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Optimizing Agronomic Technology Package for Soil Fertility and Crop Yield Restoration on the Affected Area of Sinabung Volcano Eruption, Indonesia

Abstract

The effusive Sinabung Volcano eruption resulting a large negative impact on agricultural land, causing soil acidification and nutrient imbalances, reducing crop productivity and leading to the declining farmers' income. This study was conducted on the affected area to determine a proper agronomic technology package, to assess changes in soil fertility, potato yield and quality, and to calculate the economic profit of the tested-packages. This study was laid out in a completely randomized design with five agronomic technology packages, combining organic and inorganic fertilizer, lime and sawdust. The result revealed that Package C, applying 20 t manure + 5 t sawdust + 2 t dolomite + 500 kg NPK + 100 kg Urea + 100 KCl per hectare, significantly improved soil fertility, increasing soil pH from 4.5 to 5.3 and enhancing Cation Exchange Capacity and water retention. This package also produced the highest potato yield (39.81 t/ha), which is statistically significant difference with other packages and has the best-quality tubers (grade A to C). Economically, Package C received the highest net benefit and benefit-cost ratio per hectare, by US $ 12.017.4 and 2.70, respectively. In contrast, the farmers' practices (Package E) resulted in lower yield, a decline in tuber quality and reduced economic income. These findings demonstrate that the integrated agronomic technology packages, particularly Package C, offer a sustainable and profitable solution for restoring soil fertility and enhancing crop production on the volcanic-affected areas. The study provides some actionable recommendations for farmers and policymakers to support agricultural recovery and resilience in the face of natural disasters.

Keywords:
volcano eruption, sawdust, soil fertility, potato, agronomic technology package, economic feasibility

Imelda Suryani Marpaung[1], Deddy Romulo Siagian[2]*, Delima Napitupulu[1], Palmarum Nainggolan[1], Amelia Sebayang[1], Sortha Simatupang[1], Perdinanta Sembiring[1], Novia Chairuman[2], Tulus Fernando Silitonga[3], Lermansius Haloho[4], Tumpal Sipahutar[4], Sarman Paul Lumbantobing[4]

1) Research Center for Horticultural Crops, Research Organization for Agricultural and Food, the National Research and Innovation Agency of the Republic of Indonesia, Cibinong-Bogor, West Java, Indonesia

2) Research Center for Food Crops, Research Organization for Agricultural and Food, the National Research and Innovation Agency of the Republic of Indonesia, Cibinong-Bogor, West Java, Indonesia

3) Research Center for Estate Crops, Research Organization for Agricultural and Food, the National Research and Innovation Agency of the Republic of Indonesia, Cibinong-Bogor, West Java, Indonesia

4) Research Center for Cooperative, Corporation and People's Economy, Research Organization for Governance, Economy and Community Welfare, the National Research and Innovation Agency of the Republic of Indonesia, South Jakarta, Indonesia

*Corresponding author email: dedd006@brin.go.id

Deddy Romulo Siagian
https://orcid.org/0000-0001-7721-5032

Imelda Suryani Marpaung
https://orcid.org/0000-0002-8202-3243

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1 Introduction

As one of the worst natural disasters, volcanic eruptions cause negative impacts on ecosystems, infrastructure and human livelihoods (Briffa et al., 2020; Carrillo and Díaz-Villanueva, 2021). Similarly, Sinabung Volcano eruption which is located in Karo Regency, North Sumatera Province in Indonesia (Carr et al., 2022; Sullivan and Sagala, 2020), directly affects the agricultural sector through its lava and heavy ashfall. Some consequences resulting from this eruption are led to extensive soil degradation, changes in soil pH, loss and imbalances of soil essential nutrients and physical alteration in soil fertility (Fiantis, 2019). These consequences continuing give impacts on the local farmers, reducing their crop yield and quality (Rozaki et al., 2022; Shoji and Takahashi, 2002) and surely threatening food security in Karo Regency. Thus, the implementation of innovative and well-designed agronomic technology is essential to accelerate sustainable soil fertility and agricultural production.

Reaching sustainable soil fertility after an eruption is very complicated and difficult due to both chemical and physical soil properties being degraded by volcanic ash (Mihai et al., 2023). Although volcanic ash is rich in minerals (Delmelle et al., 2015; Vogel, 2017), unfortunately, in the short term, these minerals create acidic soil that restricts nutrient availability and plant growth (Anda et al., 2016; Hue, 2022). Additionally, the eruption's impact on soil physical properties, like high bulk density and low water retention, restricts agricultural productivity (Anda et al., 2016). Undoubtedly, recovering soil fertility takes much time through the natural process and it will lead to prolonged agricultural losses. Hence, implementing certain technologies can accelerate the recovery of affected agricultural land.

Combining some agronomic technologies, called agronomic technology packages, refers to a set of scientifically developed agricultural practices and inputs which is implemented for a specific environmental condition. It is one of the promising approaches to solve soil degradation and increase crop production in agricultural land due to volcanic eruption. Organic amendments, chemical fertilizers and lime need to be applied together to achieve optimal results in soil health (Lentz et al., 2019; Tya and Bappa, 2024). Manure and sawdust, as organic amendments, have the ability to improve soil structure and texture (Lentz et al., 2019; Tya and Bappa, 2024), water holding capacity (Shaheen and Turaib Ali Bukhari, 2018), bulk density and permeability (Tya and Bappa, 2024), and microbial activity (Kazeem et al., 2024). While, lime (dolomite) helps in neutralizing soil pH and increasing nutrients availability (du Toit et al., 2022; Mahmud and Chong, 2022). The addition of chemical fertilizers plays an important role in soil chemical fertility management, especially in volcanic-affected areas. These fertilizers will provide soil nutrients (nitrogen, phosphorus and potassium) and encourage crops to grow better at the vegetative and generative phases.

A few studies have investigated the volcanic eruption impact on soil degradation and crop production and quality. Thus, this research aims to determine the most appropriate technology packages to solve the issues. Moreover, this research also evaluates the effect of different combinations of organic amendments, lime and chemical fertilizers on soil chemical and physical properties and crop yield together with its harvest quality. For the last goal, this research counts the economic feasibility by evaluating the contribution of each package to farmers' income. The field trial outputs in this research serve as an important input for farmers, extension services, local farming groups, researchers and local government to generate a comprehensive strategy for agricultural reconstruction.

2 Materials and methods

2.1 Study area

The study was conducted in Kutarayat Village, Naman Teran District, Karo Regency. It is about 4-5 km from the peak of the Sinabung Volcano eruption, and located on the highland, about 1,300 m above sea level. Karo Regency has diverse topography, placed 90 – 2,440 m above sea level and covered by Andisols soil (Qadaryanty et al., 2020; Sembiring and Fauzi, 2017). Supporting by its climatic and biophysical

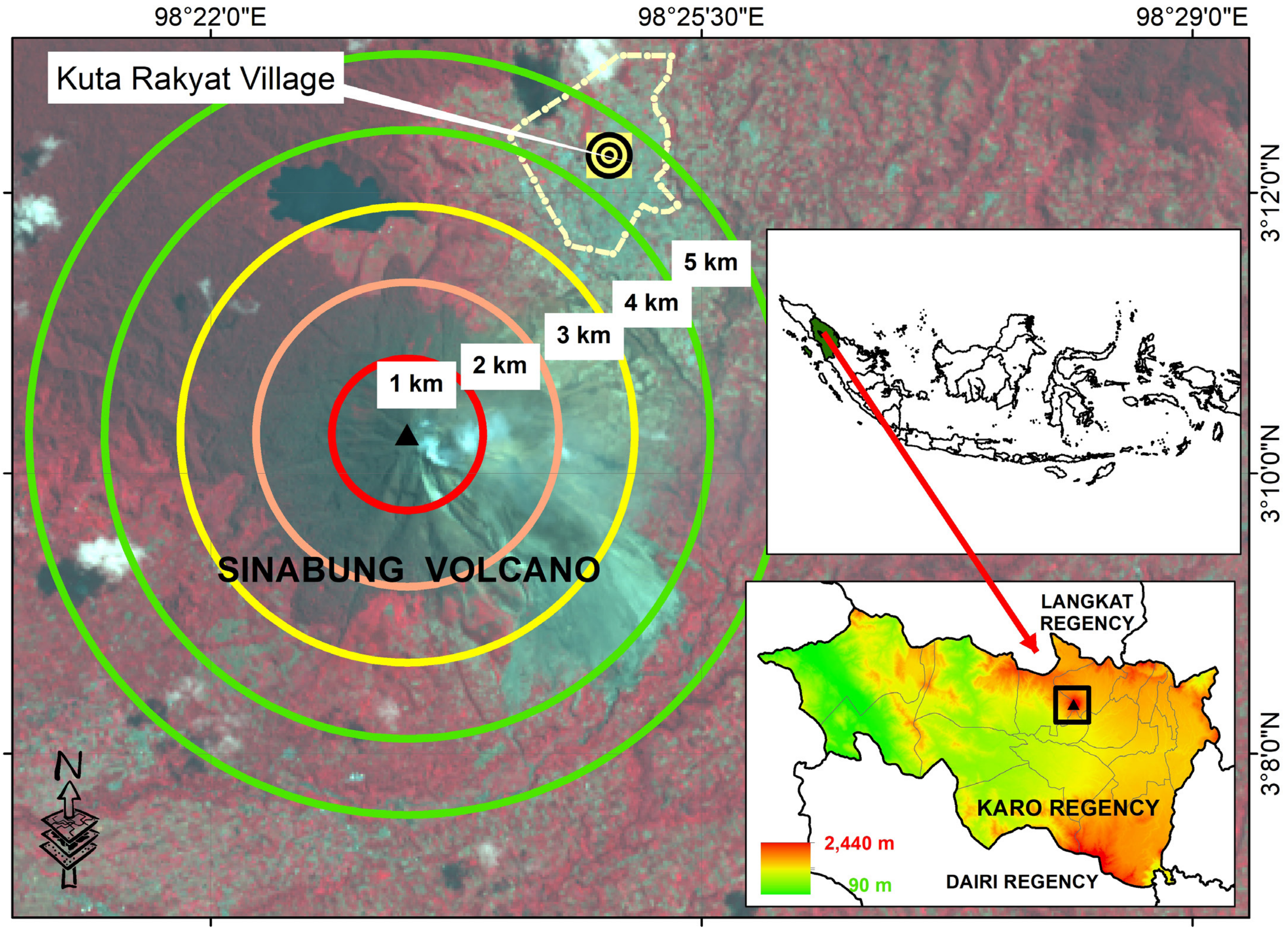

Figure 1. The area of study location.

conditions, this regency is known by its horticultural commodities (fruits, flowers and vegetables). As one of horticultural commodities, potato is widely cultivated-crop and provides significant profits for farmers in Karo Regency (Statistical Institution of Karo Regency, 2022). Besides of its highly selling price due to its high market demand, potato also rich in calories, protein and vitamins, and categorized as durable commodity (Rachman et al., 2021). The details of the study area can be observed in Figure 1.

2.2 Experimental design and treatments

Field trials were conducted on the affected area of the volcano eruption (30 12‘ 24“ N, 980 25‘ 4“ E). The applied experimental design was a randomized block design with five treatments (Package A, B, C, D and E) and five replications. These treatments, agronomic technology packages, were differentiated by the type and quantity of organic and inorganic fertilizers and the dosage of lime application. In terms of Packages A and B treatments, the study compared the output which is influenced by the implementation of high and moderate levels of the compound fertilizer (NPK). At the same time, this study needs to investigate and compare the Package D output, which has reduced inputs, with the other packages. In line with the treatment, Package D is hypothesized to have the smallest cost compared to the other. Among the treatments, the study implemented sawdust in Package C to test whether the sawdust's unique physical properties could complement manure and lime combinations, rather than as an independent variable. In addition, the study needs to investigate the Package C's role as the optimized treatment integrating all locally viable amendments (manure, lime, sawdust and reduced-NPK). Then, all the agronomic technologies for Package E specifically belong to the farmer‘s behavior, which is used

Table 1. The agronomic technologies implemented at the treatments.

Agronomic technology	**Treatment**				
	Package A	Package B	Package C	Package D	Package E
NPK (kg/ha)	750	500	500	250	250
Urea (kg/ha)	200	200	100	100	100
KCl (kg/ha)	200	200	100	100	100
Lime (t/ha)	4	4	2	2	-
Manure (t/ha)	30	30	20	20	10
Sawdust (t/ha)	-	-	5	-	-

as the control for the conventional method. The detailed five treatments can be observed in Table 1.

Land preparation was carried out before seeding the potato tubers (Granola variety), which have 1-2 cm of sprout, by clearing and tilling the soil. Each size of the treatment plot was arranged by 8 x 6 m2, and then spread the dolomite lime according to the dosage of treatment packages. For the sowing distance, this study planted the potato tubers by spacing 80 x 30 cm2; thus, there are 200 numbers of planting holes in each plot. Then, the ripe manure was applied to all the packages in the planting hole but with different dosages. The ripe manure was generated from the chicken manure, sourced from chicken husbandry, which is composted for 1-2 months. The composting is important to reduce the odor and the harmful pathogens and to stabilize the nutrients availability. This chicken manure was chosen due to its easy accessibility and consistent use by farmers. Meanwhile, the sawdust was collected from the local timber mills by removing the large debris, leaving only those measure < 1 mm. Then, the sawdust was added for Package C only by covering the top of planting hole, which is acted as a mulch. The implementation of sawdust coincided with the application of the ripe manure. In terms of Package E, all the agronomic technologies are given except dolomite lime and sawdust.

Implementation of inorganic fertilizer was started by applying compound fertilizer of nitrogen (N), phosphorus (P) and potassium (K) (16:16:16) before seedling the potato tubers. The weeding and hoarding were performed twice in one planting season, which is applied at 50 DAP (day after planting) and 65 DAP. The application of Urea and KCl fertilizers was spread at a similar time with the first weeding by giving accordingly to each package. Watering is important to support the vegetative growth, starting from planting the potato tubers until reaching 70 DAP. Last, the pest and disease outbreaks were very important to be observed and controlled by spraying insecticide and fungicide to the infected plant.

2.3 Soil sampling analysis

The soil samples were collected before and after the research conducted from each treatment plot. It was analyzed to observe the differences in soil physical and chemical fertility influenced by these treatments. These composite soil samples were taken from five points diagonally around the experimental location. A total of 500 g of soil is taken from each point which is collected from ≤50 cm from the soil surface. The depth of soil sample was also considered the volcanic ash which is covered the agricultural land up to 20 cm (Figure 2 (b)). Some of soil chemical and physical parameters are Soil Acidity (pH) by pH meter, Organic Carbon (C-org) by the walkey and black method, Potassium (K) by atomic absorption spectrophotometric (AAS) method, Calcium (Ca) by AAS method, Magnesium (Mg) by AAS method, Manganese (Mn) by AAS method, Copper (Cu) by AAS method, Cation Exchange Capacity (CEC) by AAS method, Soil Texture by hydrometer method, Bulk Density (BD) by rings sample method, Permeability by double-ring infiltrometer method and Soil Water Content (SWC) by gravimetric water content method.

2.4 Data collection

This study collected data on soil fertility, physiological growth, and yield crop parameters. For the soil fertility, the characteristics of soil were gathered from the soil samples which is analyzed before and after the experiment was conducted. All soil parameters are listed in Section 2.3. While some of the physiological growth and yield crop parameters are the height of potato plant (cm), number of stems (stems), tuber weight per plant (g), number of tubers per plant (tubers), and tuber weight per ha (kg).

The data of physiological crop and yield parameters was measured from 10 plant samples per plot; and the number of stems and height were measured at 80 DAP. The height of plant was measured from the soil surface up to the highest growing point of plant. Meanwhile, the total number and weight of tubers data were collected by taking the average value of these parameters from 10 plant samples per plot during harvesting time. In addition, the observation of tuber quality was carried out by weighing the weight and counting the number of tubers per plant according to the criteria, namely, Class A (> 200 g/tuber); Class B (151-200 g/tuber); Class C (101-150 g/tuber); Class D (46-100 g/tuber); and Class E (<46 g/tuber).

Finally, the benefit cost ratio (BCR) was calculated to measure the economic benefit for every package. The data of kind, quantity, and price of input production (seed, manure, lime, chemical fertilizer, pesticide and saw dust) and together with the labors cost which is implemented for each package were gathered based on field-based data collection. In addition, data of total production and price of potato which is produced by each package were collected as well.

2.5 Statistical analysis and cost-benefit analysis

For statistical analysis, this study used SPSS software, version 17 (SPSS Inc., Chicago, II, USA). The Analysis of Variance (ANOVA) was performed to measure the significant difference between treatments and continue with Duncan's Multiple Range Test (at $p \leq 0.05$) to recognize the specific significant differences among treatments. While, the evaluation of economic value was measured by benefit cost ratio (BCR) analysis (Alam et al., 2021; Widodo et al., 2023), as follows :

$$\pi i = TRi - TC_i \quad and \quad B/Ci = \pi i / TCi$$

where:

∏i = farming profit i-th

TRi = total farming revenue i-th

TCi = total farming cost i-th

B/Ci = farming feasibility i-th

3 Results

Undoubtedly, the Sinabung Volcano eruption bring negative impacts in many sectors, such as physical and physiological health, economic status, social life, environmental condition, etc. (Sullivan and Sagala, 2020; Tampubolon, 2018). Wright et al. (2019) reported that ten villages were in the evacuation area and about 5,000 families or approximately 15,800 people were displaced since this natural disaster occurred. These impacts resulted from the volcanic ash and gasses that spouted during eruption and spread around Sinabung Volcano. As farming is the majority occupation of people who live around Sinabung Volcano, the volcanic ash causes enormous losses, especially in the agricultural sector. The ash covered the agricultural land, and the thickness depends on the wind direction during the eruption. Qadaryanty et al. (2020) stated that agricultural land with an ash thickness of > 5 cm has lower soil fertility compared

Figure 2. a) The damaged crop by volcanic ash of Sinabung Volcano eruption, b) The thickness of volcanic ash on the ground, c) The agricultural land was covered by the volcanic ash at study area.

to < 2 cm. Figure 2 illustrates the volcanic ash of Sinabung eruption impacts on the agricultural land, which is direct to crop production failures.

3.1 The transformation on soil fertility

The majority of affected agricultural land by Sinabung Volcano eruption was covered by lava, sand and ash by varying thicknesses. These materials needed to be cleaned, removed or cultivated before starting the planting time. Unfortunately, the materials that cover the agricultural land more than 50 cm will not be cultivated for a longer period. Most of the materials from this uncultivated land, such as rock, sand and ash, were mined to be changed into construction materials (Karolina et al., 2015). Tarigan (2019) stated that materials spouted during eruption change the chemical, physical and biological soil characteristics. The ashfall damaged the agroecosystem by burning the crops, generating the surface crust, lowering soil pH and affecting soil toxicity (Anda et al., 2016). Sukarman and Suparto (2015) analyzed some ash characteristics generated from Sinabung Volcano, i.e., has the loam texture, a very strongly acid (pH) and low nutrients content (Cation Exchange Capacity).

3.1.1. The change on soil chemical properties

At the initial level of the activity, it can be observed that soil chemical fertility in the site study area is at low level. Based on the criteria for soil chemical properties evaluation (Sadovski, 2019; Siswanto, 2006), soil with a pH of 4.5 (1:1 H2O) is classified at the strongly acid level. Some soil macro and micronutrients were analyzed as well and categorized in a very low (Ca and Mg), low (Cu and Mn), and moderate availability level (C-org, K and CEC) as follows in Figure 3.

After administering the treatment of agronomic technologies, some soil chemical properties are change for the better at the specific packages. The soil pH increased for all packages, except Package E (4.14), which ranges from 4.53 (Package D) to 5.43 (Package C). In term of soil organic carbon (SOC), the content for all packages were decreased range from 1.96 % (Package C) to 2.73 % (Package D). Package B has the highest potassium and calcium contents by 1.08 me/100 g and 13.80 me/100 g, respectively, while the lowest exist in Package D and Package E, by 0.89 me/100 g and 2.39 me/100 g, respectively. The agronomic technologies treatment delivers Package C contains the highest of magnesium content by 0.94 me/100 g, while the lowest is at Package D by 0.46

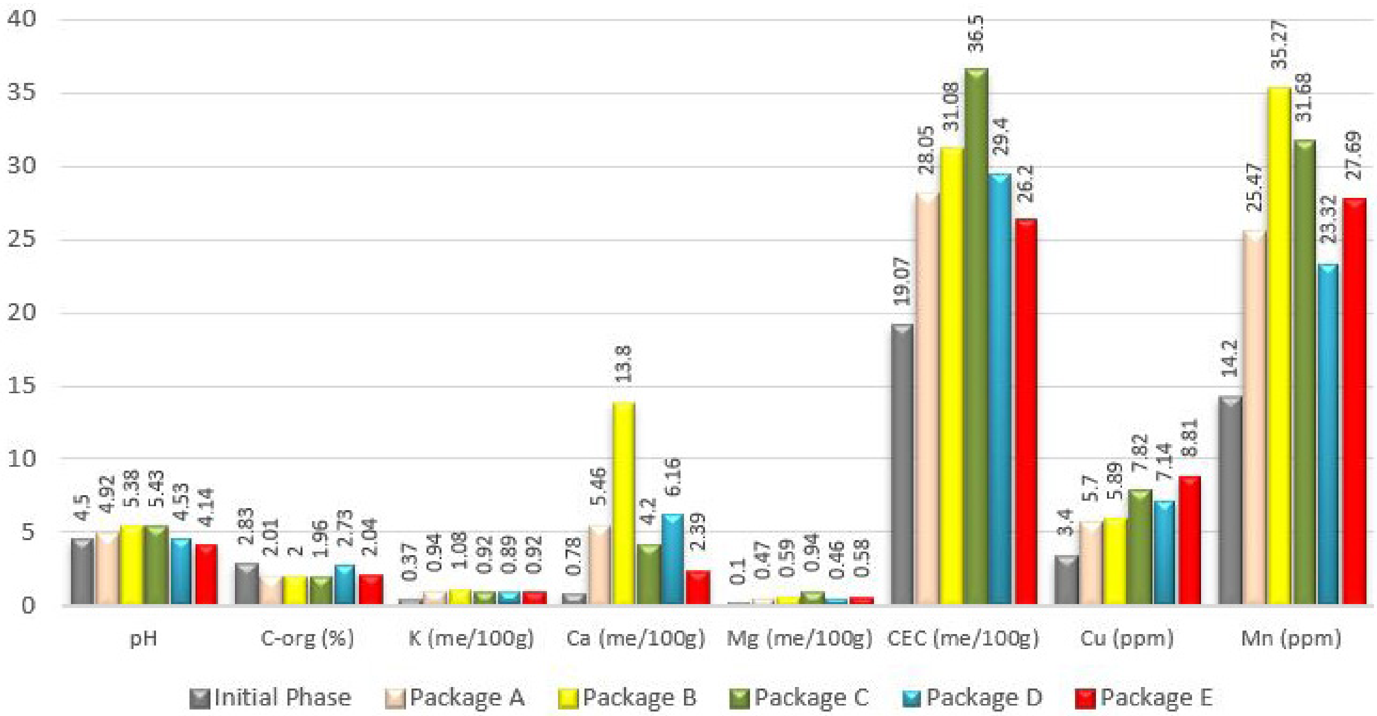

Figure 3. The changes in soil chemical properties after the treatment of agronomic technological packages.

me/100 g. Meanwhile, the increased of soil micro nutrients occurred at all packages, especially for the Package E (the farmer's behavior), bring the highest contents of copper and manganese by 8.81 ppm and 27.69 ppm, respectively. As the last important of soil parameter, cation exchange capacity, the agronomic technologies treatment of Package C and E get the highest and the lowest of CEC by 36.50 me/100 g and 26.20 me/100 g, respectively. The detail of chemical soil properties before and after treatments is presented in Figure 3.

3.1.2. The change on soil physical properties

The implementation of agronomic technologies has affected the soil physical properties as well. As presented in Figure 4, some soil physical properties such as soil texture, BD, permeability and SWC were analyzed in the soil laboratory. In the initial phase, the study area mostly covered by sand and followed by silt and clay by 64.0 %, 30.0 % and 6.0 %, respectively, which is classified as sandy loam. The value of BD, permeability and SWC were informed as well by 1.44 g/ml, 8.35 cm/hr and 15.0%, respectively. Similarly, some agronomic technologies which is implemented as the treatment in the field, bring a better result at the final stage in these soil physical properties. In terms of soil texture, the sand particles decreased for all packages, ranging from 37.75 % (Package A) to 42.22 % (Package B). Then, the silt particle increased for all packages as well, ranging from 48.49 % (Package B) to 57.19 % (Package C). Meanwhile, the clay percentage content of Package A and B increased slightly; and the rest decreased slightly. Thus, all of soil texture packages change from the initial condition, become silt loam and loam. Figure 4 also shows the transformation of soil BD and permeability. The value of BD was decreased which is ranges from 1.20 (Package C) to 1.38 (Package D). Likewise, the value of permeability was decreased which is ranges from 3.10 (Package D) to 6.68 (Package E). Lastly, in terms of the soil water content parameter, the values increase for all packages, ranging from 16.5 % (Package E) to 22.5 % (Package C).

3.2 The effect of agronomic technology packages on physiological growth and crop production

The results revealed that all parameters were significantly affected by the implementation of agronomic technologies as follows in Table 2. The Package C of agronomic technologies treatment derived the highest outputs for all parameters (height, number of stems, tubers weight/plant and tubers weight/ha), except the parameter of number of tuber/ plants. On the contrary, Package E (the farmers' technology behavior), bring the lowest output for all parameters, except the parameter of the number of tubers/ plants. In terms of the height parameter, Package

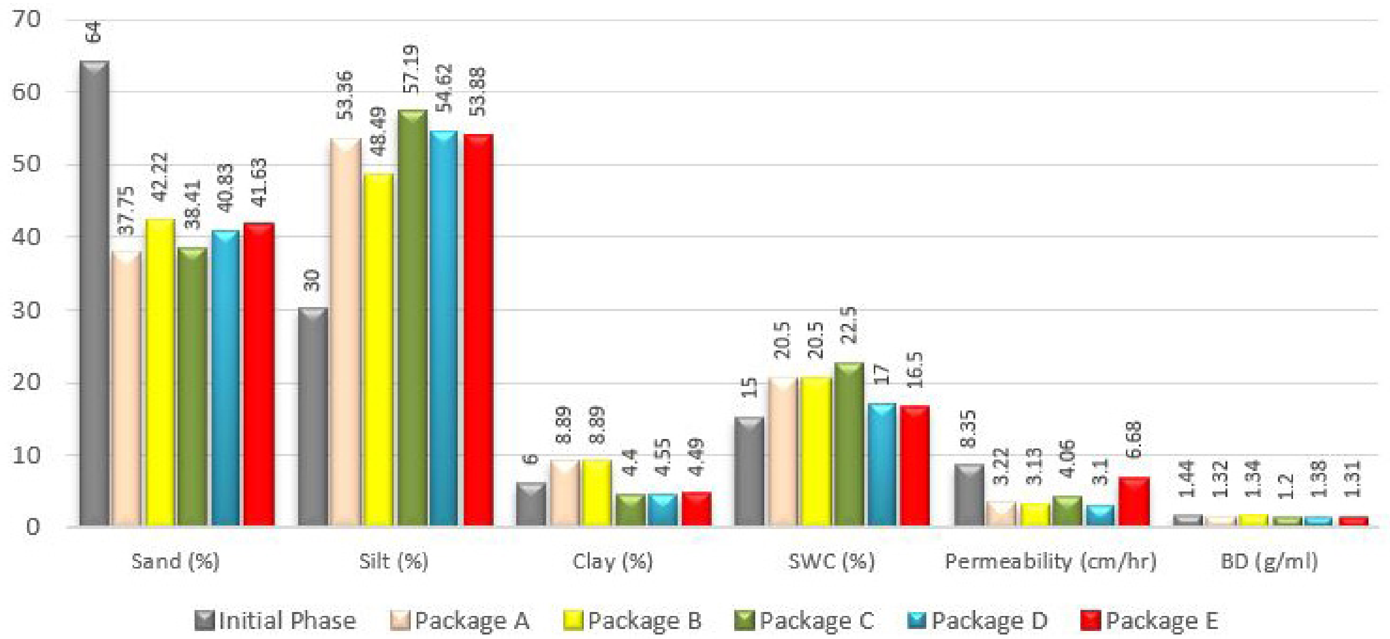

Figure 4. The changes in soil physical properties after the treatment of agronomic technological packages..

Table 2. The agronomic technologies implemented at the treatments.

Agronomic technology package	The parameter of physiological growth and potato production				
	Height (cm)	No. of Stems	Tuber Weight/ plant (g)	No. of Tuber/ plant	Tuber Weight/ha (t)
A	43.30 bc	3.88 a	1,158 ab	7.25 ab	34.40 c
B	42.64 abc	3.86 a	1,187 bc	6.95 a	33.08 bc
C	46.02 c	4.96 b	1,392 c	8.70 b	39.81 d
D	40.14 ab	3.82 a	1,020 ab	6.55 a	28.38 ab
E	39.30 a	3.80 a	950 a	10.70 c	23.79 a
Mean	42.28	4.06	1114	8.03	31.89

Note: means followed by a different letter within a column are significantly different at $p \leq 0.05$.

Table 3. The effect of agronomic technology packages on weight and number of tubers based on the potato quality.

Agronomic technology package	Weight of tuber / plant (g)					No. of tubers / plant				
	Grade A	Grade B	Grade C	Grade D	Grade E	Grade A	Grade B	Grade C	Grade D	Grade E
A	631.6 b	224.4 ab	142.4 a	107.1 a	36.8 a	2.2 bc	1.2 a	1.2 a	1.4 ab	1.3 a
B	622.1 b	236.8 abc	129.8 a	94.3 a	26.0 a	2.3 bc	1.3 a	1.3 a	1.3 ab	1.1 a
C	721.6 b	300.5 c	172.6 a	116.0 a	28.1 a	2.6 c	1.6 a	1.6 a	1.8 bc	0.9 a
D	550.8 b	194.5 a	139.9 a	70.4 a	26.8 a	2.0 b	1.1 a	1.2 a	1.0 a	1.2 a
E	309.2 a	265.9 bc	165.8 a	149.3 b	140.2 b	1.1 a	1.2 a	1.2 a	1.9 c	5.2 b

Note: means followed by a different letter within a column are significantly different at $p \leq 0.05$.

C gave the highest rate of potato crop and reached 46.02 cm, which is significant difference statistically with Package D and E, by 40.14 cm and 39.30 cm, respectively. The implementation of agronomic technologies in Package C brings the highest number of potato stems as well by 4.96 and provides significant difference with all treatments statistically. Similarly, Package C also gives the highest output in the parameter of tuber weight per hectare by 39.81 t/ha which is statistically significant difference with all packages. While, for the parameter of number of tubers per plant, Package E and D are the treatments that give the highest and the lowest outputs by 10.70 and 6.55 tubers per plant, respectively. The detailed output related to the effect of agronomic technologies treatment on physiological and potato production can be observed in Table 2.

The parameters of weight and number of tubers per plant based on the grade classification were measured as well to identify the quality of potato yield as influenced by agronomic technologies implementation. Table 3 shows that Package C resulting the highest weight of tuber per plant for grades A to C (> 100 g/tuber) by 721.6 g/plant, 300.5 g/plant and 172.6 g, respectively. Meanwhile, grades D and E (< 100 g/tuber) were delivered by Package E at 149.3 g/plant and 140.2 g/plant, respectively. A similar pattern of the result is also founded in parameter of number of tubers per plant, Package C gave the highest number of tubers for grade A to C by 2.6, 1.6 and 1.6, respectively. Then, Package E gave the lowest number by 1.9 and 5.2 for Package D and E, respectively. In addition, the implementation of agronomic technologies of Package C gives significantly different statistically for almost all parameters with Package E (the farmer's behavior) as follows in below table.

3.3 Income / financial

Based on the feasibility analysis, all tested-packages were feasible to develop because all BCR values were more than 1.00 (Alam et al., 2021; Widodo et al., 2023). This study informed that Package A spent the highest cost compared to the other packages, US $ 5,108.6, which is to provide input and labor; while Package E spent the lowest by US $ 3,596.6. Unfortunately, Package A did not provide the highest income although spent the highest cost for input production. On the other hand, Package C shares the highest income and benefit by US $ 16,474.3 and US $ 12,017.4, respectively. Then, this research stated that as the best agronomical technology package, Package C received double income compares farmers technology (Package E).

Table 4. Total income, cost and benefit-cost ratio per hectare from potato farming system based on agronomic technology package.

Component	Total expense of each agronomic technology package ($/ha)				
	A	B	C	D	E
A. Input production					
1. Seed	1,303.4	1,303.4	1,303.4	1,303.4	1,303.4
2. Manure	1,241.4	1,241.4	827.6	827.6	413.8
3. Lime	165.5	165.5	82.8	82.8	0
4. Chemical fertilizer	574.1	410.3	369	205.2	205.2
5. Pesticides	225.9	225.9	225.9	225.9	225.9
6. Saw dust	0	0	34.5	0	0
B. Labors	1,598.3	1,598.3	1,613.8	1,587.9	1,448.3
C. Total cost (C)	5,108.6	4,944.8	4,456.9	4,232.8	3,596.6
D. Total income	14,234.5	13,689.5	16,474.3	11,741.4	9,638.1
E. Benefit	9,125.9	8,744.7	12,017.4	7,508.6	6,041.5
B/C	1.79	1.77	2.70	1.77	1.68

4 Discussion

4.1 The enrichment of soil physical and chemical properties

Most of the soil parameters on the affected area of Sinabung volcanic eruption, chemical and physical properties, have improved by the application of agronomic technology packages although the extent of improvement varied across treatments. Determination of the kind and quantity of fertilizer, together with soil amendments, surely influences the outputs. The fertilizer dosage for Package E was determined by the common sum of the local farmers' application and the previous study (Agbede, 2010; Mancer et al., 2024). Meanwhile, the availability of soil nutrients has decreased in the affected area of the Sinabung eruption. Anda et al. (2016) and Nanzyo (2002) stated that the availability of P is decreased more due to fixation by ash-derived allophane, one of the nanocrystalline materials in Andisol. Additional issue reported by Grzebisz and Niewiadomska (2024) and Kunito et al. (2016) are that the low soil pH condition decreases nitrogen availability, which is influenced by the low quantity and supports microbial activity that plays a role in the nitrogen cycle. Hence, about 500-750 kg NPK was applied in this study to overcome the soil nutrients unavailability and support the potato growth, production and quality (Setiyo et al., 2018; Tulung et al., 2021).

As one of the soil chemical parameters, soil pH increases for all packages, except Package E. It indicates the effectiveness of lime (dolomite) in neutralizing soil acidity, especially for Package C which increases the soil pH from 4.50 to 5.43, at initial and final phase, respectively. In contrast with Package E, farmers' behavior treatment, to improve soil pH can be attributed to the absence of lime. This result is consistent with the previous studies (Castro and Crusciol, 2015; du Toit et al., 2022; Mahmud and Chong, 2022) that emphasize the advantage of lime (dolomit) to neutralize soil pH. Meanwhile, for the parameter of soil organic carbon (SOC), all packages showed a decrease in SOC with values ranging from 1.96% - 2.73%, at Package C and Package D, respectively. The decline of this SOC is due to the rapid mineralization of organic matter (manure) in the tropical climate. As Sierra et al. (2015) reported organic matter can decompose faster under warm and humid conditions.

In terms of macronutrient availability, all nutrients (K, Ca, and Mg) at the initial phase are categorized by very low to medium classes, then increase at the final phase by low to very high classes. Package B specifically, demonstrated the highest potassium (K) and calcium (Ca) likely due to the combination effect of manure and lime. Eckhardt et al. (2018) stated that manure is a rich source of potassium, while lime contributes to the calcium and magnesium nutrients availability. K uptake by crops, induced by lime, was facilitated by K+, Ca2+ and Al3+, with lime application increasing soil K availability (Han et al., 2019). Verde et al. (2013) showed that the application of lime resulted in increased levels of magnesium. However, Package C which include sawdust in the treatment, had the highest magnesium content (0.94 me/100 g), further emphasizing the role of lime in supplying the essential nutrients. Package E as representative of farmer's conventional practices, brings the micronutrients of Cu and Mn in the low levels to the medium level by 8.81 ppm and 27.69 ppm, respectively. It could be attributed to the lower pH in Package E itself, as acidic condition enhances the solubility and availability of micronutrients. However, the low pH in Package E also limits the availability of macronutrients, and it could be concluded that this specific package is not sustainable for overall soil health especially macro and micronutrient availability. For the last parameter, Package C achieved the highest CEC (36.50 me/100g), indicating improved soil fertility and nutrient-holding capacity. It can be related to the combined effect of manure, lime and sawdust, which enhanced soil's ability to create a resilient soil environment.

The improvement of soil fertility can be observed as well from soil physical parameters, such as soil texture, bulk density (BD), permeability and soil water content (SWC). The change in soil texture from sandy loam to silt loam and loam across the treatments indicate a significant improvement in soil structure. The reduction of sand content from 64.0% to 36.75% - 42.22% and the increase of silt content from 30% to 48.49% - 57.19% revealed that the addition of organic amendments (manure and sawdust) played a significant role in modifying soil texture. This process likely occurs because there were two hoarding steps during cultivation, which provides an opportunity for organic amendments to act as the major binding agent of soil particles, producing stable aggregates (Djajadi et al., 2012; Golchin et al., 2018). This process reduces the dominance of sand particles and increases the proportion of silt and clay, continuing to achieve a more balanced of soil texture. Peng et al. (2015) also examined that the application of organic matter, pig manure, changes the proportion of clay and silt fractions. Package C itself, showed the highest content of silt particles, likely due to the ability of sawdust to improve soil aggregation and reduced sand particle dominance. Sawdust, when properly composted, acts as a physical binding agent, enhancing the formation of silt and clay aggregates (Medina-Martinez et al., 2023; Tya and Bappa, 2024).

In terms of BD, the decreased in BD across all package treatments, ranging from 1.20 to 1.38 g/cm3, for Package C and D, respectively, which is indicates improved soil porosity and root penetration. The decrease of BD is primarily attributed to the organic amendments which have a role to promote the formation of pore spaces. Generating sponges in soil can reduce soil compaction and improve soil structure which is the main problem in soil-affected areas due to volcanic eruption. Again, Package C which included manure and sawdust, achieved the lowest BD, highlighting the synergistic effect of these amendments in enhancing soil porosity. Tahat et al. (2020) stated that the organic amendments improve soil respiration by 20-fold compared to the conventional farming. In line with the restoration from soil texture and BD, soil has more ability to absorb the water, which can be observed from the parameters of permeability and SWC. The decrease of permeability and the increase of SWC compared at the initial phase across all treatments reflects to the reduced water loss through leaching and improved water retention. One of the advantages of organic amendments, manure and sawdust is enhance soil water retention by increasing soil organic matter and improving soil soil structure. Organic matter plays a role as a reservoir for water, holding moisture in soil and making it available for plants (Bashir et al., 2021; Lentz et al., 2019). Undoubtedly, Package C which includes sawdust in the package, achieved the highest SWC by 22.5%, likely due to the ability of both manure and sawdust to improve soil aggregation and water-holding capacity and to ensure a more stable water supply for crops (Shaheen and Turaib Ali Bukhari, 2018).

4.2 The enhancement of crop physiological growth and crop production and quality

The implementation of agronomic technologies significantly influenced to the physiological growth and crop production on the affected area of Sinabung Volcanic eruption. The results revealed that Package C which included a combination of manure, lime, sawdust, and inorganic fertilizers, consistently outperformed the other packages in term of plant height, number of stems, and tuber yield (Jovovic et al., 2021). These improvements can be attributed to the enhanced soil chemical and physical fertility provided by Package C. Manure and sawdust in Package C increase soil organic matter, which is important for root development and nutrients uptake. Furthermore, the existence of lime in this package is likely to contribute to the neutralization of soil acidity, then help the sustainable soil nutrients availability (Argaw et al., 2025; Rachman et al., 2021). This condition supports the crop's physiological growth which can be observed from height and number of stem parameters. Related to the tuber weight, number of tuber and tuber yield, Package C gets the highest outputs at these parameters. These achievements are related to the support of nutrient availability, which is critical for tuber formation and growth. Rachman et al. (2021) informed that the usage of manure and lime increases the potato production and soil fertility by adding the macro and micronutrients, improving the activity of soil organisms and enriching soil physical properties. Comparing the total amount of inorganic fertilizer to Packages A and B, Package C uses less than these packages, suggesting that organic amendments can partially replace the inorganic fertilizers while maintaining high yields. Soil physical fertility specifically, Package C likely supported better BD and SWC conditions which is promote tuber growth and increase the yield (Agbede, 2010). Moreover, Package C consistently produced the highest-quality tubers in terms of weight and number for grades A to C (>100 g/tuber) which is in contrast with Package E outputs. This superior performance can be attributed to the improved soil chemical and physical condition provided by Package C. Supporting nutrient availability, pH condition, soil structure and texture, water content, and soil cation exchange capacity contribute to larger and higher quality of tubers.

4.3 Income improvement

Nowadays, an economic feasibility analysis is an important parameter as well to measure the sustainable agricultural system. The output of this study informed that Package C emerged as the most economically advantageous. Combining organic amendments (manure and sawdust) reduced the need for expensive inorganic fertilizers, resulting in lower production costs compared to Package A and B. Package C spent the total cost by $ US 4,456.9 per hectare, and generated the highest income and benefits by $ US 16,474.3 and $ US 12,017.4 per hectare, respectively. This superior economic performance can be attributed to the cost efficiency strategy of reducing unnecessary expenditures, such as inorganic fertilizers; and use the low-cost organic management, such as sawdust. Another reason, Package C produced the highest potato yield and the best-quality tubers (grades A and B), meaning the higher quality production the higher income will get by the farmers. Although all agronomic technology packages had BCR greater than 1.0, indicating their financial viability. However, Package C achieved the highest BCR by 2.70, and followed by Package A by 1.79.

It is interesting to note that, conventional farming normally has a greater capacity to increase yield compared to organic farming in the short-term (Tahat et al., 2020). Although the entire package of this research provides a beneficial economic contribution, the excessive and continuous use of chemical fertilizers inevitably results in a decline of soil health in the long-term. Several previous studies have demonstrated that the improper application of chemical fertilizers has led to degradation in soil physical (Abid et al., 2020; Alkharabsheh et al., 2021), chemical (Douillard et al., 2025; Mi et al., 2018; Moro et al., 2021) and biological (Bhunia et al., 2021; Ngongo et al., 2022; Wei et al., 2017) properties. To avoid long-term detrimental impacts that will be experienced specifically in areas affected by this volcanic eruption, this study suggests several action strategies that can be considered by farmers and local governments, such as: (i) periodically reducing the use of excessive chemical fertilizers for the next planting seasons, because the initial objective of this research activity focuses on providing nutrients that are lacking for potato plants, especially nitrogen and phosphorus; (ii) periodically adding soil amendments (organic fertilizers and sawdust) to the affected agricultural land because it will make a major contribution to soil fertility, especially its physical and biological properties; (iii) by applying lime to the affected agricultural land to maintain soil pH stability; and (iv) integrating the main crop with legumes in the following planting season to increase natural N fixation. It is believed that implementing these strategies, which require cooperation from relevant agencies within the Karo Regency government, will achieve the sustainability of the affected agricultural land.

5 Conclusions

In this study, the restoration of soil fertility and crop production on the affected area of volcanic eruption has been assessed by testing five agronomic technology packages in a field trial, which are differentiated by the type and quantity of soil amendments (organic fertilizers and sawdust), inorganic fertilizers and the dosage of lime application. Integrating of manure, sawdust, lime and inorganic fertilizer at the specific treatment was not only increases soil chemical fertility (pH, soil organic carbon, potassium, calcium and magnesium contents and cation exchange capacity) and physical fertility (soil texture, bulk density, permeability and soil water content) but also physiological growth, yield crop production and its harvest-quality. Thus, this specific treatment received double income compared to the farmers' treatment, and is certainly economically feasible to developed. It is undeniable that the research design can be expanded for further study to generate maximum results, e.g., designing a variable rate of sawdust (2.5, 5.0 and 7.5 t/ha), designing a deeper rate of the ash thickness (20, 40, 60 and 80 cm), integrating legume intercropping to fix nitrogen organically, and considering conducting field research up to four planting seasons to monitor the long-term effect. In addition, several policies can be considered by Government of Karo Regency or by other governments who have a similar issue to be implemented, namely: (i) providing price subsidies for chemical fertilizers, lime and manure, (ii) providing training to local farmers about the proper cultivation management in affected areas by volcanic eruptions, and (iii) continuing to monitor soil fertility levels for the next few years after the eruption.

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Declaration of Competing Interest

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

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