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OPTIMIZING FLORAL INDUCTION TIMING FOR GROWTH, YIELD AND FRUIT QUALITY OF MD2 PINEAPPLE ON TROPICAL PEAT SOIL UNDER FOLIAR FERTILIZATION

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ABSTRACT

Traditionally, granular fertilizers have been the primary nutrient source for pineapple cultivation on peat soils. However, foliar fertilization is becoming increasingly popular. Large scale pineapple plantations commonly adopt foliar fertilization to complement the use of plastic mulch for weed suppression and to support high density planting systems. Determining the optimum growth stage of MD2 pineapple under foliar fertilizer application before floral induction is essential for maximizing fruit yield and quality. This study was conducted using a randomized complete block design with four replications to determine the optimal timing of floral induction for MD2 pineapple cultivated on peat soil under foliar fertilization. Floral induction was applied at seven, eight, nine, ten and eleven months after planting. Vegetative growth parameters measured before floral induction including D-leaf length, D-leaf width, plant height and number of leaves showed no significant differences among treatments. However, growth parameters generally increased with plant age and were positively correlated with the timing of floral induction although growth tended to stabilize beyond a certain stage. Plant height and D-leaf weight differed significantly between seven and eight MAP but no significant differences were observed from nine to eleven MAP. A similar trend was observed for leaf number and total plant fresh weight, which increased until ten MAP before reaching a plateau. Fruit quality attributes including total soluble solids and titratable acidity were not significantly affected by the timing of floral induction. In contrast, fruit fresh weight increased with plant age at induction contributing to higher estimated yields. Floral induction at seven months after planting resulted in a significantly greater proportion of small sized fruits whereas no significant differences were observed among the other induction ages. The proportion of medium sized fruits remained consistent across all treatments. Based on overall vegetative growth, fruit yield and quality parameters, floral induction at nine months after planting was identified as the most suitable induction age for MD2 pineapple cultivated on peat soil under foliar fertilization.

Keywords: Ananas comosus, Foliar fertilizer, Floral induction timing, Peatland agriculture, Fruit quality

1. INTRODUCTION

Pineapple (*Ananas comosus* L. Merr.) particularly the MD2 cultivar is one of the most economically important tropical fruit crops due to its high yield potential, uniform fruit characteristics and strong global demand [1][2]. The expansion of pineapple cultivation into peat soil areas especially in Southeast Asia and specifically in Malaysia has introduced significant agronomic challenges including low nutrient availability, high soil acidity and poor nutrient retention capacity [3][4]. These constraints often result in inefficient fertilizer use and reduced crop productivity if not properly managed. Conventional pineapple production systems rely heavily on granular fertilizers. However, nutrient losses through leaching are particularly severe in peat soils with potassium recovery reported to be as low as 28% [3]. Recent studies have highlighted the need for improved nutrient management strategies including the integration of alternative fertilization approaches such as biochar amendments and microbial fertilizers to enhance nutrient use efficiency and plant growth [5][6]. These findings emphasize the importance of optimizing fertilization techniques for sustainable pineapple production on peat soils.

Foliar fertilization has emerged as an effective complementary strategy to soil fertilization for pineapple cultivation allowing nutrients to be directly absorbed through leaf tissues and reducing dependence on soil nutrient availability. In many bromeliad species particularly pineapple for fresh consumption, the outer leaf layer contains dead cells capable of absorbing water and nutrients while the leaf stalk facilitates their transport into the inner tissues [7]. This characteristic allows pineapple plants to efficiently absorb nutrients from fertilizers through both foliar and root pathways. Recent advances in precision agriculture have further highlighted the importance of foliar nutrient management particularly nitrogen which plays a critical role during the vegetative growth phase of pineapple [8][9]. Foliar based approaches are increasingly adopted in large scale plantations often combined with plastic mulch and high-density planting systems to improve nutrient uptake efficiency and weed control.

Vegetative growth is a key determinant of pineapple yield and fruit quality. Therefore, achieving optimal plant size prior to floral induction is essential. Parameters such as D-leaf length, width and

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weight, plant height and leaf number are commonly used indicators of plant maturity and readiness for induction. Recent studies confirm that nutrient availability strongly influences vegetative development, biomass accumulation and subsequent yield performance in MD2 pineapple [5][10]. Growth typically increases with plant age until reaching a physiological plateau beyond which further increases in vegetative parameters do not significantly enhance productivity. The timing of floral induction is a critical management decision in pineapple cultivation. Inducing flowering too early can result in smaller fruits due to insufficient vegetative growth while delayed induction may reduce cropping efficiency without substantial gains in yield. Recent experimental studies have demonstrated that vegetative parameters such as plant height, leaf biomass and total plant weight stabilize after a certain growth stage indicating an optimal window for induction [11]. Furthermore, fruit weight has been shown to increase with plant age at induction whereas key quality attributes such as total soluble solids (TSS) and titratable acidity (TTA) remain relatively unaffected.

Despite these advancements, there is still limited research focusing specifically on the interaction between foliar fertilization and optimal floral induction timing for MD2 pineapple grown on peat soils. Given the increasing adoption of foliar fertilization in commercial production systems, it is essential to establish guidelines for induction timing that maximize yield while maintaining fruit quality. Therefore, this study aims to determine the optimal growth stage for floral induction of MD2 pineapple under foliar fertilization on peat soil by evaluating vegetative growth parameters, yield components and fruit quality characteristics.

2. MATERIALS AND METHODS

2.1 Field Preparation

A field study was conducted at Malaysian Agricultural Research and Development Institute (MARDI) Pontian, Johor, Malaysia (1°30'9” N latitude, 103°27'25” E longitude) from June 2023 to December 2024. The experiment was arranged in a randomized complete block design (RCBD) with four replications. Treatments consisted of different timings of floral induction at seven, eight, nine, ten, and eleven months after planting (MAP). The experimental area was divided into four blocks each representing each replicate and each block contained five plots corresponding to the five treatments. Each plot measured 9.6 m × 5.1 m and was planted with 240 plants arranged in a double-row system (4 double rows × 30 plants). The planting spacing was 30 cm × 60 cm × 90 cm resulting in a planting density of approximately 43,000 plants per hectare. A buffer zone of 1.5 m was maintained between plots to minimize treatment interference.

Uniform and healthy MD2 pineapple planting materials, with an average size of 30 cm were selected for the study. Prior to planting, all planting materials were treated with a fungicide containing mancozeb (80% w/w; Ken-Manco, Kenso Corporation, Selangor, Malaysia) at a rate of 1 g L^{-1} solution to prevent fungal infection. The experimental plots were maintained under rainfed

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conditions with no supplementary irrigation applied throughout the study period. The water table level was maintained at approximately 1.0 – 1.5 m below the soil surface to ensure suitable moisture conditions for pineapple growth on peat soil. Weed control was performed through a combination of manual hand weeding and application of a selective herbicide containing ametryn (45% w/w; Amepax 500, Imaspro Resources, Selangor, Malaysia). All other crop management practices were applied uniformly across treatments to ensure consistency.

2.2 Fertilizer Application and Flowering Induction

Foliar fertilizer was applied monthly at a rate of 4.6 g per plant. The fertilizer used was a fully water-soluble formulation with an NPK ratio of 18:18:18 (YaraTera Kristalon Green, Yara International (M) Sdn. Bhd., Selangor, Malaysia) enriched with trace elements including B, Cu, Fe, Mn, Mo, and Zn in chelated form. Fertilizer application was carried out monthly and terminated one month prior to floral induction. No basal application of granular fertilizer was applied to the soil for any treatment.

Floral induction was performed at seven, eight, nine, ten and eleven MAP. Induction was achieved by applying approximately 50 mL of a solution containing 400 mg L^{-1} ethephon (2-chloroethyl phosphonic acid) and 15 g L^{-1} urea into the pineapple rosette during the early morning (before 10:00 a.m.). Foliar fertilizer applications were conducted using a tractor mounted boom sprayer with a 400 L tank capacity powered by the tractor power take off (PTO) which drives the pump system to deliver pressurized spray solution. The sprayer was equipped with flat fan nozzles to ensure uniform coverage of the pineapple foliage. Applications were carried out at a constant pressure and calibrated spray volume to ensure consistent distribution across all treatments with an application rate of approximately 2000 L ha^{-1}.

2.3 Plant Growth Rate

For vegetative data collection, a total of 48 plants were sampled from each treatment with 12 plants randomly selected per replication. Measurements were recorded at 2, 4, 6, 8, and 10 months after planting (MAP). The parameters assessed included plant height, D-leaf length, D-leaf width and the number of functional leaves. The D-leaf, defined as the longest leaf, was used as an indicator of plant growth and nutritional status [12]. Plant height was measured vertically from the tip of the D-leaf to ground level using a meter ruler. D-leaf length was measured from the leaf tip to its base while D-leaf width was measured horizontally approximately 10 cm above the leaf base using either a 1 m or 30 cm ruler. The number of functional leaves was determined by manual counting excluding leaves shorter than 10 cm.

Destructive sampling was conducted prior to hormonal induction involving 12 plants per subplot with a total of 48 plants collected. Plant growth data were recorded including plant height, leaf

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width and length of D-leaf, and D-leaf fresh weight. For each plant, total fresh weight, leaf weight, stem weight, and root weight were measured and the number of functional leaves was recorded including leaves shorter than 10 cm except dried leaves. Plants were carefully uprooted and cleaned to remove peat soil. All leaves were detached from the main plant leaving only the stem and root system. The stem and root portions were then separated at the point of root initiation to distinguish between stem and root biomass in pineapple plants.

2.4 Pineapple Fruit Quality and Yield

For fruit quality assessment, twelve plants were sampled from each treatment with three plants selected per replication. All samples were harvested at the same maturity index (index 2) to ensure uniformity.

Parameters measured included fresh weight and length of the fruit, inflorescence and crown. Fresh weight was determined using an electronic balance (FX-3000i, A&D, Tokyo, Japan), while fruit length was measured using a caliper. TSS and TTA were determined using a pocket brix–acidity meter (PAL-BX ACID F5, ATAGO, Japan).

Yield estimation was conducted based on the total fresh fruit weight within each treatment subplot. Fruit fresh weight was measured using an electronic balance excluding rejected fruits affected by diseases or defects or nonflowering plant within a subplot size of 10.5 m × 5.1 m (53.55 m^2). The total fresh fruit weight from each subplot was recorded and subsequently extrapolated to yield per hectare expressed as estimated yield (t ha^{-1}). In addition, fruit weight data for each treatment were classified into three categories; small (S, <1.2 kg), medium (M, 1.2–1.6 kg), and large (L, >1.6 kg).

2.5 Statistical analysis

Data were analysed using analysis of variance (ANOVA). Differences among treatment means were separated using Duncan's Multiple Range Test (DMRT) or T-Test at the 5% and 0.1% significance level. Statistical analyses were performed using IBM SPSS Statistics Version 29.0.2.0 (IBM Corp., Armonk, NY, USA).

3. RESULTS AND DISCUSSION

3.1 Plant Growth Rate During Vegetative Stage

Table 1: Plant growth rate parameters during the vegetative stage of MD2 pineapple.

	Plant height (cm)					D-leaf length (cm)				
MAP	2	4	6	8	10	2	4	6	8	10
7	44.6 b	63.4 b	75.3	-	-	41.5 b	56.1	65.5	-	-
8	44.8 b	64.6 ab	76.0	88.1	-	42.3 b	57.0	66.7	74.7	-
9	45.5 ab	63.3 b	74.7	89.7	-	43.5 ab	57.4	66.2	76.7	-
10	47.7 a	66.7 a	77.5	90.0	105.0	45.2 a	58.7	69.2	76.8	88.7
11	46.2 ab	66.5 a	77.1	90.0	103.6	43.2 ab	57.9	67.1	76.8	86.6
p	*	*	ns	ns	ns	*	ns	ns	ns	ns
	D-leaf width (cm)					No. of functional leaves				
MAP	2	4	6	8	10	2	4	6	8	10
7	2.9	4.2	5.1	-	-	25.4	31.5	36.0	-	-
8	3.0	4.3	5.2	5.7	-	26.1	31.0	36.6	42.4	-
9	2.9	4.1	5.0	5.7	-	27.3	32.8	36.7	42.5	-
10	3.0	4.4	4.9	5.5	5.9	25.1	30.6	35.2	41.3	49.8
11	3.0	4.3	5.3	5.7	5.8	26.8	32.7	36.8	42.3	48.5
p	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns

*Means in each column with different letters within the column indicate significant differences at *p ≤ 0.05 level according to DMRT meanwhile two set of data will be tested by T- Test.*

The present study evaluated vegetative growth responses of MD2 pineapple across different ages of flowering induction revealing that most growth parameters increased progressively with plant age. Plant height and D-leaf length showed significant differences at early growth stages but these differences diminished as plants matured. In pineapple, leaf nutrient status particularly in the D-leaf is strongly associated with plant growth and physiological performance. D-leaf nutrient composition especially nitrogen, phosphorus and potassium have been shown to play a critical role in regulating photosynthesis, metabolism and overall plant development [14]. Therefore, the significant differences in plant height observed in this study may reflect variations in nutrient availability and uptake during early growth stages. As the plants matured, no significant differences in plant height were detected indicating a trend toward growth stabilization and uniformity among treatments. This pattern is typical in perennial crops such as pineapple where early variability diminishes as plants approach a more uniform physiological state. Similar observations have been reported in MD2 pineapple where growth parameters such as plant height

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and leaf development become more consistent over time under uniform environmental and management conditions [15].

In contrast, D-leaf width and number of functional leaves did not show any significant differences across all MAP and sampling intervals suggesting that this parameter is relatively stable during the vegetative stage. Although D-leaf characteristics are widely used as indicators of plant vigor, the present findings indicate that not all D-leaf traits are equally sensitive to growth changes or treatment effects. D-leaf width, in particular, may be more genetically regulated and less responsive to short-term variations in environmental or nutritional conditions. The lack of significant variation in D-leaf width may also indicate that the plants were grown under relatively optimal and uniform conditions, with minimal stress or nutrient limitation. Previous research has shown that leaf morphological traits tend to remain stable under favorable conditions but exhibit greater variability under stress or nutrient deficiency [16]. Furthermore, D-leaf measurements are commonly used in pineapple growth studies as standard indicators of plant nutritional status and physiological activity including chlorophyll content and stomatal function [15].

3.2 Pineapple Growth Parameter Before Floral induction

Table 2: Plant growth rate parameters of MD2 pineapple taken a month prior to floral induction.

MAP	D-leaf weight (g)	No. of functional leaves	Total plant weight (kg)	Leaf weight (kg)	Stem Weight (g)	Root weight (g)
7	66.0 c	37.1 c	1.29 c	1.12 c	73.1 d	96.0 d
8	79.5 b	41.9 b	1.94 b	1.69 b	148.6 c	114.4 d
9	84.4 b	43.8 b	2.15 b	1.83 b	156.7 bc	160.1 c
10	94.6 a	49.2 a	2.91 a	2.48 a	192.9 a	240.9 b
11	92.2 a	47.1 a	2.95 a	2.50 a	175.5 ab	270.7 a
p	**	**	**	**	**	**

*Means in each column with different letters within the column indicate significant differences at **: $p \leq 0.001$ level according to DMRT.*

The results in Table 2 demonstrate a highly significant increase in D-leaf weight, number of functional leaves, total plant weight and biomass partitioning including leaf, stem and root as MD2 pineapple plants approached the stage prior to floral induction. The steady increase from 7 to 11 MAP indicates continuous vegetative development and the accumulation of sufficient assimilates required for successful transition from vegetative to reproductive growth. The increase in D-leaf weight reflects enhanced physiological activity and assimilate accumulation in the most functionally important leaf of pineapple. Chen et al. confirms that pineapple growth and productivity are strongly influenced by leaf nutrient dynamic particularly nitrogen, phosphorus, and potassium levels in mature leaves [14]. Moreover, MD-2 vegetative performance has been shown to improve significantly under optimized nutrient management where increased leaf biomass corresponds with higher photosynthetic capacity and better plant vigor [17].

The number of functional leaves also increased significantly across MAP indicating progressive canopy development. This is particularly important in pineapple because flowering competence is closely linked to plant maturity and leaf number. A recent review by Chen et al. emphasizes that pineapple floral induction occurs only after plants reach a critical developmental threshold defined by sufficient leaf count and plant biomass [18]. Similarly, classical work by Malezieux et al. established that leaf area and functional leaf number are key determinants of carbon assimilation capacity which directly supports reproductive development [19]. Total plant weight showed a consistent and significant increase particularly at 10 and 11 MAP suggesting that plants had reached a physiological threshold suitable for floral induction. This aligns with findings by Valleser who reported that MD2 pineapple plants at 10 to 11 months exhibited significantly higher biomass and more responsive to flowering induction treatments compared to younger plants [20]. In addition, floral induction studies have shown that plant weight is a critical maturity indicator as insufficient biomass can delay or reduce flowering success [18].

Biomass partitioning results further revealed significant increases in leaf, stem and root weight. Leaf biomass increased steadily reflecting enhanced photosynthetic capacity and assimilate production. Stem biomass also increased indicating its role as a carbohydrate storage organ that supports the high energy demand during floral transition. Root biomass showed the greatest proportional increase at 11 MAP suggesting improved water and nutrient uptake capacity. This is consistent with Taiz et al. who highlighted that balanced root and shoot development is essential for maintaining physiological stability and supporting high metabolic demand during plant maturation [21]. Rodríguez et al. demonstrated that fertilization systems significantly influence D-leaf weight, plant biomass and leaf number in MD2 pineapple with higher nutrient availability leading to earlier attainment of floral induction weight [17]. Likewise, Chen et al. reported that pineapple flowering is tightly regulated by plant developmental status particularly leaf number, biomass accumulation and physiological maturity [18].

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3.3 Pineapple Fruit Quality and Yield

Table 3: MD2 pineapple fruit quality parameters harvested on varying MAP.

MAP	Total Fruit fresh weight (kg)	Fruit fresh weight (without crown) (kg)	TSS (°Bx)	TTA (%)	Est. Yield (t ha^{-1})	Fruit to plant fresh weight ratio
7	1.40 c	0.99 c	13.2	0.47	37.1 b	0.61 c
8	1.60 b	1.20 b	12.3	0.49	53.6 a	0.85 a
9	1.86 a	1.50 a	13.5	0.52	57.2 a	0.83 a
10	1.85 a	1.52 a	12.8	0.46	58.3 a	0.73 b
11	1.85 a	1.45 a	12.6	0.58	54.7 a	0.59 c
	**	**	ns	ns	**	**

*Means in each column with different letters within the column indicate significant differences at *p ≤ 0.05 and **: p≤0.001 level according to DMRT.*

The results in Table 3 demonstrate that MD2 pineapple fruit quality and yield parameters were significantly influenced by MAP. Total fruit fresh weight and fruit weight without crown increased significantly from 7 to 9 MAP after which values stabilized from 9 to 11 MAP. This suggests that fruit growth reaches a physiological plateau during the later stages of development where assimilate accumulation and sink strength become balanced. The increase in fruit weight with advancing MAP reflects improved source–sink relationships where mature canopy enhances photosynthate production and translocation to the fruit. Recent studies on MD2 pineapple confirm that yield and fruit size are strongly dependent on vegetative biomass and leaf functional capacity particularly during the fruit filling stage [13]. Similarly, MD2 is widely recognized for its superior fruit size and uniform quality when harvested at optimal physiological maturity [22].

TSS ranged from 12.3 to 13.5 °Bx across MAP indicating consistently acceptable sweetness levels for commercial MD2 pineapple. Although differences were not statistically significant, the values fall within the typical quality range for fresh market pineapples. Recent physicochemical studies of MD2 fruit have shown that TSS tends to increase gradually with maturity due to starch hydrolysis and sugar accumulation in the pulp tissues [23]. This process is closely linked to ripening physiology and carbohydrate metabolism during fruit development. TTA ranged from 0.46 to 0.58%, showing relatively stable acid levels across MAP. This stability indicates balanced organic acid metabolism during ripening. Similar findings have been reported where acidity decreases or stabilizes as fruit maturity progresses, contributing to improved flavor balance [23][24]. The interaction between TSS and TTA determines the sugar acid ratio which is a key determinant of consumer acceptability in MD2 pineapple.

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Estimated yield increased significantly from 37.1 t ha^{-1} at 7 MAP to a maximum of 58.3 t ha^{-1} at 10 MAP before slightly declining at 11 MAP. This pattern suggests that 9–10 MAP represents the optimal yield window for MD2 pineapple under the studied conditions. MD2 yield performance is strongly influenced by planting density, nutrient management and flowering induction timing [13]. The plateau observed from 8 to 11 MAP suggests that physiological maturity for fruit weight accumulation occurs around 8 MAP in MD2 pineapple under the current conditions.

The fruit to plant ratio (FPR) is an important agronomic indicator representing the efficiency of biomass partitioning into economic yield which is fruit relative to total plant biomass. The observed increases in fruit weight and yield with MAP suggest an improvement in FPR as plants reached physiological maturity. A higher FPR indicates more efficient assimilate partitioning towards reproductive organs rather than vegetative structures. FPR is strongly influenced by plant vigor, leaf area development and carbohydrate availability during fruit filling. Fully developed plants with higher functional leaf numbers and greater D-leaf weight tend to exhibit improved assimilate translocation efficiency, resulting in higher fruit biomass proportion relative to total plant biomass. Bartholomew et al. emphasized that pineapple yield formation depends on the balance between vegetative growth and reproductive sink strength where optimal management enhances partitioning efficiency toward the fruit [25]. [13] have further highlighted that improving source–sink balance through optimized nutrient management significantly increases fruit yield proportion relative to total plant biomass thereby improving FPR and overall production efficiency. The stabilization of fruit weight and yield at 8 to 10 MAP suggests that FPR likely reached its maximum efficiency during this period indicating optimal physiological maturity for harvest.

3.4 Distribution of fruit grading based on fruit weight

Table 4: MD2 pineapple fruit grading distribution based on weight fruit grading throughout MAP.

MAP	S; <1.2kg (%)	M; 1.2-1.6kg (%)	L; >1.6kg (%)
7	63.3 a	24.3	12.3 b
8	38.8 b	26.2	35.0 a
9	30.3 b	27.3	42.5 a
10	26.0 b	26.7	47.3 a
11	31.5 b	29.0	39.5 a
p	**	ns	**

*Means in each column with different letters within the column indicate significant differences at **: p≤0.001 level according to DMRT.*

The results in Table 4 show that MD2 pineapple fruit grading distribution based on fruit weight was significantly influenced by months after planting (MAP) particularly for the small and large size fruit category which showed a highly significant difference. In contrast, the medium fruit category showed no significant differences across MAP indicating relatively stable distribution in this class. The proportion of small fruits was highest at 7 MAP and decreased markedly at later MAP stabilizing from 8 to 11 MAP. This indicates that early floral induction resulted in a higher proportion of undersized fruits likely due to insufficient assimilate accumulation due to unreadiness of plant for induction. As MAP increases, improved vegetative growth and canopy development enhance assimilate supply to the developing fruit resulting in better fruit sizing and reduced proportion of small size fruits. This trend aligns with findings by Bartholomew et al. who emphasized that pineapple fruit size is strongly dependent on plant maturity, leaf area development and carbohydrate availability during fruit filling [25].

From a commercial perspective, the reduction in small fruit proportion at later MAP is highly important as it directly improves marketable yield and economic return. Fruit grading distribution is a key postharvest quality indicator as larger and more uniform fruits typically command higher market value. Recent agronomic studies on pineapple production systems have highlighted that improved crop management and optimal harvest timing significantly increase the proportion of market-grade fruits by enhancing assimilate allocation efficiency [26].

4. CONCLUSIONS

Floral induction timing significantly affects vegetative growth, yield, fruit quality and grading distribution of MD2 pineapple on peat soil under foliar fertilization. Vegetative parameters increased with plant age and stabilized at later stages indicating sufficient physiological maturity at 10 to 11 MAP.

Fruit yield and size were highest at 8 to 10 MAP with improved fruit weight and yield while internal quality remained relatively stable. Earlier induction produced a higher proportion of small fruits whereas later induction increased the proportion of medium and large fruits improving marketable yield.

Overall, 9 MAP is the optimal range for floral induction of MD2 pineapple providing the best balance between plant maturity, yield performance and fruit quality under foliar fertilization on peat soil.

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