, 45, and 60 Days After Planting (DAP); B0=0 %, B1 = 15 %, B2 = 30 %; C = *Brassica oleracea*, H = *Brassica chinensis*, G = *Brassica juncea* Coss, R = *Raphanus sativus*

Transpiration Rate

The ANOVA results showed that bioethanol concentration had a significant effect on the transpiration rate of potato plants, whereas plant residue treatment and the Bioethanol × Plant Residue interaction did not show significant effects. At 30, 45, and 60 DAP, the application of 30 % bioethanol (B2) resulted in a lower transpiration rate than the control without bioethanol (B0) (Figure 3A).

Plant residue treatment had no significant effect on the transpiration rate of potato plants at any observation time (Figure 3B). Numerically, Chinese cabbage residue showed a relatively lower mean transpiration rate than several other residue treatments; however, the differences among residues were not statistically significant.

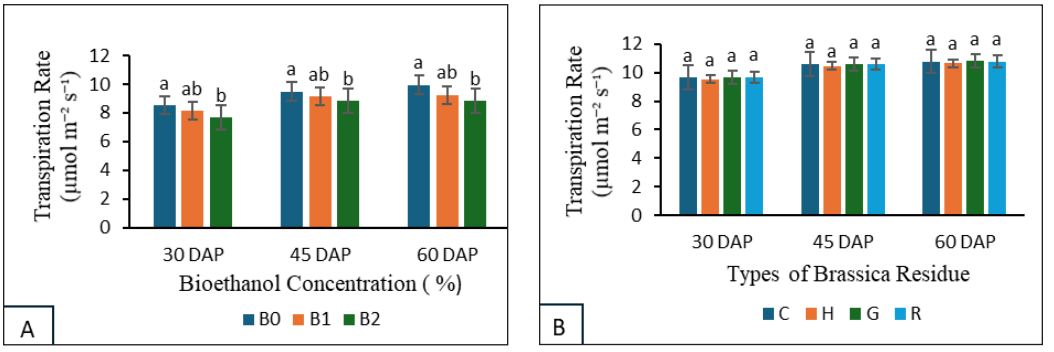

Figure 3. Transpiration rate of potato plants (mmol m^{-2} s^{-1}) at various bioethanol concentrations (A) and plant residue (B) at 30, 45, and 60 Days After Planting (DAP); B0=0 %, B1 = 15 %, B2 = 30 %; C = *Brassica oleracea*, H = *Brassica chinensis*, G = *Brassica juncea* Coss, R = *Raphanus sativus*

Growth and Production Aspects

Plant Height

ANOVA showed that bioethanol concentration and plant residue type significantly affected potato plant height, whereas the interaction between the two factors was not significant. Since the interaction was not significant, the data presented represent the main effects of each factor.

The 30 % bioethanol treatment (B2) resulted in greater plant height than the control treatment without bioethanol (B0), particularly at 45 and 60 days after planting (DAP) (Figure 4A). Plant height also differed among plant residue treatments. Numerically, Chinese cabbage residue showed the highest plant height compared with the other residue treatments (Figure 4B).

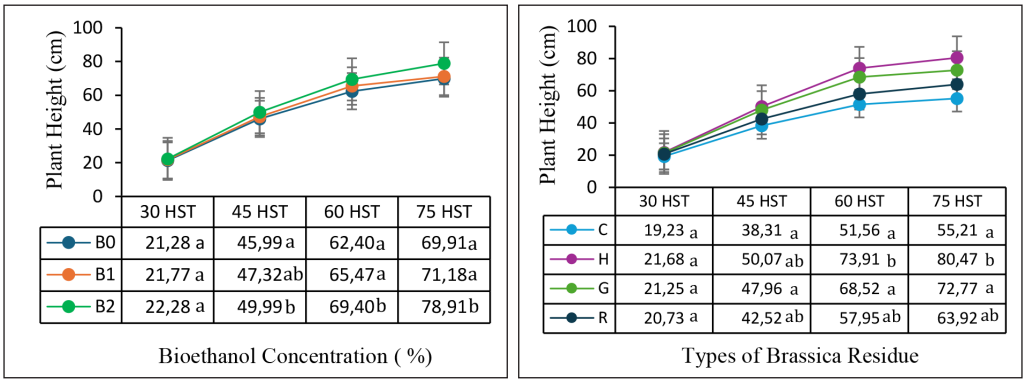

Figure 4. Effect of bioethanol concentration (A) and plant residue (B) on potato plant height (cm) at 30, 45, 60, and 75 Days After Planting (DAP); B0 = 0 %, B1 = 15 %, B2 = 30 %; C = *Brassica oleracea*, H = *Brassica chinensis*, G = *Brassica juncea* Coss, R = *Raphanus sativus*

Number of Tubers and Tuber Weight

The ANOVA results showed that bioethanol concentration and type of plant residue had significant effects on the number of tubers and tuber weight per plant, whereas the interaction between the two factors was not significant. Since the interaction was not significant, the data presented represent the main effects of each factor.

For the number of tubers, the 30 % bioethanol treatment (B2) produced a higher number of tubers per plant than the control (B0) and the 15 % bioethanol treatment (B1) (Figure 5A). Plant residue treatment also showed significant differences in the number of tubers per plant. Chinese cabbage and green mustard residues produced a higher number of tubers than cabbage and radish residues, with both treatments having the same statistical notation (Figure 5B).

For tuber weight, the 30 % bioethanol treatment (B2) also produced greater tuber weight per plant than the control (B0) and 15 % bioethanol (B1) treatments (Figure 6A). Meanwhile, based on plant residue type, Chinese cabbage and green mustard residues produced higher tuber weight per plant than cabbage and radish residues, with both

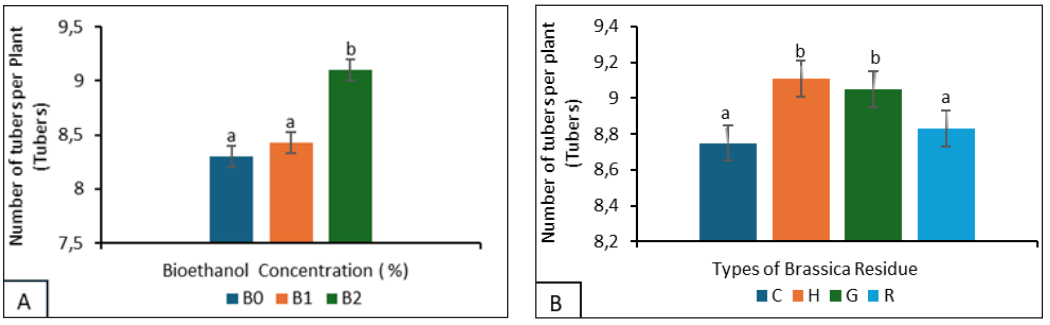

Figure 5. Effect of bioethanol concentration (A) and plant residue (B) on the number of potato tubers per plant (tubers) at the end of the study; B0 = 0 %, B1 = 15 %, B2 = 30 %; C = *Brassica oleracea*, H = *Brassica chinensis*, G = *Brassica juncea* Coss, R = *Raphanus sativus*

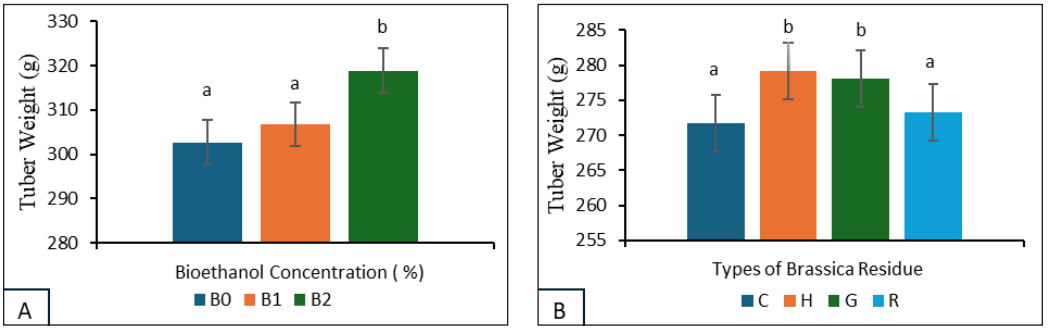

Figure 6. Effect of bioethanol concentration (A) and plant residue (B) on tuber weight per potato plant (g) at the end of the study; B0=0 %, B1=15 %, B2=30 %; C= *Brassica oleracea*, H= *Brassica chinensis*, G= *Brassica juncea* Coss, R= *Raphanus sativus*

treatments belonging to the same statistical notation group (Figure 6B). This pattern indicates that treatments producing a higher number of tubers also tended to produce greater tuber weight per plant.

DISCUSSIONS

Total Glucosinolate Content in *Brassica* spp. Samples

Differences in total glucosinolate content among plant species and tissues indicate that the biofumigation potential of *Brassica* spp. residues varies depending on the type of plant material used (Table 2). Chinese cabbage roots (*Brassica chinensis*), which had the highest total glucosinolate content, may contribute more substantially as a source of bioactive compounds in the biofumigation process. Conversely, the low total glucosinolate content in cabbage roots (*Brassica oleracea*) suggests that the effectiveness of residues as biofumigant materials may be influenced by plant species and tissue type.

Differences in total glucosinolate content are important because glucosinolates can be hydrolysed into various bioactive compounds, particularly isothiocyanates, which play a role in suppressing soil-borne pathogens. Therefore, *Brassica* spp. residues with higher total glucosinolate content may have greater biofumigation potential. However, because this study measured only total glucosinolate content and did not identify specific glucosinolate types, the results should be interpreted only in terms of biofumigation potential based on total glucosinolate content.

These results are consistent with Rhee et al. (2020), who stated that glucosinolate content can vary across plant species and tissue types. Dutta et al. (2019) also emphasised the relevance of glucosinolate profiles in distinguishing plant characteristics and their potential role in pathogen control. In addition, Ammar et al. (2023) and Ciska et al. (2021) reported that plant tissue type and processing methods can affect glucosinolate levels. Therefore, the selection of *Brassica* spp. residue type is an important aspect of developing biofumigation technology to support the management of disease symptoms in potato cultivation under medium-altitude conditions.

Disease Symptom Intensity

The reduction in disease symptom intensity under the 30 % bioethanol treatment indicates that bioethanol has the potential to suppress disease symptoms in potato plants. This response may be associated with improved plant physiological conditions following bioethanol application, enabling the plants to better withstand biotic stress. In addition, bioethanol or ethanol-based materials have also been reported to exhibit potential antimicrobial activity against certain microorganisms (Maulana et al., 2023; Pal & Srivastava, 2019; Suleiman et al., 2019). However, because this study did not directly test the antimicrobial activity of bioethanol, this explanation should be regarded as a possible mechanism.

For the plant residue treatment, the lower disease symptom intensity observed with Chinese cabbage residue was likely associated with its relatively high total glucosinolate content (Table 3). Glucosinolates in *Brassica* tissues can be hydrolysed into bioactive compounds. One of them is isothiocyanates, which are involved in biofumigation mechanisms and may suppress soil-borne pathogens. Since the Bioethanol and Plant Residue interaction was not significant, interpret the effects of these two factors as independent main effects rather than synergistic effects. In addition, because disease assessment was based only on visual symptoms, these results are more appropriately interpreted as reduced disease symptom severity rather than suppression of a specific pathogen.

Physiological Activity

Internal CO_2 Concentration

The increase in internal CO_2 concentration under bioethanol treatment was presumably associated with bioethanol's ability to enhance CO_2 availability around photosynthetic tissues, particularly at 30 % (Figure 1). This condition may improve the physiological environment of leaves, thereby supporting photosynthesis, especially in potato cultivation at medium altitudes where temperatures are relatively high. In C3 plants such as potato, improved internal CO_2 availability can support carboxylation by Rubisco and help reduce the negative effects of photorespiration (Muhibuddin et al., 2022; Taiz et al., 2018; Todaka et al., 2024).

In contrast, plant residue treatment had no significant effect on internal CO_2 concentration. This indicates that variation in internal CO_2 concentration was more closely associated with bioethanol concentration than with plant residue type. Therefore, the role of *Brassica* spp. residues in this study is more appropriately related to their biofumigation potential and the reduction of disease symptoms, rather than as a major factor affecting internal CO_2 concentration in leaves.

Photosynthetic Rate

The increase in photosynthetic rate under bioethanol treatment, particularly at the 30 % concentration, was more closely associated with bioethanol concentration than with the type of plant residue, because only the bioethanol factor had a significant effect on this parameter (Figure 2). This response was likely related to the increase in internal CO_2 concentration in the leaves, thereby improving CO_2 availability for photosynthesis. In C3 plants such as potato, increased internal CO_2 can support Rubisco carboxylation and improve photosynthetic efficiency, especially at medium altitudes where relatively high temperatures may enhance photorespiration (Muhibuddin et al., 2022).

In addition to supporting internal CO_2 availability, bioethanol was also presumed to improve leaf physiological conditions through stomatal regulation and enhanced

photosynthetic enzyme activity. This is consistent with Rahman et al. (2022) and Zhang et al. (2024), who reported that bioethanol application may be associated with stomatal regulation and increased photosynthetic enzyme activity. In contrast, plant residue treatment had no significant effect on photosynthetic rate; therefore, the role of *Brassica* spp. residues in this study is more appropriately associated with their potential to reduce disease symptoms through biofumigation mechanisms, rather than as a major factor affecting photosynthetic rate.

Transpiration Rate

The reduction in transpiration rate under the 30 % bioethanol treatment was likely associated with an increase in leaf internal CO_2 concentration. Increased internal CO_2 can contribute to partial stomatal closure, thereby reducing water loss through transpiration. This response indicates that bioethanol application has the potential to improve plant water-use efficiency, particularly in potato cultivation at medium altitudes, where plants are often exposed to relatively high temperatures. Thus, variation in transpiration rate in this study was more closely associated with bioethanol concentration than with plant residue type, as only bioethanol showed a significant effect on this parameter.

Transpiration is primarily regulated by stomatal conductance and plays an important role in nutrient transport, leaf cooling, and gas exchange (Abbas et al., 2021; Da Graça et al., 2010). The lower transpiration rate under bioethanol treatment may indicate that the plants were able to reduce water loss without fully inhibiting major physiological processes, particularly because photosynthetic rate still increased under the same treatment. This condition suggests a better balance among CO_2 uptake, photosynthesis, and water conservation.

Meanwhile, plant residue treatment had no significant effect on the transpiration rate (Figure 3). Therefore, the role of *Brassica* spp. residues in this study cannot be directly associated with stomatal regulation or reduced transpiration. Although Chinese cabbage residue showed a numerically lower transpiration value, this should be interpreted as a tendency that warrants further investigation rather than a significant effect.

Growth and Production Aspects

Plant Height

The increase in plant height under the 30 % bioethanol treatment was likely associated with increased internal leaf CO_2 availability, which may support CO_2 assimilation, enhance photosynthetic activity, and promote vegetative growth (Figure 4). Better CO_2 availability can increase carbon fixation and assimilate formation, thereby supporting plant growth, particularly under medium-altitude conditions characterised by relatively high temperatures

that may limit photosynthetic efficiency (Abbas et al., 2021; Lehretz et al., 2019; Rahman et al., 2022).

The tendency of Chinese cabbage residue to produce taller plants may be indirectly related to its relatively higher total glucosinolate content. Glucosinolates in Brassica residues can suppress disease symptoms through a biofumigation mechanism, thereby improving plant health and enabling vegetative growth to proceed more optimally. Thus, the relationship between total glucosinolate content and plant height should be interpreted as an indirect effect via improved plant health, rather than a direct effect on growth.

Number of Tubers and Tuber Weight

The increase in tuber number and tuber weight per plant under the 30 % bioethanol treatment was likely associated with increased internal leaf CO_2 availability. Improved CO_2 availability can support photosynthesis, increase assimilate production, and enhance carbon allocation to storage organs (Figure 5), including tubers (Rahman et al., 2022). In potato plants, assimilates produced through photosynthesis are subsequently translocated to the tubers to support tuber initiation, bulking, and dry matter accumulation (Chen & Setter, 2021; Darwesh et al., 2020; Naumann et al., 2020). In addition, increased CO_2 availability may suppress photorespiration, allowing more assimilates to be allocated to biomass formation and tuber yield (Saeed et al., 2022) (Figure 6).

This response is relevant to potato cultivation in medium-altitude areas, where relatively high temperatures can interfere with tuber formation and bulking. Therefore, bioethanol application has the potential to serve as an adaptive cultivation approach to support potato productivity under such environmental conditions, although its physiological mechanisms remain to be further investigated (Fang et al., 2024; Vijayakumar et al., 2024).

The higher tuber weight observed under Chinese cabbage and green mustard residue treatments was likely due to the role of Brassica residues in improving the growing environment, supporting root development, and suppressing disease symptoms through biofumigation (Abbas et al., 2021; Pacifico et al., 2021). However, because the interaction between bioethanol concentration and plant residue type had no significant effect, the effects of these two factors on tuber number and tuber weight should be interpreted as independent main effects rather than as a synergistic response.

This study was conducted under medium-altitude conditions and within a limited experimental scope. Therefore, further validation across different locations, seasons, soil conditions, and potato cultivars is still required. Future studies should also clarify the mechanisms linking bioethanol application, total glucosinolate content, disease symptom reduction, and tuber development.

The limitations of this study, relate to methodological and mechanistic aspects. Methodologically, the pot experiment using sterilised soil may not fully represent open-

field agroecosystem conditions, which are influenced by soil microbial dynamics, the presence of natural pathogens, moisture variation, and root-soil interactions. In addition, disease assessment based solely on visual symptoms, without identification of the causal pathogens, limits interpretation of the mechanisms underlying symptom reduction. The use of roots and stems as mixed residues, without separating them as treatment factors, also limits the understanding of the contribution of each plant tissue to disease suppression and improved plant growth.

CONCLUSION

The results showed that total glucosinolate content varied among Brassica spp. species and plant tissues, with the highest content observed in Chinese cabbage roots at 144.16 µmol g^{-1}, followed by Chinese cabbage stems at 97.92 µmol g^{-1} and green mustard stems at 95.20 µmol g^{-1}. These differences indicate that the potential of Brassica residues as a source of bioactive compounds for biofumigation is influenced by the plant species and tissue used. The application of 30 % bioethanol resulted in lower disease symptom intensity than the control and 15 % bioethanol treatments, particularly for leaf roll/leaf curl, leaf spot, and leaf blight symptoms at the final observation. The 30 % bioethanol treatment also produced better physiological responses, as indicated by increased internal CO_2 concentration and photosynthetic rate, along with reduced transpiration rate. In addition, 30 % bioethanol, as well as Chinese cabbage and green mustard residues, showed better responses in several growth and yield parameters, particularly plant height, number of tubers, and tuber weight per plant. No interaction was observed between bioethanol concentration and plant residue type for all observed parameters; therefore, the effects of these two factors are more appropriately interpreted as independent main effects. Because disease assessment was still based on visual symptoms, these results should be interpreted as a reduction in disease symptom intensity rather than suppression of specific pathogens.

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REFERENCES

Abbas, S., Amna, Javed, M. T., Ali, Q., Azeem, M., & Ali, S. (2021). Nutrient deficiency stress and relation with plant growth and development. In S. Fahad, O. Sönmez, S. Saud, D. Wang, C. Wu, M. Adnan, M. Arif, & Amanullah (Eds.), *Engineering tolerance in crop plants against abiotic stress* (1st ed., pp. 239-262). CRC Press. https://doi.org/10.1201/9781003160717-12

Ademe, D., Tesfaye, K., Simane, B., Zaitchik, B. F., Alemayehu, G., & Adgo, E. (2024). Optimizing agronomic practices to harness climate change impacts on potato production in tropical highland regions. *European Journal of Agronomy*, *152*, Article 127021. https://doi.org/10.1016/j.eja.2023.127021

Aklilu, Z., Berihun, T., Zena, S., & Alemu, A. (2024). Production efficiency of potato in south gondar zone, ethiopia. *Cogent Food & Agriculture*, *10*(1), Article 2378988. https://doi.org/10.1080/23311932.2024.2378988

Ammar, H. B., Arena, D., Treccarichi, S., Di Bella, M. C., Marghali, S., Ficcadenti, N., Lo Scalzo, R., & Branca, F. (2023). The effect of water stress on the glucosinolate content and profile: A comparative study on roots and leaves of *Brassica oleracea* L. Crops. *Agronomy*, *13*(2), Article 579. https://doi.org/10.3390/agronomy13020579

Bernacchi, C. J., Ruiz-Vera, U. M., Siebers, M. H., DeLucia, N. J., & Ort, D. R. (2023). Short- and long-term warming events on photosynthetic physiology, growth, and yields of field grown crops. *Biochemical Journal*, *480*(13), 999-1014. https://doi.org/10.1042/BCJ20220433

Charkowski, A., Sharma, K., Parker, M. L., Secor, G. A., & Elphinstone, J. (2020). Bacterial diseases of potato. In H. Campos & O. Ortiz (Eds.), *The potato crop* (pp. 351-388). Springer International Publishing. https://doi.org/10.1007/978-3-030-28683-5_10

Chen, C.-T., & Setter, T. L. (2021). Role of tuber developmental processes in response of potato to high temperature and elevated CO_2. *Plants*, *10*(5), Article 871. https://doi.org/10.3390/plants10050871

Ciska, E., Honke, J., & Drabińska, N. (2021). Changes in glucosinolates and their breakdown products during the fermentation of cabbage and prolonged storage of sauerkraut: Focus on sauerkraut juice. *Food Chemistry*, *365*, Article 130498. https://doi.org/10.1016/j.foodchem.2021.130498

Costa, D., Jesus, J., Virgínio E Silva, J., & Silveira, M. (2018). Life cycle assessment of bioethanol production from sweet potato (*Ipomoea batatas* L.) in an experimental plant. *BioEnergy Research*, *11*(3), 715-725. https://doi.org/10.1007/s12155-018-9932-1

Da Graça, J. P., Rodrigues, F. A., Farias, J. R. B., De Oliveira, M. C. N., Hoffmann-Campo, C. B., & Zingaretti, S. M. (2010). Physiological parameters in sugarcane cultivars submitted to water deficit. *Brazilian Journal of Plant Physiology*, *22*(3), 189-197. https://doi.org/10.1590/S1677-04202010000300006

Darwesh, O. M., El-Maraghy, S. H., Abdel-Rahman, H. M., & Zaghloul, R. A. (2020). Improvement of paper wastes conversion to bioethanol using novel cellulose degrading fungal isolate. *Fuel*, *262*, Article 116518. https://doi.org/10.1016/j.fuel.2019.116518

Diploid, D. S. C. (2019). Annual report of the potato association of America. *American Journal of Potato Research*, *96*(4), 317-378. https://doi.org/10.1007/s12230-019-09723-w

Dutta, T. K., Khan, M. R., & Phani, V. (2019). Plant-parasitic nematode management via biofumigation using brassica and non-Brassica plants: Current status and future prospects. *Current Plant Biology*, *17*, 17-32. https://doi.org/10.1016/j.cpb.2019.02.001

Eugui, D., Velasco, P., Abril-Urías, P., Escobar, C., Gómez-Torres, Ó., Caballero, S., & Poveda, J. (2023). Glucosinolate-extracts from residues of conventional and organic cultivated broccoli leaves (*Brassica oleracea* var. Italica) as potential industrially-scalable efficient biopesticides against fungi, oomycetes and plant parasitic nematodes. *Industrial Crops and Products*, *200*, Article 116841. https://doi.org/10.1016/j.indcrop.2023.116841

Fang, G., Yang, S., Ruan, B., Ye, G., He, M., Su, W., Zhou, Y., Wang, J., & Yang, S. (2024). Research progress on physiological, biochemical, and molecular mechanisms of potato in response to drought and high temperature. *Horticulturae*, *10*(8), Article 827. https://doi.org/10.3390/horticulturae10080827

Fenwick, G. R., Heaney, R. K., Mullin, W. J., & VanEtten, C. H. (1983). Glucosinolates and their breakdown products in food and food plants. *C R C Critical Reviews in Food Science and Nutrition*, *18*(2), 123-201. https://doi.org/10.1080/10408398209527361

Iraboneye, N., Charimbu, M. K., & Mungai, N. W. (2021). Effect of canola and compound fertilizer on potato (*Solanum tuberosum* L.) bacterial wilt management. *European Journal of Agriculture and Food Sciences*, *3*(1), 28-38. https://doi.org/10.24018/ejfood.2021.3.1.130

Lal, M., Kumar, A., Chaudhary, S., Singh, R. K., Sharma, S., & Kumar, M. (2022). Antagonistic and growth enhancement activities of native *Pseudomonas* spp. Against soil and tuber-borne diseases of potato (*Solanum tuberosum* L.). *Egyptian Journal of Biological Pest Control*, *32*(1), Article 22. https://doi.org/10.1186/s41938-022-00522-w

Lehretz, G. G., Sonnewald, S., Hornyik, C., Corral, J. M., & Sonnewald, U. (2019). Post-transcriptional regulation of flowering locus T modulates heat-dependent source-sink development in potato. *Current Biology*, *29*(10), 1614-1624.e1613. https://doi.org/10.1016/j.cub.2019.04.027

Mamilianti, W., Hanani, N., Mustadjab, M. M., & Asmara, R. (2019). Risk preference of farmers and production input allocation of potato farming in Tengger Highland, Indonesia. *EurAsian Journal of BioSciences*, *13*(2), 1777-1783.

Maulana, Z., Muhibuddin, A., Fitriyah, A. T., Rachmawaty, Saleh, H., & Karim, A. (2023). Methanol application and soil water content: Increased production and cultivation of soybean plants. *Nongye Jixie Xuebao/ Transactions of the Chinese Society of Agricultural Machinery*, *54*(10), 38-49.

Maulidiyah, R., Salam, M., Jamil, M. H., Tenriawaru, A. N., Rahmadanih, & Saadah. (2024). Examining the effects of input allocation on potato production, production efficiency, and technical inefficiency in potato farming: Evidence from the stochastic frontier model in search of sustainable farming practices. *Sustainable Futures*, *7*, Article 100218. https://doi.org/10.1016/j.sftr.2024.100218

McGiffen Jr., M. E., & Manthey, J. A. (1996). The role of methanol in promoting plant growth: A current evaluation. *HortScience*, *31*(7), 1092-1096. https://doi.org/10.21273/HORTSCI.31.7.1092

Molina, C. A., Dudenhoefer, D., Polar, V., Scurrah, M., Ccanto, R. C., & Heider, B. (2022). Gender roles and native potato diversity management in highland communities of Peru. *Sustainability*, *14*(6), Article 3455. https://doi.org/10.3390/su14063455

Muhibuddin, A., Maulana, Z., Salam, S., Syamsia, S., Reta, R., & Fattah, A. (2022). The effect of ethanol on potato growth and production at moderate elevation. *Research in Agricultural Engineering*, *68*(3), 113-119. https://doi.org/10.17221/45/2021-RAE

Naumann, M., Koch, M., Thiel, H., Gransee, A., & Pawelzik, E. (2020). The importance of nutrient management for potato production part II: Plant nutrition and tuber quality. *Potato Research*, *63*(1), 121-137. https://doi.org/10.1007/s11540-019-09430-3

Opoku, E., Sahu, P. P., Findurová, H., Holub, P., Urban, O., & Klem, K. (2024). Differential physiological and production responses of C3 and C4 crops to climate factor interactions. *Frontiers in Plant Science*, *15*, Article 1345462. https://doi.org/10.3389/fpls.2024.1345462

Pacifico, D., Lanzanova, C., Pagnotta, E., Bassolino, L., Mastrangelo, A. M., Marone, D., Matteo, R., Lo Scalzo, R., & Balconi, C. (2021). Sustainable use of bioactive compounds from solanum Tuberosum and Brassicaceae wastes and by-products for crop protection—A review. *Molecules*, *26*(8), Article 2174. https://doi.org/10.3390/molecules26082174

Pal, M., & Srivastava, J. (2019). Antifungal activity of the ethyl acetate extract of *Cyperus rotundus* rhizome against certain fungi responsible for food spoilage and plant diseases. *International Journal of Food Science and Nutrition*, *4*(3), 88-89.

Philiphos, F., & Tafesse, A. (2024). Analyzing the efficiency of potato production in Southern Ethiopia: A stochastic frontier analysis approach. *SN Business & Economics*, *5*(1), Article 10. https://doi.org/10.1007/s43546-024-00771-x

Rahman, M. M., Mostofa, M. G., Das, A. K., Anik, T. R., Keya, S. S., Ahsan, S. M., Khan, M. A. R., Ahmed, M., Rahman, M. A., Hossain, M. M., & Tran, L.-S. P. (2022). Ethanol positively modulates photosynthetic traits, antioxidant defense and osmoprotectant levels to enhance drought acclimatization in soybean. *Antioxidants*, *11*(3), Article 516. https://doi.org/10.3390/antiox11030516

Rhee, J.-H., Choi, S., Lee, J.-E., Hur, O.-S., Ro, N.-Y., Hwang, A.-J., Ko, H.-C., Chung, Y.-J., Noh, J.-J., & Assefa, A. D. (2020). Glucosinolate content in Brassica genetic resources and their distribution pattern within and between inner, middle, and outer leaves. *Plants*, *9*(11), Article 1421. https://doi.org/10.3390/plants9111421

Rusli, M., Chaerul, M., & Marzuki, I. (2021). Adaptation of climate change to vulnerability of raw water availability in Bantaeng, South Sulawesi. *Journal of Physics: Conference Series*, *1899*(1), Article 012062. https://doi.org/10.1088/1742-6596/1899/1/012062

Rykaczewska, K. (2015). The effect of high temperature occurring in subsequent stages of plant development on potato yield and tuber physiological defects. *American Journal of Potato Research*, *92*(3), 339-349. https://doi.org/10.1007/s12230-015-9436-x

Saeed, S., Samer, M., Mohamed, M. S. M., Abdelsalam, E., Mohamed, Y. M. A., Abdel-Hafez, S. H., & Attia, Y. A. (2022). Implementation of graphitic carbon nitride nanomaterials and laser irradiation for increasing bioethanol production from potato processing wastes. *Environmental Science and Pollution Research*, *29*(23), 34887-34897. https://doi.org/10.1007/s11356-021-18119-5

Sagar, N. A., Pareek, S., Sharma, S., Yahia, E. M., & Lobo, M. G. (2018). Fruit and vegetable waste: Bioactive compounds, their extraction, and possible utilization. *Comprehensive Reviews in Food Science and Food Safety*, *17*(3), 512-531. https://doi.org/10.1111/1541-4337.12330

Santos, C. A. D., Abboud, A. C. D. S., & Carmo, M. G. F. D. (2021). Biofumigation with species of the brassicaceae family: A review. *Ciência Rural*, *51*(1), Article e20200440. https://doi.org/10.1590/0103-8478cr2020040

Suleiman, W. B., El Bous, M. M., El Said, M., & El Baz, H. (2019). In vitro evaluation of *Syzygium aromaticum* L. Ethanol extract as biocontrol agent against postharvest tomato and potato diseases. *Egyptian Journal of Botany*, *59*(1), 81-94. https://doi.org/10.21608/ejbo.2018.3838.1180

Taiz, L., Zeiger, E., Mller, E. I. M., & Murphy, A. (2018). *Fundamentals of plant physiology*. Sinauer Associates.

Tian, Q., Rosselot, R. A., & Schwartz, S. J. (2005). Quantitative determination of intact glucosinolates in broccoli, broccoli sprouts, brussels sprouts, and cauliflower by high-performance liquid chromatography-electrospray ionization-tandem mass spectrometry. *Analytical Biochemistry*, *343*(1), 93-99. https://doi.org/10.1016/j.ab.2005.04.045

Todaka, D., Quynh, D. T. N., Tanaka, M., Utsumi, Y., Utsumi, C., Ezoe, A., Takahashi, S., Ishida, J., Kusano, M., Kobayashi, M., Saito, K., Nagano, A. J., Nakano, Y., Mitsuda, N., Fujiwara, S., & Seki, M. (2024). Application of ethanol alleviates heat damage to leaf growth and yield in tomato. *Frontiers in Plant Science*, *15*, Article 1325365. https://doi.org/10.3389/fpls.2024.1325365

Upadhaya, A. (2018). *Plant-parasitic nematodes in field pea and potato and their effect on plant growth and yield* [Master's thesis, North Dakota State University].

Vijayakumar, S., Wang, Y., Lehretz, G., Taylor, S., Carmo-Silva, E., & Long, S. (2024). Kinetic modeling identifies targets for engineering improved photosynthetic efficiency in potato (*Solanum tuberosum* cv. Solara). *The Plant Journal*, *117*(2), 561-572. https://doi.org/10.1111/tpj.16512

Zhang, K., Han, X., Fu, Y., Khan, Z., Zhang, B., Bi, J., Hu, L., & Luo, L. (2024). Biochar coating promoted rice growth under drought stress through modulating photosynthetic apparatus, chloroplast ultrastructure, stomatal traits and ROS homeostasis. *Plant Physiology and Biochemistry*, *216*, Article 109145. https://doi.org/10.1016/j.plaphy.2024.109145