How to cite: Mukhlis, A.V.A., E. Syam'un, K. Mantja & M. Faried, 2026. Growth and production of potato (*Solanum tuberosum* L.) are affected by cutting size and NAA concentrations. Ege Univ. Ziraat Fak. Derg., 63 (1): 55-66-, https://doi.org/10.20289/zfdergi.1719585

Research Article
(Araştırma Makalesi)

https://doi.org/10.20289/zfdergi.1719585

Growth and production of potato (*Solanum tuberosum* L.) are affected by cutting size and NAA concentrations

Patatesin (*Solanum tuberosum* L.) büyümesi ve üretimi, kesim boyutu ve NAA konsantrasyonlarından etkilenir

Andi Vira Alviani MUKHLIS[1]

Elkawakib SYAM'UN [1*]

Katriani MANTJA[1]

Muhammad FARIED [1]

[1] Hasanuddin University, Faculty of Agriculture, Department of Agrotechnology Master Program, 90245, Makassar, South Sulawesi, Indonesia

* Corresponding author (Sorumlu yazar):

elkawakibsyam@gmail.com

Received (Alınış): **14.06.2025** **Accepted** (Kabul Tarihi): **13.03.2026**

ABSTRACT

Objective: The objective of this research was to determine and analyze the effect of the different cuttings sizes and the concentration of auxin NAA on increasing the growth and production of potatoes.

Materials and Methods: This study was conducted in Muntea Hamlet, Bonto Lojong Village, Ulu Ere Subdistrict, Bantaeng Regency, South Sulawesi, from September 22, 2024, to January 4, 2025. This study was designed using a Split Plot Design (SPD), with the main factor being the cutting size treatment (2, 3, and 4 nodes). Subplots used NAA at 4 levels: 0, 100, 200, and 300 mg L^{-1}.

Results: The number of nodes (4 nodes) produced the highest mean on the number of leaves, and NAA concentration of 200 mg L^{-1} produced the highest mean on the number of leaves, leaf chlorophyll content, root length, root volume, root fresh weight, number of tubers, tuber length, tuber diameter, tuber weight, tuber weight per plant, yield per plot, and yield per hectare.

Conclusion: The 200 mg L^{-1} NAA treatment provided the most optimal results compared to other treatments. Therefore, NAA at a concentration of 200 mg L^{-1} is recommended as the most effective treatment for further research.

Keywords: Cutting, NAA, number of nodes, potato, production

Anahtar sözcükler: Çelikleme, NAA, boğum sayısı, patates, üretim

ÖZ

Amaç: Bu araştırmanın amacı, farklı kesim boyutlarının ve oksin NAA konsantrasyonunun patateslerin büyümesi ve üretiminin artması üzerindeki etkisini belirlemek ve analiz etmekti.

Materyal ve Yöntem: Bu çalışma, 22 Eylül 2024 ile 4 Ocak 2025 tarihleri arasında Güney Sulawesi, Bantaeng İlçesi, Ulu Ere Alt Bölgesi, Bonto Lojong Köyü, Muntea Hamlet'te gerçekleştirilmiştir. Bu çalışma, ana faktör kesim boyutu işlemi (2, 3 ve 4 düğüm) olmak üzere Bölünmüş Parsel Tasarımı (SPD) kullanılarak tasarlanmıştır. Alt parsellerde 4 seviyede NAA kullanılmıştır: 0, 100, 200 ve 300 mg L^{-1}.

Sonuçlar: Boğum sayısı (4 boğum) yaprak sayısı üzerinde en yüksek ortalamayı üretirken, 200 mg L^{-1} NAA konsantrasyonu yaprak sayısı, yaprak klorofil içeriği, kök uzunluğu, kök hacmi, kök taze ağırlığı, yumru sayısı, yumru uzunluğu, yumru çapı, yumru ağırlığı, bitki başına yumru ağırlığı, parsel başına verim ve hektar başına verim üzerinde en yüksek ortalamayı göstermiştir.

Sonuç: 200 mg L^{-1} NAA uygulaması, diğer uygulamalara kıyasla en iyi sonuçları sağlamıştır. Bu nedenle, 200 mg L^{-1} konsantrasyonundaki NAA, ileri araştırmalar için en etkili uygulama olarak önerilmektedir.

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INTRODUCTION

Potato (*Solanum tuberosum* L.) is currently the third most important food crop in the world after rice and wheat due to its high yield potential (Anil et al., 2023). Its calorie, carbohydrate, mineral and vitamin content make potatoes suitable as a staple food. Potatoes are widely cultivated in upland areas with low air temperatures and moderate to high rainfall. Highlands with altitudes between 500-1500 meters above sea level are ideal locations for cultivating potatoes (Sari, 2021). One of the most widely cultivated potato varieties in Indonesia is the Granola variety. Granola potato cultivation accounts for about 85-90% of the total potato farming area in Indonesia. The Granola variety has several advantages, including high productivity, oval round tuber shape, yellow tuber flesh color, and shallow tuber eyes (Tomatala et al., 2023). It is now widely cultivated in potato production centers such as Toraja, Enrekang, Bantaeng, Dieng, Lembang, and Tengger (Yustisia et al., 2018).

Potato is one of the leading commodities chosen to support food diversification programs in order to achieve sustainable food security. According to data from the Central Bureau of Statistics (2025), potato production in Indonesia in 2024 reached 1.26 million tons. This number increased by 1.61% compared to the previous year which amounted to 1.24 million tons. Meanwhile, in South Sulawesi province, potato production in 2024 reached 60,321 tons, with a planting area of 3,148 hectares and a productivity level of 19.16 tons ha^{-1}. This figure shows a decrease in productivity compared to 2023, which reached 19.53 tons ha^{-1} (Central Bureau of Statistics, 2025). Nationally, potato production and productivity are still low compared to other countries. This is mainly due to the limited availability of high-quality seed potatoes. Traditionally, potatoes are still propagated using seed tubers. However, this method triggers the accumulation of tuber-borne viruses, fungi and bacteria from previous harvests, leading to a gradual decline in tuber quality and yield over time (Wardana et al., 2024). Therefore, efforts to increase potato production should focus on high-quality seed multiplication.

One of the propagation methods that can be used on potato plants is the cuttings technique. According to Rafindo (2022), seed production can be done using rapid propagation techniques through cuttings to obtain large quantities of seeds in a short time and under controlled conditions. For the purpose of potato seed production, a propagation technique is needed that can meet production needs both in terms of quality and quantity. The use of the cuttings technique aims to overcome the limitations of conventional seed production methods. This is due to its high propagation rate, so that superior varieties can be propagated quickly, produce healthier seeds, require relatively small planting space, less planting material and mother plants, and allow seed production on a large scale and in a short time (Fatahillah et al., 2024).

In addition to increasing the number of quality cuttings, this method also serves as potato planting material that is free from pathogens and has high quality. Cuttings can be used as a vegetative propagation method for plant species that are difficult to propagate generatively and have the advantage of transferring all the properties of the parent plant to its offspring (Rafindo et al., 2022). Cuttings in plant propagation involve the use of stem parts separated from the parent plant, which then grow into a new plant as a whole (Chiyaroh et al., 2021). To achieve optimal growth in seed cuttings, it is important to pay attention to root and shoot development, including the use of healthy, high-quality cutting material with a certain number of internodes, usually two or more internodes.

Previous research conducted by Rafindo et al. (2022) on potato plants showed that cuttings with 3 internodes increased plant height, number of stomata, and number of tubers per plant, while cuttings with 2 internodes increased tuber weight per plant. This is in line with another study by Yulifar et al. (2024), which found that cutting two nodes resulted in taller plants, longer roots, and larger stem diameters compared to cutting one node.

Propagation through cuttings combined with the application of the auxin hormone NAA is an alternative method that is expected to produce healthy and high-quality seed potatoes in a short time. One of the techniques to obtain superior seed potatoes is through this method, because it can accelerate cell division and elongation, and regulate the growth of roots, stems, and fruits (Sari et al., 2021). Auxin is a hormone that can induce callus formation, root or shoot development, promote embryogenesis, and affect the genetic stability of plant cells, including internode development and growth. The addition of auxin can stimulate the formation of adventitious roots so that minerals and nutrients absorbed through root branches can optimally trigger shoot growth (Choiruninisa et al., 2023). Auxin is very important in the process of callus and root formation. The use of auxins basically accelerates the physiological processes of plants, allowing the formation of root primordia (Nofri et al., 2021).

One of the most widely used auxin group plant growth regulators (ZPT) to stimulate root formation in cuttings or joints is NAA. According to Astutik et al. (2021), the use of NAA and Indole Butyric Acid (IBA) is better than Indole Acetic Acid (IAA), because IBA and NAA are chemically more stable and easier to move in plants. Their effects are also more long-lasting and remain around the application area, do not affect other growth processes, and produce healthy and well-structured roots. In contrast, IAA tends to move towards the shoot and can inhibit shoot development. Among NAA and IBA, NAA is considered the most effective in stimulating root formation. This is in line with the research of Agustiansyah et al. (2018) which showed that NAA is more effective than IBA in inducing root formation in guava joints, both in terms of the number of primary roots formed and the speed of root emergence. According to Agustiarini et al. (2021), the combination of cuttings with NAA immersion treatment can increase the success rate of cuttings, number of roots, root length, plant height, and leaf area.

NAA is commonly used in horticultural crops to promote vegetative propagation and support plant growth by stimulating cell division, cell elongation, and cell differentiation that trigger plant organ development. NAA is essential in the formation of root cambium and epithelium, which can stimulate lateral root formation. This hormone also affects physiological processes, accelerates ripening, improves fruit quality, and affects other aspects such as increasing the number of branches, fresh weight, yield, stimulating early flowering, and preventing flower and fruit drop (Ahmed et al., 2021). Previous research conducted by Wang et al. (2022) on tea plants showed that NAA significantly increased root formation in tea stem cuttings. Another study by Ahmed et al. (2021) on potato plants found that NAA concentration of 100 mg L^{-1} can increase productivity and chemical content of potato plants. This is in line with the research of Astutik et al. (2021) on *Dendrobium* sp., which showed that the type and concentration of auxins-naphthalenacetic acid (NAA) and indole butyric acid (IBA)-interact to support the growth of leaf length, leaf width, and root length in Dendrobium orchids, with an optimal concentration of 200 mg L^{-1} up to three months after acclimatization.

Until now, research on the growth and production of potato plants is still limited. Therefore, it is necessary to conduct further research on the growth and production of potato plants (*Solanum tuberosum* L.) with the number of cuttings internodes and NAA concentration in field conditions.

MATERIALS and METHODS

Study area

The research was conducted in Muntea Hamlet, Bonto Lojong Village, Ulu Ere Sub-district, Bantaeng Regency, South Sulawesi, at the coordinates -5°26'1.53658“ N-S 119°56'53.97911” E with an altitude of 1,400 meters above sea level. This research was conducted between 22 Sept 2024 and 4 January 2025.

Experimental design

This experiment was designed using a Split Plot Design (SPD), where the main factor was stem cutting treatment (2, 3, and 4 stems), the number of nodes per treatment being nodes above ground, and no nodes below ground; roots will grow from the cut end of the stem below ground. while the secondary factor consisted of four different NAA concentrations: 0 mg L^{-1}, 100 mg L^{-1}, 200 mg L^{-1}, and 300 mg L^{-1}, each cutting was soaked for 15 minutes according to the NAA treatment. In total, there were 12 treatment combinations, each repeated three times, resulting in 36 experimental units. Each experimental plot measured 0.8 m x 1.5 m, with a planting distance of 20 cm x 20 cm.

Propagation technique

Seed potato propagation is carried out in a greenhouse using a stem cuttings system from young potato plants. The process begins with the preparation of media and seedling material from G0 tubers, which are then planted for 3 to 4 weeks until plant shoots appear above the soil surface. After that, the potato stems are cut according to the number of internodes according to the treatment, soaked in naphthalene acetic acid (NAA) solution, and replanted in the seedling tray. After the roots of the cuttings have grown, the cuttings are transferred to the planted in experimental plots.

Data collection

The traits measured in this study included plant height (cm), number of branches, number of leaves, leaf chlorophyll index, leaf chlorophyll index observations were made using a Content Chlorophyll Meter (CCM 200+), days to flowering (days), root length (cm) measured using a tape measure from the root base to the root tip, root volume (mL) observed by placing the roots in a measuring cup and observing the increase in water level or water volume, fresh root weight (g), dry root weight (g) measured by weighing the roots that had been dried for 24 hours until the water content in the roots was completely removed, number of tubers, tuber length (cm), tuber diameter (cm), average tuber weight (g), tuber weight per plant (g), tuber yield per plot (kg), and estimated tuber yield per hectare (t ha^{-1}).

Data analysis

Analysis of Variance (ANOVA) was used to evaluate the data collected. When treatment differences were found to be significant or highly significant, further comparisons were made using the Least Significant Difference (LSD) test with a significance level of α = 0.05%. All data analysis processes were performed using Microsoft Excel 2019 software.

RESULTS

Vegetative trait

The analysis of variance presented in Table 1 shows that the number of nodes had a highly significant effect (*p*>0.01 and 0.05) on the number of leaves, and NAA concentration also had a highly significant effect (*p*>0.01 and 0.05) on the number of leaves. In addition, the leaf chlorophyll index trait was significantly affected by the NAA concentration treatment.

Table 1. Summary of ANOVA results on the effect of different cutting size and NAA concentration on the vegetative traits

Çizelge 1. *Vejetatitif özellikler üzerine farklı kesim boyutu ve NAA konsantrasyonunun etkisine ilişkin ANOVA sonuçlarının özeti*

Source of variance	F-calculation				
	Height of plant (cm)	Branch number	Number of leaves	Leaf chlorophyll index	Flowering time (day)
Number of nodes	0.71^{ns}	6.28^{ns}	88.28^{**}	1.65^{ns}	3.83^{ns}
Napthalena Acetic Acid	0.96^{ns}	2.25^{ns}	11.37^{**}	3.82^{*}	1.47^{ns}
Interaction	0.23^{ns}	0.60^{ns}	0.41^{ns}	1.18^{ns}	0.49^{ns}

*Remaks: ns = not significantly different at 0.05 level; * = significantly different at 0.05 level; ** = significantly different at 0.01 level.*

To observe the differences among treatment means in more detail, the results are presented in Table 2. Based on the data, the number of leaves was affected by the 4-node treatment, which produced the highest average of 123.7 leaves, and by the 200 Mg L^{-1} NAA treatment, with an average of 119.96 leaves. The leaf chlorophyll index was influenced by the 200 Mg L^{-1} NAA concentration, with an average value of 28.91.

Table *2.* Mean values of vegetative traits and grouping according to the LSD test

Çizelge 2. *Vejetatif özelliklerin ortalama değerleri ve LSD testine göre gruplandırma*

Number of nodes	Height of plant	Branch number	Leaf number	Leaf chlorophyll index	Flowering time
2 nodes	46,65±0,64	2,57±0,02	109.5^c	23.95±0.83	41,92±2,06
3 nodes	48,09±0,35	2,80±0,17	116.8^b	27.90±1.31	41,75±2,16
4 nodes	48,14±0,89	3,13±0,15	123.7^a	27.77±1.58	39,92±4,19
LSD α0.05			2.98		
Napthalena Acetic Acid	Height of plant	Branch number	Leaf number	Leaf chlorophyll index	Flowering time
0 mgL^{-1}	45,53±0,75	2,67±0,17	112.91^b	24.04^d	42,11±2,73
100 mgL^{-1}	47,08±0,74	2,69±0,08	115.07^b	27.14^b	40,67±2,6
200 mgL^{-1}	48,81±0,80	3,12±0,27	119.96^a	28.91^a	40,22±2,91
300 mgL^{-1}	48,22±0,25	2,84±0,18	118.62^a	26.06^c	41,78±1,2
LSD α0.05			2.47	0.26	

** Means followed by letters that are not significantly different according to the LSD α0.05.*

Root trait

The analysis of variance presented in Table 3 shows that NAA concentration has a significant effect (p>0.05) on root length and root wet weight. In addition, root volume is significantly affected by NAA concentration treatment (p>0.01 and 0.05).

Table 3. Summary of ANOVA results on the effect of different cutting size and NAA concentration on the root traits ***Çizelge 3.*** *Farklı kesim boyutu ve NAA konsantrasyonunun kök özellikleri üzerindeki etkisine ilişkin ANOVA sonuçlarının özeti*

Source of variance	F-calculation			
	Root Length	Root Volume (ml)	Root Fresh Weight (g)	Root Dry Weight (g)
Number of nodes	5.82^{ns}	0.42^{ns}	6.87^{ns}	0.80^{ns}
Napthalena Acetic Acid	3.30*	5.91**	4.43*	2.47^{ns}
Interaction	0,67^{ns}	0.30^{ns}	0.89^{ns}	0.39^{ns}

*Remaks: ns = not significantly different at 0.05 level; * = significantly different at 0.05 level; ** = significantly different at 0.01 level.*

This study analyzed the effect of the number of nodes and NAA on root growth of potato plants. Based on Table 4, the number of nodes had no significant effect on root length, root volume, root fresh weight, or root dry weight. However, cuttings with 2 nodes had the longest average root length (19.08 cm), while cuttings with 3 nodes showed the highest average root volume (9.18 mL), fresh root weight (3.42 g), and dry root weight (1.08 g). These findings suggest that although the number of nodes did not have a statistically significant effect, cuttings with 2 and 3 nodes can slightly increase root growth parameters.

In contrast, NAA concentration significantly affected root length, root volume, and root fresh weight but had no significant effect on root dry weight. A concentration of 200 mg L^{-1} NAA was found to be the most effective dose among the tested concentrations for all root growth measurements. This treatment produced the highest average root length (20.27 cm), root volume (11.00 mL), root fresh weight (3.50 g), and root dry weight (1.21 g).

Table 4. Mean values of root traits and grouping according to the LSD test

***Çizelge 4.** Kök özelliklerinin ortalama değerleri ve LSD testine göre gruplandırma*

Number of nodes	Root length (cm)	Root volume (mL)	Root fresh weight (g)	Root dry weight (g)
2 nodes	19.08±0.77	9.16±0.90	2.79±0.41	1.03±0.06
3 nodes	17.39±1.32	9.18±0.94	3.42±0.50	1.08±0.13
4 nodes	18.19±0.62	8.93±0.96	2.48±0.33	0.96±0.09
Napthalena Acetic Acid	Root length (cm)	Root volume (mL)	Root fresh weight (g)	Root dry weight (g)
0 Mg L^{-1}	16.85^{c}	7.39^{d}	2.15^{c}	0,86±0.03
100 Mg L^{-1}	17.10^{c}	7.76^{c}	2.49^{b}	0,89±0,09
200 Mg L^{-1}	20.27^{a}	11.00^{a}	3.50^{a}	1,21±0.05
300 Mg L^{-1}	18.80^{b}	10.22^{b}	3.45^{a}	1.13±0.09
LSD α0.05	2.22	0.32	0.25	

** Means followed by letters that are not significantly different according to the LSD test α0.05.*

Generative trait

The analysis of variance presented in Table 5 shows that NAA concentration has a very significant effect (p>0.01 and 0.05) on the number of tubers. In addition, NAA concentration has a significant effect (p>0.05) on tuber length and tuber diameter.

Table 5. Summary of ANOVA results on the effect of different cutting size and NAA concentration on the tuber morphology
Çizelge 5. Farklı kesim boyutu ve NAA konsantrasyonunun yumru morfolojisi üzerindeki etkisine ilişkin ANOVA sonuçlarının özeti

Source of variance	F-calculation		
	Number of tubers	Tuber length (cm)	Tuber diameter (cm)
Number of nodes	0.17^{ns}	3.36^{ns}	0.88^{ns}
Napthalena Acetic Acid	13.72*	3.58*	3.56*
Interaction	3.80^{ns}	0.72^{ns}	0.46^{ns}

*Remaks: ns = not significantly different at 0.05 level; * = significantly different at 0.05 level; ** = significantly different at 0.01 level*

This study examined the effect of the number of nodes and NAA on the growth and yield of potato plants, focusing on the generative phase, which consists of tuber morphology, tuber weight and production. Based on Table 6, potato cuttings with four nodes had a significant effect on the number of tubers (3.93), but no significant effect on tuber length (7.77 cm) or tuber diameter (3.92 cm). This finding indicates that although the number of internodes treatment did not have a statistically significant effect on all parameters, cuttings with four internodes tended to slightly increase the number, length, and diameter of tubers.

Table 6. Mean values of tuber morphology and grouping according to the LSD test

***Çizelge 6.** Yumru morfolojisi ortalama değerleri ve LSD testine göre gruplandırma*

Number of nodes	Number of tubers	Tuber length (cm)	Tuber diameter (cm)
2 nodes	3.77^{a}	5.29±0.48	3.49±0.13
3 nodes	3.83^{a}	6.85±1.49	3.63±0.29
4 nodes	3.93^{a}	7.77±0.98	3.92±0.29
LSD α0.05	0.82		
Napthalena Acetic Acid	Number of tubers	Tuber length (cm)	Tuber diameter (cm)
0 Mg L^{-1}	3.29^{ab}	5.34^{c}	3.61^{b}
100 Mg L^{-1}	3.71^{ab}	5.87^{b}	3.42^{c}
200 Mg L^{-1}	4.38^{a}	9.20^{a}	4.33^{a}
300 Mg L^{-1}	4.00^{a}	6.14^{b}	3.35^{c}
LSD α0.05	0.64	0.40	0.14

** Means followed by letters that are not significantly different according to the LSD α0.05.*

In this study, NAA concentration had a significant effect on tuber number, length and diameter. Among the various concentrations tested, 200 mg L-1 NAA proved to be the most effective in increasing all the measured tuber morphological traits. The highest mean values recorded were 4.38 tubers, 9.20 cm length, and 4.33 cm diameter. Furthermore, the 5% LSD test confirmed that the 200 mg L^{-1} NAA treatment was significantly different from the other concentration treatments.

The analysis of variance presented in Table 7 shows that NAA concentration has a significant effect (p>0.05) on weight per tuber, tuber weight per plant, tuber production per plot, and tuber production per hectare.

Table 7. Summary of ANOVA results on the effect of different cutting size and NAA concentration on the tuber weight and production

Çizelge 7. *Farklı kesim boyutu ve NAA konsantrasyonunun yumru ağırlığı ve üretimi üzerindeki etkisine ilişkin ANOVA sonuçlarının özeti*

Source of variance	F-calculation			
	Weight per tuber (g)	Tuber weight per plant (g)	Tuber production per plot (kg)	Tuber production per hectare (t ha-1)
Number of nodes	3.81^{ns}	4.05^{ns}	4.00^{ns}	4.00^{ns}
Napthalena Acetic Acid	3.95*	3.23*	3.24*	3.24*
Interaction	0.63^{ns}	1.06^{ns}	1.05^{ns}	1.05^{ns}

*Remaks: ns = not significantly different at 0.05 level; * = significantly different at 0.05 level; ** = significantly different at 0.01 level.*

The study analyzed the impact of the number of internodes and NAA on tuber weight and potato production, as presented in Table 5, showing that the number of internodes did not significantly affect tuber weight per tuber, tuber weight per plant, tuber yield per plot, or tuber yield per hectare. However, potato cuttings with four internodes showed the highest mean values for tuber weight per tuber (47.01g), tuber weight per plant (152.61g), production per plot (3.20 kg), and production per hectare (29.43 t ha^{-1}) (Table 8). This indicates that although the number of internodes was not statistically significant, four internode cuttings tended to slightly increase these parameters.

In contrast, NAA concentration had a significant effect on tuber weight per tuber, tuber weight per plant, production per plot, and production per hectare. Application of 200 mg L^{-1} NAA proved to be the most effective among the concentrations tested for all yield-related measurements. This treatment produced the highest mean values for tuber weight per tuber (47.89 g), tuber weight per plant (151.83 g), production per plot (3.19 kg), and production per hectare (29.29 t ha^{-1}). Furthermore, the 5% LSD test confirmed that the 200 mg L^{-1} NAA treatment was significantly different from the other treatment levels.

Table 8. Mean values of tuber weight and production and grouping according to the LSD test

Çizelge 8. *LSD testine göre yumru ağırlığı ve üretiminin ortalama değerleri ve gruplandırılması*

Number of nodes	Weight per tuber (g)	Tuber weight per plant (g)	Tuber production per plot (kg)	Tuber production per hectare (t ha^{-1})
2 nodes	35.95±1.39	126.60±8.64	2.66±0.18	24.42±1.66
3 nodes	45.03±5.21	141.38±6.80	2.97±0.14	27.62±1.31
4 nodes	47.01±2.85	152.61±4.64	3.20±0.10	29.43±0.90
Napthalena Acetic Acid	Weight per tuber (g)	Tuber weight per plant (g)	Tuber production per plot (kg)	Tuber production per hectare (t ha^{-1})
0 Mg L^{-1}	34.51^{d}	126.09^{ab}	2.65^{ab}	24.31^{ab}
100 Mg L^{-1}	41.90^{c}	143.16^{a}	3.01^{a}	27.62^{a}
200 Mg L^{-1}	47.89^{a}	151.83^{a}	3.19^{a}	29.29^{a}
300 Mg L^{-1}	46.34^{b}	139.67^{a}	2.93^{a}	26.95^{a}
LSD α0.05	**0.59**	**15.34**	**0.32**	**2.96**

** Means followed by letters that are not significantly different according to the LSD α0.05.*

DISCUSSION

Based on the results of the study, it can be stated that the cutting size of nodes in potato has a very significant effect on the number of leaves parameter. The findings showed that the highest average number of leaves was observed in the treatment with 4 nodes. In contrast, plant height and number of branches did not show statistically significant differences. However, all three parameters tended to reach the highest values in the 4 internode treatment. This significant effect on the number of leaves indicates that an increase in the number of internodes directly affects the physiological activities of the plant, particularly in leaf formation. This is likely due to the availability of more buds and nutrient reserves in cuttings with a higher number of internodes, which can stimulate optimal leaf growth. This statement is in line with several findings, such as those reported by Luthfiani (2021), which state that the greater the number of internodes, the more leaves will be produced. Similarly, Anjani et al. (2022) explains that internodes are leaf attachment points; therefore, the more internodes a plant has, the more leaves it will produce. On the other hand, the absence of significant effects on plant height and number of branches suggests that these parameters are more influenced by genetic or environmental factors rather than the number of internodes alone. Although the differences were not statistically significant, the highest values were still observed in the 4 internode treatment, which corroborates the assumption that increasing the number of internodes tends to increase overall vegetative growth.

Napthalene acetic acid is a plant growth regulator type of auxin that is more stable than other types of auxin (Matur, 2022). This experiment showed that the treatment of potato cuttings immersed in NAA solution with a concentration of 200 mg L^{-1} significantly increased the number of leaves, leaf chlorophyll index, root length, root volume, root fresh weight, number of tubers, tuber length, tuber diameter, tuber weight per unit, tuber weight per plant, and tuber production per plot and per hectare.

NAA affects vegetative parameters such as leaf number and leaf chlorophyll index. This finding is in line with the statement of Warnita et al. (2017) which explains that NAA is able to stimulate proliferation and elongation of leaf cells, which ultimately supports leaf development. Furthermore, Ahmed et al. (2021) state that NAA is widely used in horticultural crops to increase vegetative propagation and support overall plant growth, including increasing the number of leaves in potato plants. Harahap (2018) also noted that the application of growth regulators at optimal concentrations can increase protein synthesis. The synthesized proteins are then used in the development of plant organs such as roots, stems, and leaves. Giving NAA to potato cuttings can increase chlorophyll content in the leaves, which is directly related to the photosynthetic capacity of plants and supports overall growth. Another statement by Salsabila et al. (2021) also mentioned that NAA is an auxin compound that can affect plant growth, including the number of leaves, chlorophyll content, and root development.

Certain concentrations of NAA significantly affected various root characteristics, including root length, root volume and root fresh weight. These findings are in line with research conducted by Astutik et al. (2021) on *Dendrobium* sp., which identified a NAA concentration of 200 mg L^{-1} as the most optimal. NAA is a synthetic auxin that is widely used in agriculture to stimulate root growth in plants. Its effect on root development is very important especially during the rooting process of cuttings. As a synthetic auxin hormone, NAA plays an important role in commercial plant propagation as a rooting agent, which is commonly used to support vegetative propagation from stem or leaf cuttings (Permana, 2021). According to Yulianto (2025), auxin functions in cell division activity in meristem tissues by stimulating cell elongation located directly behind the meristem. These cells elongate and fill with water, auxin affects the cell wall by reducing cell wall pressure on the protoplast. Growth is defined as an irreversible increase in the number of cells in an organism, followed by an increase in biomass. Growth is then accompanied by development, as both are interrelated processes. The first stage, for example, involves the roots which are the underground, tapered, soil-penetrating part of the plant. Behind the root hood is a growing point that consists of meristematic cells that continue to divide. Behind this area is a zone of large, elongated cells known as the elongation zone, where growth is strongly influenced by hormone activity in the root. Meanwhile, root fresh weight is strongly related to the amount of photosynthate distributed to leaves and stems, and the number of leaves can affect the amount of photosynthate produced (Gupitasari et al., 2019). Fresh weight responds specifically to the type of plant growth regulator (ZPT) applied. The increase in fresh weight occurs due to cell enlargement and division which is influenced by auxin activity. Root fresh weight is influenced by NAA which is able to stimulate root formation and increase the ability of plants to absorb nutrients (Angelina et al., 2017).

Tuber parameters are also affected by the application of NAA as a plant growth regulator. Naphthalenacetic acid has a significant effect on the number of tubers, tuber length, tuber diameter, tuber weight per unit, tuber weight per plant, and tuber production per plot and per hectare. According to Choiruninisa et al. (2023), the addition of auxin NAA can stimulate the formation of adventitious roots, which increases the absorption of minerals and nutrients, thus potentially increasing the number of tubers. The concentration of 200 mg L^{-1} is able to increase the elasticity of the cell wall, thus elongating the tubers and enlarging their diameter. This finding is supported by research by Le (2017), who reported that plant growth regulator NAA can increase the length and diameter of apple fruit. Further research by Khusni et al. (2023) found that the increase in fruit/tuber diameter due to the application of NAA 200 mg L^{-1} showed its ability to mobilize carbohydrate absorption so as to significantly enlarge cell size.

In addition, the right concentration of NAA can increase the weight per tuber. According to Khusni et al. (2023), the use of NAA tends to accelerate the induction of flowering, which is directly related to the increase in yield. The right concentration of NAA can trigger earlier flowering, so that plants divert their resources from vegetative growth (leaves and stems) to storage organs such as tubers, which ultimately increases yields in terms of tuber weight. The auxin content in plants helps maintain tuber development and increase tuber weight, while ensuring a high supply of assimilates required for tuber growth and development (Satriowibowo, 2014). This finding supports the research results of Ahmed et al. (2021), who reported that NAA plays a role in enhancing physiological functions, accelerating maturation, and improving tuber quality. Other studies have also shown that the hormone auxin affects tuber formation and weight in potato plants. For example, Suharjo et al. (2017) found that auxin affected tuber development and contributed to tuber weight. Similarly, Hakim et al. (2019) noted that external hormone application increases the storage capacity of photosynthetic products (such as fruits and tubers) by enlarging cells in storage tissues, thus allowing greater photosynthate accumulation and resulting in larger storage organs. Among various types of auxins, NAA has been shown to be the most effective in stimulating tuber formation compared to other types (Asmono et al., 2019). Some studies have also observed similar effects in other plants. For example, Askarieh et al. (2021) found that application of the auxin-type plant growth regulator Naphthalene Acetic Acid increased cherry fruit yield. Auxins are also known to stimulate growth and fruit enlargement in tomato plants (Andianingsih et al., 2021) and have been shown to double corn production (Tscharn et al., 2022). These findings suggest that Naphthalene Acetic Acid can also affect tuber development in potatoes, although its effectiveness depends on the concentration of auxin used as well as its interaction with other treatment factors.

The interaction between the number of potato stem internodes and NAA had a significant effect on the number of tubers parameter. The number of internodes in potato stem cuttings combined with the right NAA concentration produces many shoots, and NAA encourages the formation of adventitious roots from the cuttings, which can strengthen photosynthesis and nutrient absorption, thus potentially increasing the number of tubers. This is because many internodes that grow actively receive a supply of photosynthetic products. This statement is supported by Choiruninisa et al. (2023), which states that the addition of auxin can stimulate the formation of adventitious roots so that minerals and nutrients absorbed through root branches can be more optimally used to initiate internode growth. Each developing internode produces leaves, which are where photosynthesis occurs, and the resulting photosynthesis is used for tuber growth, so potato cuttings have the potential to increase the number of tubers. This is in line with Siagian (2021), who states that potatoes derived from cuttings and micro tubers produce more tubers than conventional potato seeds. According to Maharijaya et al. (2020), the more tubers formed, the smaller the weight per tuber tends to be; therefore, NAA application can help improve tuber quality and support the growth of larger tubers. Thus, it is very important to find the right balance between the number of internodes used in the cuttings and the concentration of auxin NAA applied.

CONCLUSIONS

Based on the research conducted. it can be concluded that:

The treatment with a concentration of 200 mg L^{-1} NAA provided the most optimal growth and yield response compared to other treatments. Thus, NAA with a concentration of 200 mg L^{-1} is recommended as the most effective treatment to be used and developed in further research.

ACKNOWLEDGEMENTS

The authors wish to express their sincere gratitude to all parties who have contributed to this research.

Data Availability

Data will be made available upon reasonable request.

Author Contributions

Conception and design of the study: ES, MF; sample collection: AVAM, MF; analysis and interpretation of data: AVAM, ES; statistical analysis: AVAM, ES; visualization: KM, MF; writing manuscript: AVAM, KM.

Conflict of Interest

There is no conflict of interest between the authors in this study.

Ethical Statement

We declare that an ethics committee is not required for this study.

Financial Support

This study was not supported by external financing.

Article Description

This article was edited by Section Editor Prof. Dr. Fatma AYKUT TONK.

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