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OPTIMIZING THE USE OF SINABUNG VOLCANIC ASH AND ORGANIC MATTER AS SOIL AMENDMENTS TO SUPPRESS LATE BLIGHT (PHYTOPHTHORA INFESTANS) AND INCREASE POTATO (SOLANUM TUBEROSUM) PRODUCTION IN THE KARO HIGHLANDS

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Abstract

This research was conducted in Surbakti Village, Simpang Empat District, Karo Regency, North Sumatra Province, Indonesia, at an altitude of approximately 1,250 meters above sea level (masl). The research was carried out from August to November 2025. This research was supervised by Dr. Ir. Muhammad Rizwan, M.P. as the Head Supervisor and Dr. Ir. Diapari Siregar, M.P. as the Assistant supervisor. Potato is a strategic horticultural commodity in North Sumatra, whose productivity has declined due to decreasing soil fertility and increasing pest and disease incidence. This study aimed to determine the effect of volcanic ash and organic matter formulations on soil nutrient status in potato cultivation fields in Surbakti Village.The experiment employed a Randomized Complete Block Design (RCBD). The first factor was the formulation of volcanic ash and organic matter, consisting of: A0 = control; A1 = 5 tons/ha (60% volcanic ash + 40% rice husk); A2 = 5 tons/ha (60% volcanic ash + 40% cattle manure); and A3 = 5 ton/ha (40% volcanic ash + 30% rice husk + 30% cattle manure). The second factor was the application time of the volcanic ash and organic matter, consisting of: B1 = one week before planting; B2 = at planting; and B3 = one week after planting.The results showed that the volcanic ash formulations significantly affected plant height, number of leaves per plant, stem diameter, number of tubers per plant, tuber yield, tuber diameter, and the severity of late blight disease. The application timing significantly affected plant height, number of leaves per plant, number of tubers per plant, tuber yield, and tuber diameter. Furthermore, the interaction between volcanic ash formulation and application timing significantly affected plant height and the number of leaves per plant

Keywords: potato, volcanic ash formulation, volcanic ash application timing.

INTRODUCTION

Potato (Solanum tuberosum L.) is a strategic horticultural commodity because it contributes to food diversification, farm income, and the food-processing industry. The thesis data show that national potato production fluctuated over recent years, increasing from approximately 1.23 million tons in 2020 to 1.28 million tons in 2022 before declining to approximately 1.22 million tons in 2023 (Badan Pusat Statistik, 2024). These fluctuations are important for production regions such as North Sumatra, where potatoes support both fresh markets and processing demand. The challenge is not only to increase harvested output, but to stabilize production under changing weather, pest and disease pressure, and gradual deterioration of soil quality.

North Sumatra is one of Indonesia's major potato-producing provinces, and Karo Regency is an important highland production center. The thesis reports that provincial production declined from 334,800 tons in 2020 to 310,200 tons in 2023, while Karo contributed a substantial share of the provincial supply. Ecologically, Karo's high elevation and relatively cool temperatures are suitable for potato cultivation; however, the same humid highland conditions are highly favorable for late blight. This creates a production paradox: an environment that supports tuber development may simultaneously support rapid disease development when inoculum, leaf wetness, and cool temperatures coincide.

Late blight, caused by Phytophthora infestans, is among the most destructive diseases of potato. The pathogen attacks leaves, stems, and tubers and can cause severe yield loss when disease develops rapidly. The thesis cites losses of 70–100% under epidemic conditions when the disease is not effectively controlled (Ginting et al., 2022). Conventional production therefore often relies on repeated fungicide applications. Although fungicides remain an important component of disease management, intensive dependence on synthetic inputs creates concerns related to production cost, residues, environmental burden, and the potential evolution of resistant pathogen populations (Hidayati & Sari, 2022). These limitations strengthen the rationale for complementary strategies that improve host vigor and soil health while reducing disease-favorable plant stress. A second challenge is the long-term maintenance of soil fertility. Potato has a relatively shallow root system and high nutrient demand during vegetative growth, stolon initiation, and tuber bulking. Repeated cultivation with insufficient organic matter replacement can reduce aggregate stability, soil carbon, nutrient-retention capacity, and biological activity. Brady and Weil (2017) emphasize that organic matter is central to soil physical, chemical, and biological functioning, while Diacono and Montemurro (2010) show that long-term organic amendments can improve soil fertility and crop productivity. In a high-input vegetable system, integrating locally available mineral and organic resources can therefore be agronomically and environmentally relevant.

Mount Sinabung erupted repeatedly from 2010 to 2021 and deposited substantial quantities of volcanic ash across parts of Karo. Instead of being considered only as a disruptive material, this ash may also represent a local mineral resource. Volcanic ash contains silicate minerals and plant nutrients such as K, Ca, Mg, Fe, and other elements that may be released gradually during weathering (Fiantis, 2006; Rajmi et al., 2022; Sihaloho, 2021). The ash may also contribute to the formation of non-crystalline minerals characteristic of volcanic soils, affecting nutrient retention and organic matter stabilization. The agronomic effect, however, depends on the chemical composition of the ash, the soil environment, amendment rate, and the time allowed for weathering and interaction with organic materials.

Organic materials can complement the mineral fraction of volcanic ash. Chicken manure supplies readily decomposable organic matter and relatively high concentrations of N, P, and K, whereas rice husk contributes carbon, porosity, and silica. In the thesis, chicken manure and rice husk were selected as locally relevant organic components. Their combination with volcanic ash was expected to improve nutrient availability, soil aeration, water retention, and microbial activity while also enhancing the physiological condition of the potato plant. Such combined effects are particularly relevant in highland systems where nutrient loss, heavy rainfall, and disease pressure can occur within the same cropping season.

Silicon is a particularly important link between volcanic materials, rice husk, and disease resistance. Although silicon is not traditionally classified as an essential element for all higher plants, many studies describe beneficial effects on structural strength and stress tolerance. Silicon can be deposited in epidermal tissues, strengthening physical barriers, and may also influence induced defense pathways. Xue et al. (2021), as cited in the thesis, reported enhanced potato resistance to P. infestans through silicon-associated signaling pathways. Thus, an ash–organic amendment may influence late blight indirectly through improved nutrition and plant vigor and, potentially, more directly through silicon-mediated defense mechanisms.

Previous work reviewed in the thesis generally examined volcanic ash, organic amendments, or disease management as separate topics. The specific research gap addressed here is the integrated evaluation of Sinabung volcanic ash formulation together with application timing and its simultaneous effects on soil nutrient status, vegetative growth, yield components, and late blight intensity in potato. The novelty lies in using a locally abundant post-eruption material in combination with organic matter and testing it under field conditions in the Karo Highlands.

Accordingly, this study aimed to determine the effect of volcanic ash–organic matter formulations on soil C, N, P, and K status; evaluate how application timing affects late blight development; and assess the combined responses of potato growth and productivity. The central hypothesis was that an appropriate formulation and timing of volcanic ash and organic materials would improve soil fertility and crop performance while reducing disease intensity compared with an untreated control.

LITERATURE REVIEW

Potato growth requirements and yield formation

Potato is a short-duration crop in the family Solanaceae. Its economic organ is the tuber, which develops from underground stolons through coordinated processes of stolon initiation, cell division, carbohydrate translocation, and starch accumulation. The crop performs well in cool highland environments and on soils with good aeration, drainage, and sufficient organic matter. The thesis notes an optimum soil reaction commonly around pH 5.5–6.5. At lower pH, Al and Mn toxicity can increase and microbial activity may decline; at excessively high pH, the availability of P and some micronutrients can decrease. These characteristics make soil chemical balance especially important for potato production. The vegetative canopy provides the photosynthetic source for tuber growth. Plant height, leaf number, and stem diameter therefore serve as useful indicators of crop vigor before final yield is assessed. Nitrogen supports leaf expansion and chlorophyll formation; phosphorus is important for energy transfer and root development; potassium is central to osmotic regulation, enzyme activation, and carbohydrate transport; calcium stabilizes cell walls and membranes; and magnesium is required for chlorophyll. Marschner (2012) and Taiz et al. (2015) provide the physiological basis for these relationships, while the thesis uses them to interpret treatment responses in height, leaf number, and stem growth.

Tuber number and tuber size are not controlled by exactly the same processes. The number of tubers reflects stolon formation and early tuber initiation, whereas tuber diameter and final production weight depend strongly on continued photosynthate supply and the capacity of developing tubers to function as sinks. Potassium is particularly important in potato because of its role in translocation and starch metabolism. Koch et al. (2020) emphasized the importance of potassium for potato yield and tuber quality, which is relevant to volcanic ash containing K-bearing minerals and to organic amendments that improve nutrient retention.

Soil ameliorants and the role of organic matter

A soil ameliorant is a material applied primarily to improve the physical, chemical, or biological condition of soil rather than to function only as a direct nutrient fertilizer. The thesis groups soil amendments into organic and inorganic materials and notes that their effects may include improved aggregation, porosity, water-holding capacity, cation-exchange capacity, pH buffering, and microbial activity. Aulia et al. (2025) and Paradelo et al. (2024) are cited as supporting the use of amendments for restoring or maintaining soil quality, especially where repeated cultivation has degraded soil properties.

Organic matter contributes both nutrients and reactive functional groups. During decomposition and humification, organic residues form compounds containing carboxyl and phenolic groups that generate negative charge and help retain nutrient cations. In volcanic soils, this role can be amplified by interactions with non-crystalline minerals such as allophane. Shoji et al. (1993) and Dahlgren et al. (2004) describe stable organo-mineral complexes that protect soil carbon and influence nutrient retention. Consequently, organic amendments can function as a nutrient source, a physical conditioner, and a regulator of nutrient-release dynamics.

Chicken manure is a concentrated organic amendment compared with many crop residues. Its nutrient content varies with feed, bedding, handling, and decomposition, but it generally contributes N, P, K, and organic carbon. The thesis cites Havlin et al. (2005) to support the role of manure in increasing nutrient availability and improving soil fertility. Properly decomposed manure can also support microbial activity without the risks associated with immature organic materials. For potato, improved nutrient supply and soil tilth can support both root development and tuber expansion.

Rice husk provides a contrasting organic component. It is rich in carbonaceous structural materials and contains appreciable silica. Its relatively porous structure can lower bulk density and improve aeration, while gradual decomposition can add organic carbon. Guntzer et al. (2012) and Ma and Yamaji (2015) are cited in the thesis to explain the agronomic value of silicon-rich plant residues. The combined use of chicken manure and rice husk therefore offers a balance between more readily available nutrients and a more structurally persistent carbon- and silica-rich material.

Volcanic ash as a mineral amendment

Volcanic ash is a fine pyroclastic material containing glass and mineral particles whose composition reflects the parent magma and eruption process. In agricultural soils, freshly deposited ash may initially create physical constraints, but weathering can release base cations and other nutrients. The thesis reports that volcanic ash may contain K, Ca, Mg, Fe, Mn, Zn, Cu, P, S, and silicon-bearing minerals (Fiantis, 2006). The agronomic value of these minerals is often gradual rather than immediate because nutrient release depends on dissolution and weathering.

The Sinabung ash used in this study contained 26.74% SiO2 together with measurable K, Ca, Mg, and Fe. In the thesis classification, this silica concentration was described as falling within a basic/alkaline volcanic-material category. The practical implication is not that the ash acts like a conventional soluble fertilizer, but that it represents a multi-mineral input that can alter the chemical environment over time. Its slow-release character helps explain why application timing may influence crop response: ash placed before planting has more time to interact with soil moisture and organic matter than ash applied later.

Volcanic ash can also influence the development of volcanic-soil minerals. Allophane and related short-range-order minerals are important in Andisols because they have high surface area and strong interactions with organic matter and phosphate. Nanzyo et al. (1993), Shoji et al. (1993), and Dahlgren et al. (2004) are cited in the thesis to explain how these mineralogical characteristics contribute to high organic carbon stabilization but may also increase phosphorus retention. Thus, the same mineral system that conserves organic matter can complicate phosphorus availability, making integrated amendment strategies important.

Studies cited in the thesis describe positive crop responses to volcanic materials, including improved pH, exchangeable bases, and nutrient availability. Anda et al. (2015) and Fiantis et al. (2016) linked volcanic mineralogy with nutrient dynamics, while Simanjuntak and Gultom (2022) were cited for potato responses to Sinabung ash in Karo. These findings provide a basis for evaluating volcanic ash not simply as geological residue but as a potentially useful agricultural input when combined with appropriate organic materials and rates.

Late blight epidemiology and plant resistance

Phytophthora infestans is an oomycete pathogen capable of rapid epidemic development in susceptible potato crops. Early symptoms include water-soaked greenish lesions that turn brown to black and expand under favorable conditions. High relative humidity, prolonged leaf wetness, and cool temperatures promote sporulation and infection. In severe epidemics, foliage can collapse quickly and tubers may also become infected. Fry (2008) is cited in the thesis to emphasize the importance of environmental conditions and inoculum in determining epidemic intensity.

This environmental sensitivity has two implications for amendment-based disease management. First, soil amendments cannot be expected to replace direct disease-control measures when weather strongly favors infection. Second, improved nutrition and tissue strength may still reduce susceptibility or slow disease development enough to contribute to an integrated strategy. The thesis explicitly notes that the effect of volcanic ash on disease is indirect and that climatic conditions may dominate late-blight progression at some observation dates.

Silicon offers a plausible mechanism for increased plant resistance. Silicon absorbed by roots can be deposited in epidermal cell walls, increasing tissue rigidity and creating a more difficult physical barrier for pathogen penetration. The thesis also describes biochemical responses involving phenolic compounds, lignification, antioxidant enzymes, and induced defense. Xue et al. (2021) is cited for silicon-associated resistance to P. infestans in potato. These mechanisms provide a biological rationale for the lower disease intensity observed in the most complex volcanic ash–organic formulation.

Nutritional balance is equally important. Excessive or deficient nutrient supply can alter tissue composition and host susceptibility. Adequate Ca, Mg, K, and other elements can support cell-wall integrity, osmotic balance, photosynthetic function, and defense metabolism. The thesis cites studies associating healthier nutrient status with lower late-blight severity. Hence, amendment effects on disease should be interpreted as the combined result of mineral nutrition, organic-matter effects, silicon availability, host vigor, and environmental pressure rather than as a direct fungicidal effect of volcanic ash.

Research gap and conceptual expectation

The literature reviewed in the thesis supports three separate propositions: volcanic ash can supply mineral nutrients and affect soil chemistry; organic matter can improve nutrient retention, physical condition, and biological activity; and silicon-rich inputs can strengthen plant tissues and contribute to resistance. What remained insufficiently tested was whether these processes could be integrated in a field-scale potato system using Sinabung ash, locally available organic materials, and contrasting application times. The current experiment was designed around that integration.

The expected pathway was that volcanic ash would provide a mineral source, chicken manure would provide readily decomposable nutrients and organic carbon, and rice husk would improve physical condition while adding carbon and silica. Application timing was expected to regulate the degree of interaction among ash, soil moisture, organic matter, and roots before or during critical growth phases. Improved soil status was then expected to support vegetative growth, photosynthesis, tuber initiation and bulking, with a parallel reduction in late-blight intensity through stronger plant condition and silicon-related defense.

METHOD

The field experiment was conducted in Surbakti Village, Simpang Empat District, Karo Regency, North Sumatra Province, Indonesia, at approximately 1,250 m above sea level. The work covered one potato growing season from August through November 2025. This highland location represents a major potato-production environment in Karo and also provides climatic conditions in which late blight can develop during the growing season.

Planting material consisted of certified Granola potato seed tubers. The amendment materials were sieved and chemically characterized Sinabung volcanic ash, chicken manure, and rice husk. Compost was used as a common basal input outside the experimental treatment structure. Field equipment included standard land-preparation tools, watering equipment, measuring tapes or rulers, scales, cameras, plot labels, and stakes.

The experiment used a factorial randomized complete block design with three replications. Factor A was the formulation of volcanic ash and organic matter: A0 = untreated control; A1 = 5 t ha−1 consisting of 60% volcanic ash + 40% rice husk; A2 = 5 t ha−1 consisting of 60% volcanic ash + 40% chicken manure; and A3 = 5 t ha−1 consisting of 40% volcanic ash + 30% rice husk + 30% chicken manure. Factor B was application timing: B1 = one week before planting; B2 = at planting; and B3 = one week after planting. The 4 × 3 factorial generated 12 treatment combinations, each replicated three times for a total of 36 experimental plots.

Each plot measured 1 m × 3 m and contained 14 potato plants at a spacing of 40 cm within rows and 70 cm between rows. Land preparation included removal of weeds and crop residues, primary tillage followed by approximately seven days of aeration, and secondary tillage to form beds. Initial soil samples were collected for chemical analysis before treatment application. Healthy seed tubers of approximately 30–50 g per tuber were planted 5–10 cm deep.

Amendments were applied according to the assigned formulation and timing. B1 treatments were incorporated during the second land-preparation stage one week before planting. B2 treatments were applied at planting in association with the planting hole. B3 treatments were placed around the plant base one week after planting and watered. Crop maintenance included irrigation every two to three days depending on soil moisture and weather, manual weeding at approximately weeks 3 and 6, and hilling at approximately weeks 4 and 7 to support tuber development.

Disease monitoring was performed every seven days. Late blight symptoms were identified from characteristic water-soaked green lesions developing into brown to black necrotic areas, followed by leaf wilting and loss under severe infection. Disease observations were made from 35 to 77 days after planting (HST) at seven-day intervals. Five sample plants were evaluated in each plot.

Vegetative variables included plant height, leaf number, and stem diameter at 30, 45, and 60 HST. Plant height was measured from the soil surface to the highest growing point. Fully developed healthy leaves were counted on the five sample plants per plot. Stem diameter was measured approximately 2–3 cm above the soil surface. Yield variables included the number of marketable tubers (>30 g) per plant, tuber weight, total plot production, and tuber diameter at harvest.

Late blight intensity was calculated using the Townsend and Heuberger approach as reported in the thesis: $I = [\Sigma(n \times V)/(N \times Z)] \times 100\%$, where I is disease intensity, n is the number of leaves in a given severity class, V is the observed severity score, N is the total number of leaves assessed, and Z is the maximum score. The visual scale ranged from 0 (no symptoms) to 5 (>80% affected), with intermediate classes representing <20%, >20–40%, >40–60%, and >60–80% severity.

Soil chemical analysis was conducted at the Soil, Plant, Fertilizer and Water Laboratory in North Sumatra. The variables reported in the thesis were organic C, total N, Bray-I available P, and exchangeable K. Volcanic ash was analyzed for K, Ca, Mg, Fe, and SiO_2, while chicken manure and rice husk were analyzed for organic C, total N, P_2O_5, and K_2O.

The thesis reports analysis of variance at the 5% significance level and mean separation using Duncan's Multiple Range Test (DMRT) at 5% where applicable. Accordingly, treatment means presented in the results retain the significance-letter notation from the thesis tables. Main effects of formulation and timing were interpreted separately, and formulation × timing interactions were discussed when the analysis indicated a significant response.

Table 1. Experimental factors and treatment levels

Factor	Code	Treatment description
Formulation	A0	Control, no volcanic ash–organic amendment
Formulation	A1	5 t ha^{-1}: 60% volcanic ash + 40% rice husk
Formulation	A2	5 t ha^{-1}: 60% volcanic ash + 40% chicken manure
Formulation	A3	5 t ha^{-1}: 40% volcanic ash + 30% rice husk + 30% chicken manure
Timing	B1	One week before planting
Timing	B2	At planting
Timing	B3	One week after planting

RESULTS AND DISCUSSION

Chemical characteristics of volcanic ash and organic materials

The Sinabung volcanic ash used in the experiment contained exchangeable K, Ca, Mg, Fe, and a substantial silica fraction. The measured SiO2 concentration was 26.74%. The thesis interprets this value within a basic/alkaline volcanic-material category and emphasizes that the ash contains minerals capable of contributing to the nutrient reserve of agricultural soil. Unlike a soluble fertilizer, this mineral contribution is expected to occur progressively as ash particles weather and react with the soil environment.

The organic materials showed contrasting nutrient profiles. Chicken manure contained 20.36% organic C, 3.13% total N, 1.35% P2O5, and 4.26% K2O, indicating a comparatively nutrient-rich material. Rice husk contained more organic C (31.09%) but substantially less N, P2O5, and K2O. This contrast supports the formulation logic: chicken manure contributes more immediately available nutrient potential, whereas rice husk contributes a carbon-rich, porous, silica-containing material. The A3 treatment combines both organic materials with volcanic ash and therefore integrates their complementary properties.

Table 2. Chemical composition of the Sinabung volcanic ash used in the experiment

No.	Analysis	Value
1	K-dd (me/100 g)	0.32
2	Ca (me/100 g)	1.35
3	Mg (me/100 g)	0.30
4	Fe (ppm)	73
5	SiO_2 (%)	26.74

Table 3. Chemical composition of the organic materials

No.	Analysis	Chicken manure	Rice husk
1	Organic C (%)	20.36	31.09
2	Total N (%)	3.13	0.55
3	P_2O_5 (%)	1.35	0.10
4	K_2O (%)	4.26	0.43

Plant height

Formulation significantly affected plant height at 30, 45, and 60 HST. At 30 HST, A3 produced the greatest mean height (27.3 cm), compared with 15.8 cm in the untreated control. The same ranking remained evident later in the season: at 45 HST A3 reached 64.3 cm and at 60 HST 66.8 cm, while A0 reached 58.4 and 61.2 cm, respectively. These responses indicate that the combined amendment improved vegetative growth relative to the control. A1 and A2 were generally intermediate, suggesting that both ash–rice-husk and ash–manure combinations provided benefits, but the three-component A3 formulation produced the most consistent increase.

Application timing also influenced height at later observation dates. At 45 HST, B1, B2, and B3 were close in absolute value, but the statistical grouping indicated a timing effect. At 60 HST, B2 and B3 produced means around 65.0–65.3 cm, whereas B1 averaged 63.9 cm. The relatively small numerical differences show that timing altered the expression of the formulation effect rather than generating large independent changes in plant height.

The formulation × timing interaction was significant at 45 and 60 HST. At 60 HST, A3B2 produced the greatest recorded height (68.1 cm), essentially similar to A3B3 (68.0 cm), whereas A0B1 was lowest (57.2 cm). The interaction is agronomically plausible because volcanic minerals require time and moisture for weathering, while organic materials begin decomposing and releasing nutrients on a different schedule. When these processes align with the crop's early vegetative demand, cell division, cell elongation, and canopy development can be enhanced.

The mineral composition of volcanic ash provides a mechanistic basis for the response. K supports enzyme activation and osmotic regulation, Ca contributes to cell-wall and membrane stability, Mg is central to chlorophyll, and Fe participates in photosynthetic and respiratory processes. Organic matter can improve the retention and gradual supply of these nutrients while also improving soil physical condition. Fiantis (2006), Suharta et al. (2018), Rajmi et al. (2022), and Sihaloho (2021) are cited in the thesis to support these interpretations.

Table 4. Mean plant height as affected by formulation, application timing, and their combinations

Treatment	30 HST	45 HST	60 HST
Formulation (A)			
A0	15.8 b	58.4 c	61.2 b
A1	26.9 ab	62.6 b	64.9 ab
A2	26.8 ab	62.3 ab	65.9 ab
A3	27.3 a	64.3 a	66.8 a
Timing (B)			
B1	24.5	62.1 a	63.9 ab
B2	25.6	61.5 ab	65.0 a
B3	22.5	61.3 ab	65.3 a
Interaction A×B			
A0B1	14.2	55.5 c	57.2 c
A0B2	16.2	59.9 c	63.3 bc
A0B3	17.1	59.9 c	63.1 bc
A1B1	28.8	63.0 ab	66.0 ab
A1B2	28.7	61.9 b	64.5 b
A1B3	23.3	62.8 ab	64.3 b
A2B1	28.3	64.5 ab	67.9 ab
A2B2	27.5	60.3	63.9 bc
A2B3	24.6	62.2 b	65.9 b
A3B1	26.8	65.3 a	64.3 b
A3B2	30.0	63.7 ab	68.1 a
A3B3	25.1	63.9 ab	68.0 a

Values followed by different letters within the same observation column differ at the 5% level according to DMRT, as reported in the thesis.

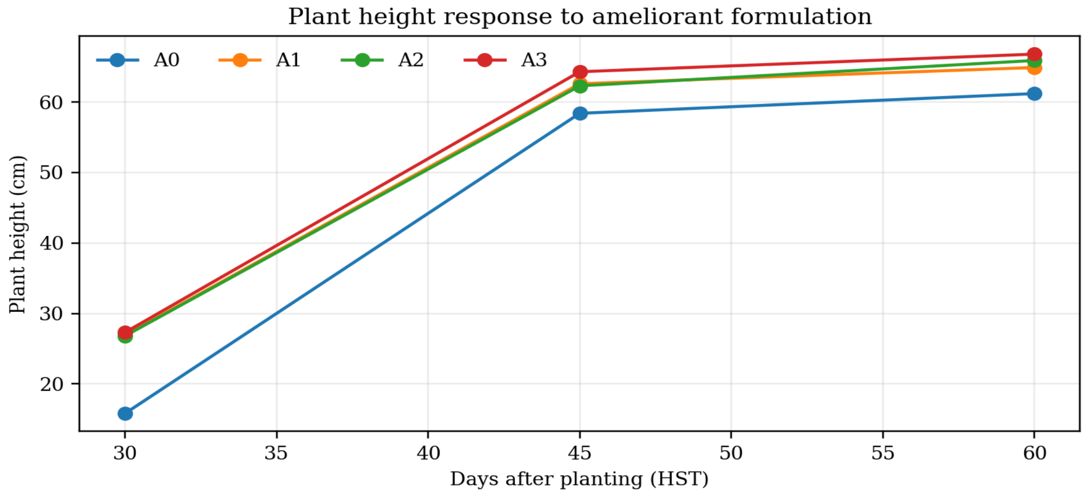

Figure 1. Plant height response to volcanic ash–organic matter formulation across observation dates.

Leaf number

Leaf number responded in a pattern similar to plant height. Formulation had a significant effect at 30, 45, and 60 HST. A3 produced 26.4 leaves at 30 HST, 55.7 leaves at 45 HST, and 59.3 leaves at 60 HST, while the control produced 15.3, 49.9, and 53.7 leaves, respectively. This consistent advantage indicates that the three-component amendment promoted canopy formation throughout the vegetative period.

Timing significantly affected leaf number, with B2 producing the largest mean at 30 and 45 HST and B1 producing the largest mean at 60 HST. B3 tended to be lower, especially at 30 HST. These results suggest that the crop benefited when amendment materials were present in the root zone by planting or shortly before it, allowing mineral release and organic-matter decomposition to begin before the canopy demand became high.

The A × B interaction was significant for leaf number. At 60 HST, A3B1 produced 61.5 leaves and A2B1 produced 60.0 leaves, while the control combinations remained lower. The interaction supports the idea that formulation quality and timing are not completely independent during canopy development. Nitrogen from chicken manure can support leaf expansion, while K, Mg, and other mineral nutrients from ash contribute to photosynthesis and physiological balance. Rice husk can improve aeration and may add silicon, creating a root-zone condition favorable for sustained vegetative growth.

More leaves do not automatically guarantee greater yield, but a healthy canopy increases the potential photosynthetic source available for tuber growth. In the present study, treatments with improved leaf number also tended to show higher tuber number, production weight, and tuber diameter. This coherence among vegetative and reproductive responses strengthens the interpretation that the amendments improved overall crop functioning rather than affecting a single isolated trait.

Table 5. Mean number of leaves per plant under formulation, timing, and interaction treatments

Treatment	30 HST	45 HST	60 HST
Formulation (A)			
A0	15.3 b	49.9 b	53.7 bc
A1	25.1 ab	53.0 ab	56.9 b
A2	25.5 ab	53.6 ab	58.1 ab
A3	26.4 a	55.7 a	59.3 a
Timing (B)			
B1	24.2 ab	53.2 ab	57.8 a
B2	25.4 a	53.4 a	57.1 a
B3	19.6 c	52.5 b	56.1 ab
Interaction A×B			

Treatment	30 HST	45 HST	60 HST
A0B1	14.4 cd	47.0 c	51.2 c
A0B2	15.8 cd	53.3 ab	56.5 c
A0B3	15.5 cd	49.5 c	53.3 c
A1B1	28.3 ab	54.6 ab	58.5 ab
A1B2	27.8 b	53.0 ab	56.7 c
A1B3	19.3 d	51.3 b	55.3 c
A2B1	28.1 ab	55.3 a	60.0 a
A2B2	27.4 b	51.8 b	56.6 b
A2B3	21.0 c	53.8 ab	57.7 b
A3B1	26.0 bc	55.9 a	61.5 a
A3B2	30.6 a	55.7 a	58.3 ab
A3B3	22.5 c	55.4 a	58.1 ab

Different letters indicate significant differences at the 5% DMRT level within the same observation column, following the thesis table.

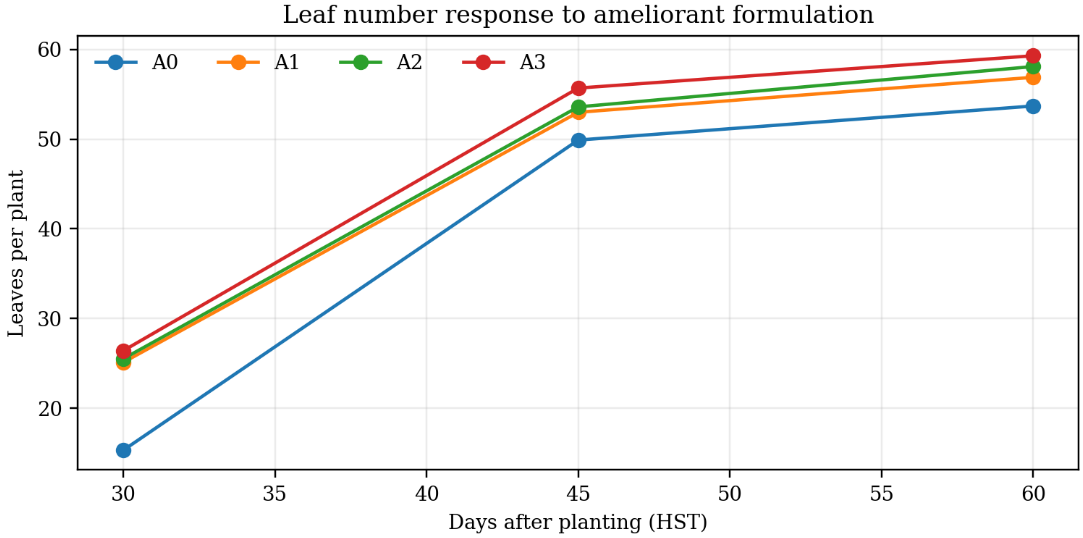

Figure 2. Leaf number response to volcanic ash–organic matter formulation across observation dates.

Stem diameter

Stem diameter was significantly affected by formulation, particularly at 60 HST. The A3 treatment produced the largest mean diameter (22.5 mm) compared with 20.5 mm in A0, while A1 and A2 were intermediate at 21.7 and 21.8 mm. Timing did not significantly affect stem diameter, and the interaction was also not significant. The narrow range among B1, B2, and B3 indicates that stem thickening was more responsive to the composition of the amendment than to the precise date of application.

A stronger stem reflects greater radial growth and can support canopy development as well as transport of water and nutrients. The thesis attributes the formulation response to the mineral contribution of K, Ca, Mg, Fe, and Si and to the improved physical and chemical environment produced by organic matter. Calcium contributes to cell-wall structure, magnesium supports photosynthesis, and potassium contributes to turgor and metabolic regulation. These effects are compatible with the higher stem diameter under A3.

Although the interaction was not significant, the largest combination mean at 60 HST was A3B3 (22.6 mm) and the lowest was A0B1 (20.0 mm). This pattern again shows the general advantage of the A3 formulation, but the lack of statistical interaction cautions against over-interpreting the numerical ranking of individual A × B combinations.

Table 6. Mean stem diameter under formulation, timing, and interaction treatments

Treatment	30 HST	45 HST	60 HST
Formulation (A)			
A0	9.2 b	19.8 b	20.5 b
A1	13.8 a	21.2 ab	21.7 ab
A2	13.3 ab	21.1 ab	21.8 ab
A3	13.8 a	22.0 a	22.5 a
Timing (B)			
B1	14.0	20.8	21.5
B2	13.4	21.0	21.5
B3	10.1	21.3	21.8
Interaction A×B			
A0B1	9.5	18.8	20.0
A0B2	10.0	20.1	20.6
A0B3	8.2	20.4	20.9
A1B1	15.8	21.1	21.6
A1B2	14.9	21.3	21.7
A1B3	10.8	21.2	21.7
A2B1	15.5	21.4	22.0
A2B2	13.7	20.6	21.4
A2B3	10.6	21.4	22.0
A3B1	15.1	22.0	22.4
A3B2	15.2	21.9	22.5
A3B3	11.0	22.1	22.6

Letters indicate the 5% DMRT grouping reported in the thesis.

Tuber number

Tuber number per plant was significantly affected by both formulation and application timing. A3 produced the greatest formulation mean (12.7 tubers), followed closely by A2 (12.4) and A1 (12.2), while A0 produced 10.5 tubers. The statistical grouping indicates that all amended treatments improved tuber number relative to the control, with no significant differences among A1, A2, and A3. Thus, the presence of volcanic ash combined with either rice husk, chicken manure, or both was sufficient to increase tuber initiation relative to the untreated condition.

Timing also affected tuber number. B1 produced 12.4 tubers per plant, B2 produced 11.9, and B3 produced 11.5. The better performance of B1 is consistent with an amendment that benefits from pre-plant incorporation. Applying one week before planting provides additional time for soil–amendment interaction, early organic decomposition, and initial release of mineral nutrients before stolon initiation begins.

The A × B interaction was not significant, although A3B1 produced the highest numerical mean (13.1 tubers) and A0B2 and A0B3 the lowest (10.3). This result indicates that the main effects provide a more reliable basis for interpretation than any single treatment combination. From a physiological perspective, adequate P and K are important during stolon initiation and early tuber formation, while balanced N supports canopy development without excessively delaying tuberization.

Table 7. Mean tuber number per plant

Formulation	B1	B2	B3	Mean A
A0	10.9	10.3	10.3	10.5 b
A1	12.5	12.1	11.8	12.2 a
A2	12.9	12.3	11.8	12.4 a
A3	13.1	12.7	12.2	12.7 a
Mean B	12.4 a	11.9 ab	11.5 ab	

Production weight and agronomic productivity

Total production weight followed the same general response as tuber number. Formulation had a significant effect, with A3 producing 1.4 kg, A2 1.2 kg, A1 1.0 kg, and A0 0.9 kg in the reported mean table. Timing also had a significant effect, and B1 produced the largest mean (1.2 kg) compared with approximately 1.1 kg for B2 and B3. The interaction was not significant. The highest numerical treatment combination was A3B1 at 1.451 kg, whereas A0B2 was reported as the lowest at 0.919 kg.

The thesis reports a total tuber production of 569.79 kg from the 36 experimental plots and a converted yield of 52.76 t ha^{-1}. This converted value was higher than the approximately 30 t ha^{-1} potential yield cited in the varietal description of Granola used by the thesis. Because plot-scale conversion can magnify local experimental conditions, this value should be understood in the context of the experimental plot size and management rather than treated automatically as a commercial-farm expectation. Nevertheless, the treatment ranking clearly demonstrates that the amended plots produced more tuber biomass than the control.

Several processes can explain the higher production under A3. Chicken manure supplied N, P, K, and decomposable organic matter; rice husk contributed carbon, porosity, and silica; and volcanic ash contributed mineral K, Ca, Mg, Fe, and Si. Organic matter can increase cation-retention capacity and water-holding capacity, while volcanic minerals may provide a slow-release nutrient source. Diacono and Montemurro (2010), Guntzer et al. (2012), Anda et al. (2015), and Fiantis et al. (2016) provide the literature basis used by the thesis to interpret these processes.

Potassium is particularly relevant to tuber yield because it supports carbohydrate translocation and starch accumulation. When the canopy has sufficient photosynthetic capacity and the root zone can supply K and other nutrients, assimilates can be transferred effectively to the developing tubers. The positive treatment effects on height and leaf number are therefore consistent with the higher production weight observed under the richer amendment formulations.

Table 8. Mean total production weight

Formulation	B1	B2	B3	Mean A
A0	1.0	0.9	0.9	0.9 bc
A1	1.1	1.0	1.0	1.0 b
A2	1.2	1.2	1.1	1.2 ab
A3	1.5	1.3	1.3	1.4 a
Mean B	1.2 a	1.1 ab	1.1 ab	

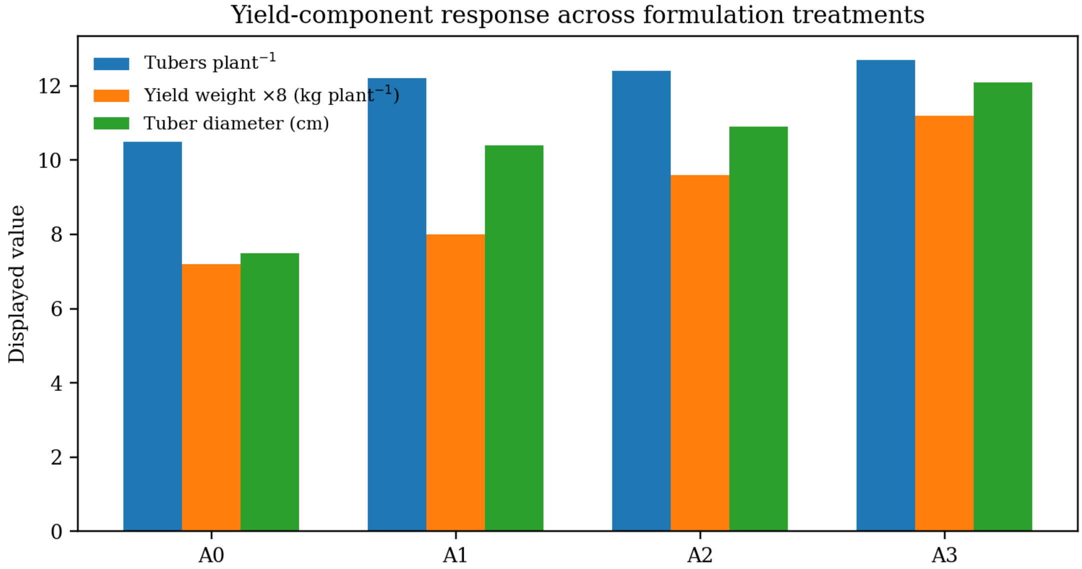

Figure 3. Comparison of key yield components across volcanic ash–organic matter formulations. Production weight is multiplied by eight only for visual comparability in this figure; the original values are reported in Table 8.

Tuber diameter

Tuber diameter was significantly affected by formulation and timing, but not by the interaction. A3 produced the greatest mean diameter (12.1 cm), compared with 7.5 cm in the control, while A1 and A2 produced 10.4 and 10.9 cm. The magnitude of this difference is agronomically important because tuber size is a major component of marketable yield and is strongly linked to the duration and efficiency of tuber bulking.

For timing, B1 produced the largest mean diameter (10.5 cm), followed by B2 (10.3 cm) and B3 (9.9 cm). The numerical advantage of B1 supports the interpretation that pre-plant application allowed earlier amendment interaction with the soil. Although some statistical groupings overlapped, the general trend was consistent with the tuber-number and production-weight responses.

Koch et al. (2020) emphasized the role of potassium in potato production and tuber quality. Potassium regulates osmotic relations and enzyme activity and supports carbohydrate movement toward storage organs. Volcanic ash can contribute K-bearing minerals, while organic matter can reduce nutrient losses by increasing exchange capacity. The combination of nutrient supply and improved retention therefore provides a reasonable explanation for the larger tubers under A3.

Table 9. Mean tuber diameter

Formulation	B1	B2	B3	Mean A
A0	7.7	7.5	7.3	7.5 b
A1	10.8	10.3	10.2	10.4 ab
A2	10.8	11.1	10.6	10.9 ab
A3	12.6	12.4	11.4	12.1 a
Mean B	10.5 a	10.3 a	9.9 ab	

Late blight intensity

Formulation significantly affected late blight intensity at several observation dates. The untreated control consistently showed the highest or among the highest disease values, while A3 produced the lowest values at key stages. At 63 HST, disease intensity was 19.1% in A0 compared with 7.1% in A3. At 70 HST, A0 reached 66.7% while A3 was 46.2%, and at 77 HST A0 reached 76.9% compared with 60.9% under A3. The disease increased sharply in all treatments late in the season, but the A3 formulation delayed or reduced the intensity relative to the control.

The treatment effect is consistent with a plant-health mechanism rather than a direct pesticidal action. Volcanic ash provides silicon and mineral nutrients, chicken manure improves nutrient availability and biological activity, and rice husk adds carbon and silica. Silicon can strengthen epidermal tissues and is associated with induced resistance, lignification, phenolic responses, and antioxidant activity. Xue et al. (2021), as cited in the thesis, supports the possibility that silicon can enhance potato resistance to P. infestans through defense-signaling pathways.

Application timing did not significantly affect late blight intensity, and the A × B interaction was also not significant. Although B1 generally produced somewhat lower means and some A3 combinations showed lower late-season disease numerically, the statistical results indicate that the formulation itself was the more consistent treatment factor. This finding is important because it prevents overstatement of timing as a disease-control tool.

The strong late-season increase in disease across all treatments also demonstrates the importance of the environment. Fry (2008) emphasized that cool, moist conditions and available inoculum can dominate epidemic development. The thesis therefore interprets volcanic ash primarily as a soil amendment that may improve host resistance rather than as a substitute for integrated late-blight management. In practical systems, amendment use should be combined with resistant varieties where available, sanitation, crop monitoring, and appropriately targeted disease-control measures.

Table 10. Mean late blight intensity (%) across observation dates

Treatment	35	42	49	56	63	70	77 HST
Formulation (A)							
A0	5.8 a	9.3 a	11.1 a	11.6 a	19.1 a	66.7 a	76.9 a
A1	0.0 b	5.8 ab	6.7 ab	8.0 ab	12.9 ab	55.1 ab	65.3 ab
A2	0.0 b	2.7 b	4.9 b	8.4 ab	11.1 b	55.1 ab	64.9 ab
A3	0.0 b	0.4 c	2.2 bc	2.2 b	7.1 bc	46.2 b	60.9 b
Timing (B)							
B1	1.0	3.3	4.7	6.7	11.0	52.7	65.0
B2	1.3	4.3	7.0	8.3	12.0	59.0	70.3
B3	2.0	6.0	7.0	7.7	14.7	55.7	65.7
Interaction A×B							
A0B1	4.0	9.3	9.3	10.7	21.3	65.3	76.0
A0B2	5.3	9.3	13.3	13.3	17.3	74.7	82.7
A0B3	8.0	9.3	10.7	10.7	18.7	60.0	72.0
A1B1	0.0	4.0	4.0	8.0	12.0	53.3	62.7
A1B2	0.0	6.7	8.0	8.0	10.7	57.3	70.7
A1B3	0.0	6.7	8.0	8.0	16.0	54.7	62.7
A2B1	0.0	0.0	4.0	6.7	6.7	50.7	62.7
A2B2	0.0	1.3	4.0	9.3	12.0	56.0	65.3
A2B3	0.0	6.7	6.7	9.3	14.7	58.7	66.7
A3B1	0.0	0.0	1.3	1.3	4.0	41.3	58.7
A3B2	0.0	0.0	2.7	2.7	8.0	48.0	62.7
A3B3	0.0	1.3	2.7	2.7	9.3	49.3	61.3

Different letters in the formulation rows denote the 5% DMRT groupings reported in the thesis. Timing and interaction effects were reported as not significant for disease intensity.

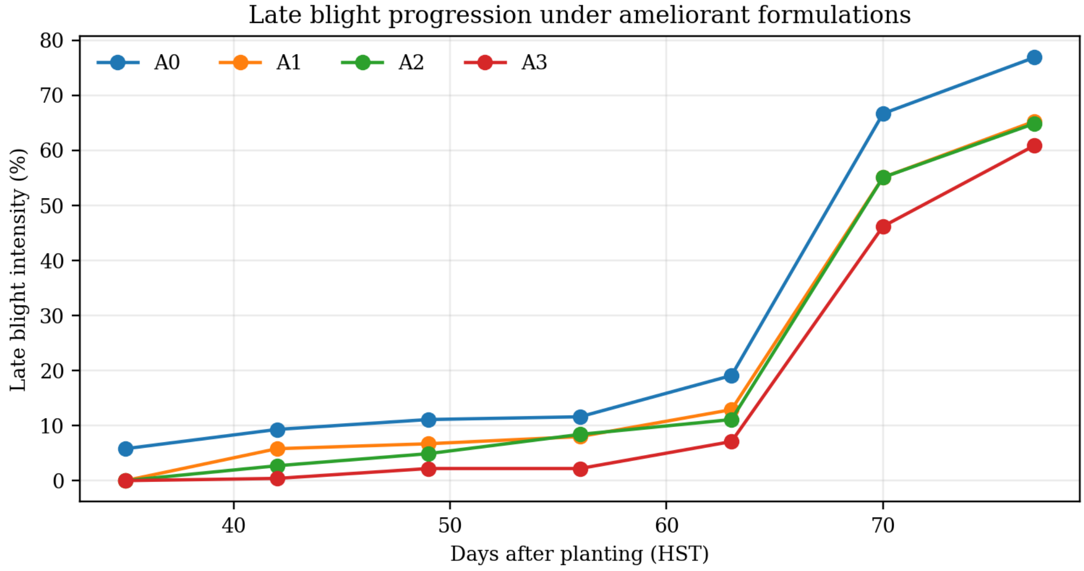

Figure 4. Progression of late blight intensity under the four volcanic ash–organic matter formulations.

Soil nutrient status before and after treatment

The soil analysis showed increases in all four measured fertility indicators after the experiment. Organic C increased from 3.89% to 3.95%, total N from 0.44% to 0.49%, Bray-I P from 25.80 to 26.02 ppm, and exchangeable K from 1.60 to 2.09 me/100 g. The increase in K was proportionally the largest, approximately 30.6%, which is consistent with the presence of K-bearing volcanic minerals and the improved cation-retention environment created by organic matter.

The modest rise in organic C is meaningful because the experiment covered only one growing season. Chicken manure and rice husk added organic carbon, but some carbon was simultaneously decomposed. In Andisol-type volcanic soils, allophane and related minerals can stabilize organic matter by forming organo-mineral complexes. Shoji et al. (1993) and Dahlgren et al. (2004) describe these interactions as a characteristic feature of volcanic soils, helping protect organic carbon and contributing variable negative charge to the soil. Total N increased along with organic C. Chicken manure was the most N-rich amendment component, and decomposition can release mineral N while a portion remains stored in organic forms. The thesis interprets the allophane–humus association as a mechanism that may reduce rapid loss and support gradual nutrient release. Such a reservoir function is especially valuable in high-rainfall environments where soluble nutrients can otherwise be leached.

Available P increased only slightly. This limited response is compatible with the strong P-retention capacity of volcanic soils. Allophane surfaces can adsorb phosphate, reducing the immediate change in Bray-extractable P even when organic and mineral amendments are added. Thus, the small numerical increase should not be interpreted as evidence that the amendment had no effect; it may reflect the balance between P addition, plant uptake, and sorption to reactive mineral surfaces.

Exchangeable K increased from 1.60 to 2.09 me/100 g. This response supports the proposed complementary mechanism: volcanic ash supplies K through mineral weathering, whereas organic matter contributes exchange sites that retain released K against leaching. Fiantis et al. (2019) describe volcanic material as a source of exchangeable base cations released over time. The increase in soil K also corresponds well with the higher tuber number, production weight, and tuber diameter in amended treatments because potato has a high K requirement during tuber development.

Table 11. Soil nutrient status before and after the field experiment

No.	Analysis	Before treatment	After treatment
1	Organic C (%)	3.89 (high)	3.95 (high)
2	Total N (%)	0.44 (medium)	0.49 (high)
3	P-Bray I (ppm P)	25.80 (medium)	26.02 (medium)
4	K-dd (me/100 g)	1.60 (high)	2.09 (high)

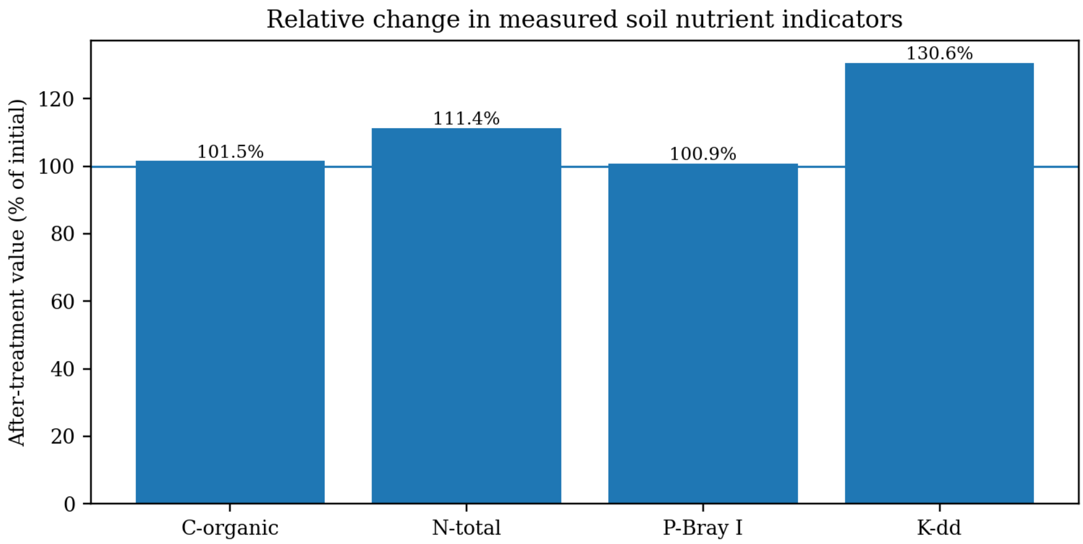

Figure 5. Relative change in soil fertility indicators after volcanic ash–organic matter treatment.

Integrated interpretation and practical implications

Across the measured variables, A3 was the most consistently favorable formulation. It produced the greatest main-effect means for plant height, leaf number, stem diameter, tuber number, production weight, and tuber diameter, while also producing the lowest late-blight intensity among formulations at important late-season observation dates. This consistency is more informative than any single trait because it indicates a coordinated improvement in soil–plant functioning.

The A3 formulation differs from A1 and A2 by combining both organic materials while retaining a substantial volcanic-ash fraction. Chicken manure provides a nutrient-rich, readily decomposable component; rice husk provides a more carbon-rich and structurally porous component with silica; and volcanic ash provides mineral nutrients and additional silicon. The combination therefore broadens the timing and type of nutrient and soil-conditioning effects available during the season. In contrast, A1 lacks the nutrient density of chicken manure and A2 lacks the physical and silica-related contribution of rice husk.

Application timing produced a more variable pattern. B1 was favorable for tuber number, production weight, and tuber diameter, while some vegetative responses peaked at B2 or differed only slightly among dates. This is consistent with distinct physiological phases. Early incorporation can benefit soil conditioning and the nutrient environment before tuber initiation, whereas at-plant application can synchronize some nutrient supply with early canopy development. Because the interaction was significant mainly for height and leaf number and not for most yield or disease traits, practical recommendations should emphasize the robust formulation effect and use timing as a management refinement rather than as the sole determinant of outcome.

The disease results require equally careful interpretation. A3 reduced late-blight intensity relative to the control, but all treatments showed a strong increase late in the season. The amendment therefore did not eliminate disease. The most defensible interpretation is that improved nutrition, silicon availability, and plant vigor contributed to partial suppression or delayed progression, while environmental conditions eventually became sufficiently favorable for high disease intensity in all plots. This distinction is important for translating the findings into farmer recommendations.

The soil data provide a supporting link between amendment application and plant response. The simultaneous increase in organic C, total N, available P, and exchangeable K suggests that the amendment system improved the chemical resource base of the soil. The especially strong K increase is relevant to potato because K is central to carbohydrate transport and tuber filling. The increase in N supports canopy development, while the maintenance of organic C and P indicates broader improvements in the soil nutrient-retention environment.

From a resource-use perspective, the study demonstrates a pathway for converting locally abundant volcanic ash into a productive agricultural input when combined with organic residues. This approach aligns with circular and place-based agriculture: a material generated by volcanic disturbance is integrated with locally available organic resources to support crop production. The concept is especially attractive in Karo because ash availability, potato cultivation, and disease pressure occur in the same regional production system.

At the same time, the findings should not be generalized beyond the experimental conditions without further testing. The experiment covered a single season, one potato variety, one ash source, one total amendment rate, and one highland location. Volcanic ash composition can vary spatially and temporally, and manure and rice-husk properties also vary. Multi-season trials are needed to determine whether the positive soil and yield responses persist, accumulate, or change with repeated application.

Future studies should therefore evaluate a wider range of application rates, repeated-season effects, additional organic-material ratios, and integration with standard fertilization programs. Measuring soil pH, cation-exchange capacity, microbial activity, plant tissue silicon, nutrient uptake, and disease microclimate would strengthen the mechanistic interpretation. Disease studies should also record rainfall, relative humidity, leaf-wetness duration, and inoculum pressure to separate amendment effects from environmental drivers more precisely.

Economically, the key question is whether the yield gain and potential disease reduction justify collection, transport, processing, and application of volcanic ash and organic materials. A farm-scale cost-benefit analysis was outside the scope of the thesis, but it is essential before large-scale recommendation. Such analysis should include the local availability of ash, labor for mixing and application, manure and rice-husk costs, potential reductions in synthetic fertilizer or fungicide use, and changes in marketable tuber yield.

Overall, the experiment provides a coherent agronomic signal: a mixed volcanic ash–organic amendment can improve soil nutrient status, support vegetative and reproductive growth, and reduce the intensity of late blight relative to an untreated control. The treatment A3, particularly when applied before planting for yield-related responses, emerges as the most promising practical direction for further field validation in the Karo Highlands.

Agronomic meaning of application timing and nutrient synchrony

The timing factor provides an important management perspective because volcanic ash and organic matter do not become agronomically active at exactly the same rate. The thesis describes volcanic-ash minerals as relatively slow-release sources whose effectiveness depends on weathering, moisture, and contact with the soil matrix (Badan Geologi Kementerian ESDM, 2014). Chicken manure, in contrast, begins microbial decomposition after incorporation and can release mineral N and other nutrients more rapidly, while rice husk decomposes more slowly because of its higher structural carbon content. Therefore, the date of application influences how these materials overlap with the crop's changing demand for nutrients during establishment, canopy development, stolon initiation, and tuber filling.

The observed plant-height response illustrates this temporal component. At 45 and 60 HST, application timing significantly affected height, although the numerical differences among B1, B2, and B3 were relatively modest. The thesis interprets this result as evidence that timing can influence the availability of nutrients during critical vegetative stages. At 60 HST, B2 and B3 produced means of 65.0 and 65.3 cm, respectively, compared with 63.9 cm under B1. These data show that there was no single timing treatment that maximized every vegetative trait; rather, nutrient release and plant demand interacted differently over time.

Leaf number followed a similarly dynamic pattern. At 30 HST, B2 produced the greatest mean number of leaves (25.4), while B1 averaged 24.2 and B3 only 19.6. At 45 HST, B2 remained slightly higher, whereas by 60 HST the highest mean was associated with B1 (57.8 leaves). This shift indicates that application timing affected early canopy establishment and later persistence in different ways. The result is consistent with the thesis discussion that potato vegetative growth is sensitive to the synchronization of N and K availability with meristematic activity and leaf expansion.

Yield-related variables gave a clearer advantage to pre-plant application. The B1 treatment produced 12.4 tubers per plant, compared with 11.9 under B2 and 11.5 under B3. Production weight also favored B1 at 1.2 kg, while B2 and B3 each averaged about 1.1 kg. Tuber diameter followed the same tendency, with B1 at 10.5 cm, B2 at 10.3 cm, and B3 at 9.9 cm. Although several of these differences were small, their directional consistency suggests that having the amendment in the soil before planting improved the root-zone environment before stolon initiation and tuber bulking became dominant sinks.

The absence of a significant timing effect for stem diameter and late-blight intensity is also informative. It indicates that some responses were governed more strongly by amendment composition or by environmental conditions than by the seven- to fourteen-day difference among application dates. Stem thickening may have integrated nutrient supply over a longer period, reducing sensitivity to the exact timing of incorporation. Disease intensity, meanwhile, was strongly influenced by the external disease environment, especially the cool and humid highland conditions described in the thesis, so relatively small shifts in amendment timing were insufficient to consistently alter epidemic development.

From a practical standpoint, the timing results support incorporation before planting when the primary objective is yield formation. Pre-plant incorporation allows the organic fraction to begin decomposition and creates more time for ash particles to interact with soil moisture, exchange sites, and organic ligands. However, the significant formulation × timing effects for height and leaf number show that timing should not be interpreted independently of formulation. The best vegetative combinations differed among observation dates, demonstrating why field recommendations should be based on the integrated performance of growth, yield, disease, and soil indicators rather than on a single measurement.

Linking vegetative growth with tuber initiation and final yield

The experiment provides a useful sequence from vegetative response to economic yield. Plant height and leaf number improved under the amended treatments, particularly A3, and this was followed by higher tuber number, production weight, and tuber diameter. In physiological terms, the canopy functions as the photosynthetic source, whereas developing tubers become strong sinks. A treatment that improves leaf area and maintains a vigorous canopy can increase the supply of assimilates available for translocation, provided that nutrient balance and environmental conditions also support tuber initiation and bulking. This source–sink framework is used in the thesis to connect the separate growth and yield measurements.

At 60 HST, A3 reached 66.8 cm in height and 59.3 leaves per plant, compared with 61.2 cm and 53.7 leaves in the untreated control. The difference in canopy development was accompanied by an increase in tuber number from 10.5 tubers per plant in A0 to 12.7 in A3. The A3 formulation also produced the highest production weight (1.4 kg in the treatment mean) and the largest mean tuber diameter (12.1 cm), compared with 0.9 kg and 7.5 cm under A0. The parallel direction of these responses suggests that the amendment improved both source capacity and sink development rather than simply producing vegetative luxuriance without yield benefit.

Nitrogen is particularly important during early canopy formation because it is required for proteins, chlorophyll, and expanding leaf tissue. The chicken-manure analysis in this experiment showed 3.13% total N, much higher than the 0.55% measured in rice husk. This difference helps explain why combining manure with ash can complement the mineral contribution of the volcanic material. Nevertheless, nitrogen must remain balanced: excessive vegetative growth can compete with tuber formation, whereas inadequate N limits photosynthesis. The A3 results indicate that the tested formulation provided a favorable balance under the conditions of this field season.

Potassium has an especially direct relationship with potato yield because it supports stomatal regulation, enzyme activation, carbohydrate transport, osmotic adjustment, and starch accumulation. The volcanic ash contained exchangeable K and other base cations, while the chicken manure also contained 4.26% K_2O. Koch et al. (2020) and Zörb et al. (2014), as cited in the thesis, support the role of adequate K in crop productivity and tuber quality. The increase in soil exchangeable K from 1.60 to 2.09 me/100 g after treatment provides field evidence that the amendment system altered the K resource available in the soil.

Phosphorus and calcium also contribute to yield formation through different mechanisms. Phosphorus supports energy transfer and root development, while calcium is important for cell-wall structure and membrane stability. The ash contained measurable Ca and the organic components contained P. Even though the increase in Bray-I P was numerically small, from 25.80 to 26.02 ppm, the maintenance of P availability during a high-demand potato crop is meaningful in an Andisol where phosphate can be strongly retained by reactive mineral surfaces. The thesis therefore interprets yield response as a consequence of a broader nutrient balance rather than the effect of one element alone.

The interaction results reinforce this interpretation. For tuber number and production weight, the A × B interaction was not statistically significant even though A3B1 showed the greatest numerical values, including 13.1 tubers per plant and approximately 1.451 kg production weight. This means that the main formulation and timing effects explained the response more consistently than any unique combination. Agronomically, a nonsignificant interaction does not erase the practical value of a numerically superior combination, but it does require caution: the recommendation should emphasize the reliable main effects while treating A3B1 as a promising combination for validation rather than as universally superior.

The total harvested production reported in the thesis was 569.79 kg from the 36 experimental plots, equivalent to approximately 52.76 t ha^{-1} using the thesis conversion. This value exceeded the approximately 30 t ha^{-1} potential yield stated in the varietal description for Granola. The thesis interprets this high productivity as evidence that field conditions strongly supported tuber formation and filling. Because the comparison involves an experimental conversion and a varietal reference value rather than a side-by-side commercial benchmark, the most appropriate journal interpretation is that the season demonstrated high yield potential under the tested conditions, not that the amendment will necessarily increase every farm field to the same hectare-level yield.

Silicon, plant vigor, and the late-blight response

The late-blight results are among the most important findings because they connect soil amendment with crop health. Disease intensity increased with crop age in every treatment, but the formulation treatments separated clearly at several observation dates. At 35 HST the control already showed 5.8% intensity while A1, A2, and A3 were at or near zero. By 63 HST, the control had reached 19.1%, whereas A3 was only 7.1%. The contrast remained evident during the rapid epidemic phase: at 70 HST A0 reached 66.7% and A3 46.2%, and at 77 HST A0 reached 76.9% compared with 60.9% in A3.

These data indicate suppression rather than complete disease control. The steep increase between 63 and 70 HST in all treatments shows that the pathogen eventually encountered conditions favorable for epidemic development. This is consistent with the thesis discussion of P. infestans as a pathogen favored by cool temperatures, high relative humidity, rainfall, and prolonged leaf wetness. Fry (2008) is used in the thesis to emphasize that environmental conditions and inoculum availability can dominate epidemic behavior. Consequently, a soil amendment should not be presented as a substitute for integrated disease management when disease pressure becomes high.

Silicon provides one plausible component of the observed formulation effect. The Sinabung ash used in the study contained 26.74% SiO_2, and rice husk is also described in the thesis as a silica-rich organic residue. Silicon taken up by plants can be deposited in epidermal tissues and contribute to a stronger physical barrier. Xue et al. (2021), cited in the thesis, reported that silicon can enhance potato resistance to P. infestans through defense-related signaling pathways. The thesis further discusses increased lignification, phenolic compounds, and antioxidant activity as mechanisms through which silicon may reduce tissue damage and slow pathogen development.

The disease response is unlikely to be explained by silicon alone. Better nutritional status can improve plant vigor and the capacity to replace or maintain functional tissue during infection. Balanced K, Ca, and Mg support membrane stability, osmotic regulation, photosynthesis, and structural integrity. Organic matter can improve root-zone water relations and nutrient retention, indirectly reducing nutritional stress. The lower disease intensity in A3 therefore probably reflects an integrated plant-health effect in which silicon, mineral nutrition, and improved soil condition operate together rather than a direct fungicidal action of volcanic ash.

This distinction is supported by the nonsignificant effects of timing and the A × B interaction on late-blight intensity. If the amendment acted primarily as a direct toxicant against the pathogen, stronger and more consistent timing-dependent responses might be expected. Instead, formulation composition was the significant factor, while the exact application date within the tested window did not consistently change disease intensity. The thesis explicitly notes that volcanic ash is primarily a soil and nutrient amendment and should not be interpreted as a direct pathogen-control product.

The late-season disease pattern also suggests an important agronomic trade-off. The amendment delayed or reduced disease development relative to the control, thereby helping preserve canopy function during a period when tuber filling was still important. Even a partial delay can be valuable if it maintains photosynthetic leaf area during critical stages. At the same time, the remaining disease intensity above 60% at 77 HST shows that additional management remains necessary. In practice, the amendment should be positioned as one component of an integrated strategy involving healthy seed, field sanitation, resistant or tolerant varieties where available, disease monitoring, and judicious fungicide use according to local recommendations.

Future disease-focused trials should quantify weather conditions alongside disease progression. The thesis observations were made every seven days from 35 to 77 HST, providing a useful epidemic curve, but interpretation would be strengthened by concurrent measurements of rainfall, relative humidity, temperature, and leaf-wetness duration. Measuring silicon in plant tissue would also help establish whether the lower disease intensity in A3 was associated with greater Si uptake. Such measurements would allow the proposed soil–silicon–defense pathway to be tested directly rather than inferred from ash chemistry and disease outcomes.

Soil-fertility mechanisms in a volcanic highland soil

The before-and-after soil analysis offers an important bridge between amendment chemistry and crop response. Organic C increased from 3.89 to 3.95%, total N from 0.44 to 0.49%, Bray-I P from 25.80 to 26.02 ppm, and exchangeable K from 1.60 to 2.09 me/100 g. Because the experiment lasted only one growing season and the measurements represent the field before and after the treatment period, the changes should be interpreted as evidence of improved nutrient status rather than as a complete mass balance. Nevertheless, all four indicators moved in a favorable direction while a nutrient-demanding crop was being grown.

The relatively small increase in organic C is agronomically reasonable over a single season. Chicken manure and rice husk introduce organic carbon, but part of that carbon is mineralized by microorganisms and part is incorporated into more stable soil organic matter. Diacono and Montemurro (2010) are cited in the thesis to explain that repeated organic amendment can gradually build or maintain soil carbon over longer periods. The present result therefore demonstrates short-term maintenance and slight improvement rather than a claim of rapid, large-scale carbon sequestration.

The thesis places the organic-C response in the context of Andisol mineralogy. Volcanic soils commonly contain non-crystalline minerals such as allophane and imogolite, whose reactive surfaces can interact strongly with organic matter. Shoji et al. (1993), Nanzyo et al. (1993), and Dahlgren et al. (2004) describe the formation of organo-mineral associations that can stabilize humus and create variable-charge surfaces. These interactions are important because stabilized organic matter contributes negatively charged functional groups that retain nutrient cations and reduce their susceptibility to leaching.

The increase in total N is consistent with the composition of chicken manure and the protective role of organic matter. The manure contained 3.13% N, creating a direct organic-N input. During decomposition, a portion of this N can be mineralized and become available to plants, while another portion remains in organic forms. The thesis notes that allophane–humus complexes may help retain organic N and moderate its release. Thus, the final increase from 0.44 to 0.49% occurred despite simultaneous crop N uptake, indicating that the amendment contributed to the soil N reservoir.

Phosphorus behaved differently because volcanic soils can have high P sorption. The small increase in Bray-I P does not necessarily imply a weak P contribution from the amendment. Reactive Al- and Fe-bearing surfaces can adsorb phosphate, while crop uptake removes P from the soil solution. Nanzyo et al. (1993) are used in the thesis to explain the strong phosphate retention typical of volcanic soils. Organic matter can partly compete for sorption sites or complex reactive metals, but the balance among P input, sorption, and plant uptake can still result in only modest changes in extractable P over one season. Exchangeable K showed the largest proportional increase, about 30.6%, and this result is central to the agronomic interpretation. Volcanic ash contains K-bearing primary minerals that release K gradually through weathering. At the same time, organic-matter-derived exchange sites help retain K^+ in the soil. The combined amendment therefore couples a mineral source with a retention mechanism. This complementary process is consistent with the higher tuber number, production weight, and diameter observed in A3, because potato has a substantial K requirement during translocation and tuber filling.

Calcium and magnesium were measured in the ash but were not included in the final before-and-after soil table. Their presence remains relevant to the broader mechanism because both elements can contribute to nutrient balance and plant structural function. However, the article should distinguish between measured ash composition and measured soil change: the experiment demonstrates that the ash contained Ca and Mg, but it does not quantify the final change in soil exchangeable Ca and Mg. This boundary is important for maintaining a direct connection between the thesis data and the interpretation.

The soil results also support the rationale for mixing ash with organic materials rather than applying a mineral amendment alone. Volcanic ash can contribute mineral nutrients, but its weathering is gradual and newly released cations may be lost if soil retention is poor. Organic matter contributes exchange capacity, water-holding ability, microbial substrate, and physical aggregation. Rice husk adds a porous structural component, while chicken manure contributes nutrients and readily decomposable organic matter. The A3 formulation combines these functions and therefore has a stronger theoretical basis for improving nutrient-use efficiency than any single component by itself.

Local-resource value, limitations, and directions for validation

The study has particular relevance to the Karo Highlands because the major materials investigated are locally connected to the production system. Sinabung ash is generated by regional volcanic activity, while rice husk and chicken manure are agricultural by-products that can be sourced from farming systems. Turning these materials into an ameliorant creates a resource-recovery pathway: a disruptive volcanic deposit and organic residues are combined to improve soil conditions for a high-value horticultural crop. The approach therefore has potential environmental value in addition to the measured agronomic response.

Local availability, however, does not automatically guarantee safe or economical use. Volcanic ash can vary in particle size and chemical composition among eruptions and collection sites. The ash in this experiment was sieved and chemically characterized before use, and the measured elements were K, Ca, Mg, Fe, and silica. Farm-scale implementation should preserve this principle of characterization because recommendations based on one ash source cannot automatically be transferred to all deposits. Handling fine ash also requires practical attention to dust exposure during transport, mixing, and application.

The organic materials likewise vary in quality. Chicken manure nutrient content depends on feed, bedding, moisture, storage, and degree of decomposition, while rice husk characteristics depend on whether it is fresh, composted, or burned. The thesis used specific analyzed materials with organic-C and nutrient values reported in Table 3 of this article. For replication, farmers and researchers should recognize that the same percentage mixture may deliver different actual nutrient amounts if raw-material quality differs. This variability is one reason why field validation should include basic chemical analysis of each batch.

The experiment tested one total amendment rate, 5 t ha−1, across three amended formulations. It therefore identifies a promising composition but does not define the dose-response curve. A lower rate might provide similar benefits at lower cost, whereas a higher rate might improve soil properties further or create nutrient imbalance. The thesis consequently recommends testing a wider range of doses and combinations, including integration with organic and inorganic fertilization. Such experiments should distinguish the contribution of volcanic ash from the contribution of the organic components more explicitly.

A further limitation is the single-season and single-location design. The trial was conducted from August to November 2025 in Surbakti Village at approximately 1,250 m above sea level using Granola potato. Soil moisture, rainfall distribution, disease pressure, and temperature can differ substantially among seasons and locations in the Karo Highlands. Repeating the experiment would show whether the A3 advantage is stable across environmental variation and whether repeated amendment application produces cumulative effects on soil organic matter, pH, nutrient availability, or disease response.

Economic analysis is also necessary before recommendation beyond experimental plots. The thesis demonstrates agronomic potential but does not provide a full cost-benefit calculation. A practical assessment should include ash collection and transport, sieving, mixing labor, manure and rice-husk costs, application labor, changes in conventional fertilizer requirements, possible changes in fungicide use, and the value of additional marketable yield. The most agronomically effective treatment will only be attractive to farmers if the additional revenue and input savings exceed these costs under realistic local prices.

The disease-management implications require similar caution. A3 lowered disease intensity but did not prevent the late-season epidemic. Therefore, future validation should compare the amendment within an integrated disease-management program rather than as a standalone replacement for fungicides. Factorial trials could combine A3 with reduced or optimized fungicide schedules, resistant varieties, or biological-control components. Such designs would determine whether improved soil and plant nutrition can reduce chemical dependency without exposing farmers to unacceptable late-blight risk.

Additional measurements would also clarify mechanism. The thesis recommends broader evaluation of soil and plant responses; useful variables include soil pH, cation-exchange capacity, bulk density, water retention, microbial biomass, available silicon, plant-tissue nutrient concentrations, and plant-tissue Si. Tracking these indicators through time would reveal whether the yield response is driven primarily by nutrient supply, improved soil physical properties, silicon-mediated stress resistance, or a combination of mechanisms. This mechanistic information would make subsequent recommendations more transferable across sites.

Despite these limitations, the consistency of the A3 response across multiple independent variables gives the treatment practical credibility for further testing. A3 improved the main-effect means of height, leaf number, stem diameter, tuber number, production weight, and tuber diameter, while also producing the lowest disease intensity among formulations at important late-season dates. The final soil analysis moved in the same direction, with increases in organic C, total N, available P, and exchangeable K. This convergence across plant, disease, and soil indicators is the strongest evidence supporting A3 as the priority formulation for larger validation trials.

Comparative performance of A1, A2, and A3 formulations

The three amended formulations allow the role of mixture composition to be considered more closely. A1 combined 60% volcanic ash with 40% rice husk, A2 combined 60% volcanic ash with 40% chicken manure, and A3 reduced the ash fraction to 40% while adding both rice husk and chicken manure at 30% each. All three were applied at the same total rate of 5 t ha−1. Consequently, differences among A1, A2, and A3 reflect the relative contribution of the organic components and their interaction with the ash rather than a difference in total amendment mass.

A1 consistently improved performance over the control, demonstrating that ash plus rice husk can create a useful amendment even without manure. At 60 HST A1 reached 64.9 cm in height and 56.9 leaves, and it produced

12.2 tubers per plant with a mean tuber diameter of 10.4 cm. Rice husk has relatively low N, P, and K in the chemical analysis, but its high organic C content, porous structure, and silica contribution can improve the root environment. The A1 response therefore supports a physical and mineral-conditioning role in addition to direct nutrient supply.

A2 also performed better than the control and tended to exceed A1 in several yield-related traits. Its 60-HST height was 65.9 cm, leaf number 58.1, tuber number 12.4, production weight 1.2 kg, and tuber diameter 10.9 cm. The higher nutrient concentration of chicken manure provides a logical explanation for this pattern. With 3.13% total N, 1.35% P2O5, and 4.26% K2O, the manure fraction contributes nutrients that complement the slow-release mineral source represented by volcanic ash.

A3 achieved the most consistent overall response despite containing a smaller proportional ash fraction than A1 and A2. This is important because it suggests that simply maximizing the amount of ash within the fixed 5 t ha−1 rate was not the determining factor. Instead, combining ash with two organic materials created a more balanced amendment. A3 had the highest means for all major growth and yield variables and the lowest late-blight intensity at the important late-season observations. The result supports the thesis proposition that mineral and organic components can act complementarily.

The A3 advantage can be interpreted as functional diversification within the amendment. Chicken manure supplies nutrient-rich and relatively decomposable organic matter; rice husk provides persistent structural carbon, porosity, and additional silicon; and volcanic ash contributes mineral nutrients and silicate material. These components operate through different processes and potentially over different time scales. Their combination may therefore buffer the crop against limitations that would remain when only one organic component is paired with ash.

The comparison also shows why statistical grouping is important. For some variables, A3 had the numerically greatest mean but was not significantly different from A1 or A2. For example, tuber number was 12.7 in A3, 12.4 in A2, and 12.2 in A1, and the three amended treatments shared the same statistical group. This means that all amended formulations were effective relative to the control for that trait. The value of A3 emerges not from dominating every individual comparison, but from its repeated high ranking across a broad set of variables.

Table 12. Cross-variable summary of the main formulation responses

Variable	A0 Control	A1 Ash + husk	A2 Ash + manure	A3 Ash + husk + manure
Plant height, 60 HST (cm)	61.2	64.9	65.9	66.8
Leaves, 60 HST (no.)	53.7	56.9	58.1	59.3
Stem diameter, 60 HST (mm)	20.5	21.7	21.8	22.5
Tubers plant−1	10.5	12.2	12.4	12.7
Production weight (kg)	0.9	1.0	1.2	1.4
Tuber diameter (cm)	7.5	10.4	10.9	12.1
Late blight, 77 HST (%)	76.9	65.3	64.9	60.9

This summary reproduces the formulation main-effect means reported in the thesis tables; statistical significance differs among variables and should be interpreted from the corresponding detailed tables.

Interpretation of statistical evidence and response consistency

The experiment was analyzed as a two-factor randomized complete block design with three replications, using analysis of variance at the 5% level and DMRT for mean separation as reported in the thesis. This structure is appropriate for distinguishing the main effect of formulation, the main effect of application timing, and the formulation × timing interaction. The results show that formulation was the most consistently significant source of variation, while timing was significant for selected traits and the interaction was concentrated mainly in plant height and leaf number.

This pattern has a practical implication. A strong main formulation effect means that differences among A0–A3 were relatively stable across the tested application dates. For tuber number, production weight, tuber diameter, and late-blight intensity, the interaction was not significant. Accordingly, the agronomic advantage of an amended formulation does not depend on one narrowly defined date within the tested window. This improves the feasibility of farm use because growers may have some flexibility in scheduling application around land preparation and planting operations.

Conversely, the significant interaction for plant height and leaf number indicates that early vegetative growth was more sensitive to the alignment between formulation and application time. Such interactions are biologically plausible because early root development occurs while mineral weathering and organic decomposition are still changing the nutrient environment. The highest height and leaf values therefore appeared in different A3 timing combinations at different observation dates rather than following one fixed pattern throughout the season.

The statistical results should also be distinguished from numerical trends. Several nonsignificant interactions still showed combinations with high means, such as A3B1 for tuber number and production weight. These combinations are useful for generating recommendations for further testing, but the absence of a significant interaction means the experiment does not establish that their superiority is reproducible beyond the observed means. The article therefore treats A3 and B1 as strong main-effect directions and A3B1 as a promising field combination rather than making a stronger causal claim than the thesis supports.

Response consistency across multiple endpoints strengthens the agronomic interpretation. A3 ranked highest for growth, yield components, and soil-linked performance while ranking lowest for disease intensity. Independent variables can be influenced by different sources of measurement variation; when several of them shift coherently in the same treatment, the probability that the overall pattern reflects a meaningful biological response is greater than when only one trait changes. This cross-variable coherence is a central strength of the field experiment.

At the same time, one season and three blocks provide limited information about year-to-year and landscape-scale variability. Statistical significance within this trial describes the evidence under the specific Surbakti conditions of August–November 2025. It should not be interpreted as proof that the same effect magnitude will occur in every Karo field. Replication across seasons, soil positions, farms, and ash batches is necessary to estimate treatment-by-environment interactions and to build a recommendation with a wider domain of validity.

CONCLUSION

Sinabung volcanic ash combined with organic materials improved potato growth and production under the conditions of the Karo Highland field experiment. The formulation effect was significant for plant height, leaf number, stem diameter, tuber number, total production weight, tuber diameter, and late-blight intensity. The A3 formulation (40% volcanic ash + 30% rice husk + 30% chicken manure at a total rate of 5 t ha^{-1}) produced the most consistently favorable agronomic response and the lowest disease intensity among the formulation treatments at key late-season observations.

Application timing significantly influenced several growth and yield variables, with one-week pre-plant application (B1) particularly favorable for tuber number, production weight, and tuber diameter. Formulation × timing interactions were more limited and were most evident for plant height and leaf number. Therefore, formulation composition was the more robust determinant of overall response, while timing refined specific growth and yield outcomes.

Soil organic C, total N, Bray-I P, and exchangeable K all increased after treatment, with the largest proportional change observed for exchangeable K. These changes support the interpretation that volcanic ash and organic matter acted complementarily as a mineral source and a soil-conditioning system. The study therefore supports further development of Sinabung volcanic ash–organic formulations as a locally based amelioration strategy for potato production. Additional multi-season, multi-location, dose-response, and economic studies are recommended before broad farm-scale adoption.

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