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Reduction of the mangosteen tree (*Garcinia mangostana* L.) production cycle: effect of soil type and fertilisers

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Abstract

Background Shortening the vegetative cycle of slow-growing crops is a significant challenge for breeders, agronomists, and growers. This reduction is particularly crucial for the mangosteen (*Garcinia mangostana*) as it would make it easier for farmers to adopt this crop. The mangosteen tree is notoriously slow-growing, taking between 8 and 15 years to produce its first fruits. The plant's slow growth and late fruiting pose a significant obstacle to its adoption and spread in rural areas. In Côte d'Ivoire, these constraints have limited its cultivation to small farms owned by a few producers. However, it could be an alternative for diversifying agricultural income and contributing to poverty reduction in rural areas. This study aims to evaluate the effects of soil type and fertiliser on the agronomic parameters of mangosteen tree growth. The goal is to contribute to shortening its vegetative phase.

Results The study results indicate that soil type and fertiliser have a significant effect on mangosteen growth parameters. Evaluating the agronomic performance of mangosteen, it was found that lowland soil promotes better plant growth. Growth rate and height growth were found to be significantly influenced ($p = 0.03$). After 36 months of monitoring, the growth rates for mangosteen trees grown on lowland soil were 53.08 ± 7.30%, while those grown on forest soil were 41.51 ± 13.43%. Additionally, the use of foliar and granular N-P-K fertilisers resulted in earlier fruiting, starting from the 5th year of cultivation.

Conclusions The results showed that fertilisers play a crucial role in managing and shortening the juvenile phase of the mangosteen tree. Foliar and NPK fertilisers performed exceptionally well, resulting in earlier fruiting of mangosteen trees, starting from the 5th year of cultivation.

Keywords Mangosteen, Fertilisation, Plant growth, Production, Soil type

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Background

Côte d'Ivoire's fruit sector is a crucial contributor to the country's economy, generating over $400 million in foreign exchange annually. Bananas, pineapples, and mangoes dominate the country's fruit exports, while other crops are often overlooked due to their classification as minor crops. The mangosteen is one crop that is often overlooked in agricultural research evaluations (Haba et al. 2023).

The mangosteen tree (*Garcinia mangostana* L.) is a tropical fruit tree cultivated mainly in Southeast Asia, specifically in Indonesia, Thailand, and Cambodia (Setiawan et al. 2023). Thailand is the main producer of mangosteen globally, with an estimated annual production of 240,000 tonnes out of the total global production of 700,000 tonnes (Altendorf 2018). The mangosteen is not only highly prized for its flavour, earning it the title of 'Queen of Fruits', but also for its excellent medicinal properties. Research efforts have focused on highlighting the plant's therapeutic virtues (Aizat et al. 2019). Studies have shown that mangosteen has remarkable antioxidant, antitumour, anti-allergic, anti-inflammatory, antibacterial, and antiviral properties (Gina 2023). The plant and its fruit, particularly the pericarp, contain a wealth of bioactive substances, such as vitamins, catechins, polysaccharides, and polyphenols. However, it is the high concentration of xanthones (over 40) that makes this fruit an effective tool in preventing and treating various diseases.

Among the beneficial effects of the mangosteen is its role in limiting the effects of bad cholesterol, thus preventing the risk of atherosclerosis and blood clot formation. According to Muchtaridi et al. (2018) and Beatrice and Pietradewi (2020), mangosteen pericarp extracts would limit the growth of various liver and pancreatic cancer cells.

In Côte d'Ivoire, the mangosteen tree was introduced in 1970 through the fruit programme of the Research Institute for Colonial Fruits and Citrus (IFAC) in Azaguié. The work initiated by Bourdeaut and Moreuil (1970) on the possibilities of introducing the species in Côte d'Ivoire was convincing and encouraged some growers to move towards this crop. Since then, its cultivation has been limited to small farms belonging to a few producers, although it could be an alternative for diversifying agricultural recipes (Florent et al. 2021). Indeed, there are many constraints to mangosteen cultivation that are a real obstacle to its spread. To date, very little information is available on mangosteen production techniques in Côte d'Ivoire. The very slow growth and late fruiting of the tree are the main constraints that have led to its reluctance to be adopted by farmers (Haba et al. 2023). In such a context, shortening the mangosteen production cycle through fertilisation would be a solution worth exploring. In fact, fertilisation is the best way for the plant to meet its mineral requirements (Hafez et al., 2020. Several research studies have highlighted the very significant influence of fertilisation in improving flowering and fruiting in plants. This is the case of work initiated by Amit et al, (2021) who have shown that late flowering to fruit development is a period of high mineral demand. It has also been shown that the structural and mineral quality of the soil has a significant effect on crop development. For example, soils that are poor in organic matter may not release minerals from the soil efficiently. Post-harvest fertilisation can therefore help to support late harvests (Długosz and Piotrowska, 2023). In view of the above, it is necessary to determine the type of soil and fertiliser suitable for mangosteen cultivation. In fact, the vegetative development of the mangosteen could be influenced by the type of soil and fertiliser used. However, it must be said that this solution has not yet been researched. Therefore, it makes sense to conduct research aimed at shortening the vegetative phase of the tree and its production time. The present study was therefore initiated with the aim of evaluating the effects of soil type and fertiliser on the agronomic parameters of mangosteen growth with a view to shortening the vegetative phase.

Material and methods

Presentation of the study area

The experimental studies presented in this study were carried out in the commune of Azaguié (Agneby-Tiassa region), located in south-eastern Côte d'Ivoire, about 40 km North of the Abidjan district, between the coordinates 5°35 and 6°15 North latitude and 3°55 and 4°40 West longitude (Kouadio et al. 2021). The commune covers an area of 201.3 km^2 and is bordered to the north by the sub-prefecture of Agou, to the south by the commune of Anyama, to the east by the communes of Alépé, and to the west by the commune of Agboville (Fig. 1). The study site is located about 2.5 km from the village of Abbèbegnini (villages of the commune of Azaguié). This site is located between the coordinates 5°62 North latitude and 3°98 West longitude. The vegetation cover of the site consists of an alternation of forest, fallow land, and farms, which is very characteristic of the region. The area of the property is approximately 60 hectares, of which mangosteen is the main crop and occupies approximately 23 hectares.

The evolution of temperature and rainfall at the study site over the three years (2019–2021) during which the experiments took place shows that the site is characterised by high rainfall. The recorded rainfall was 1836 mm in 2019, 2112 mm in 2020, and 2052 mm in 2021. The average temperatures recorded were 25.1 °C, 26.1 °C, and 25.3 °C, respectively, during these three years. The data collected made it possible to distinguish four growing seasons for each year. These seasons consist of a long dry season (November to March), a rainy season (April to June), a short dry season (July to August), and a rainy season (September to October).

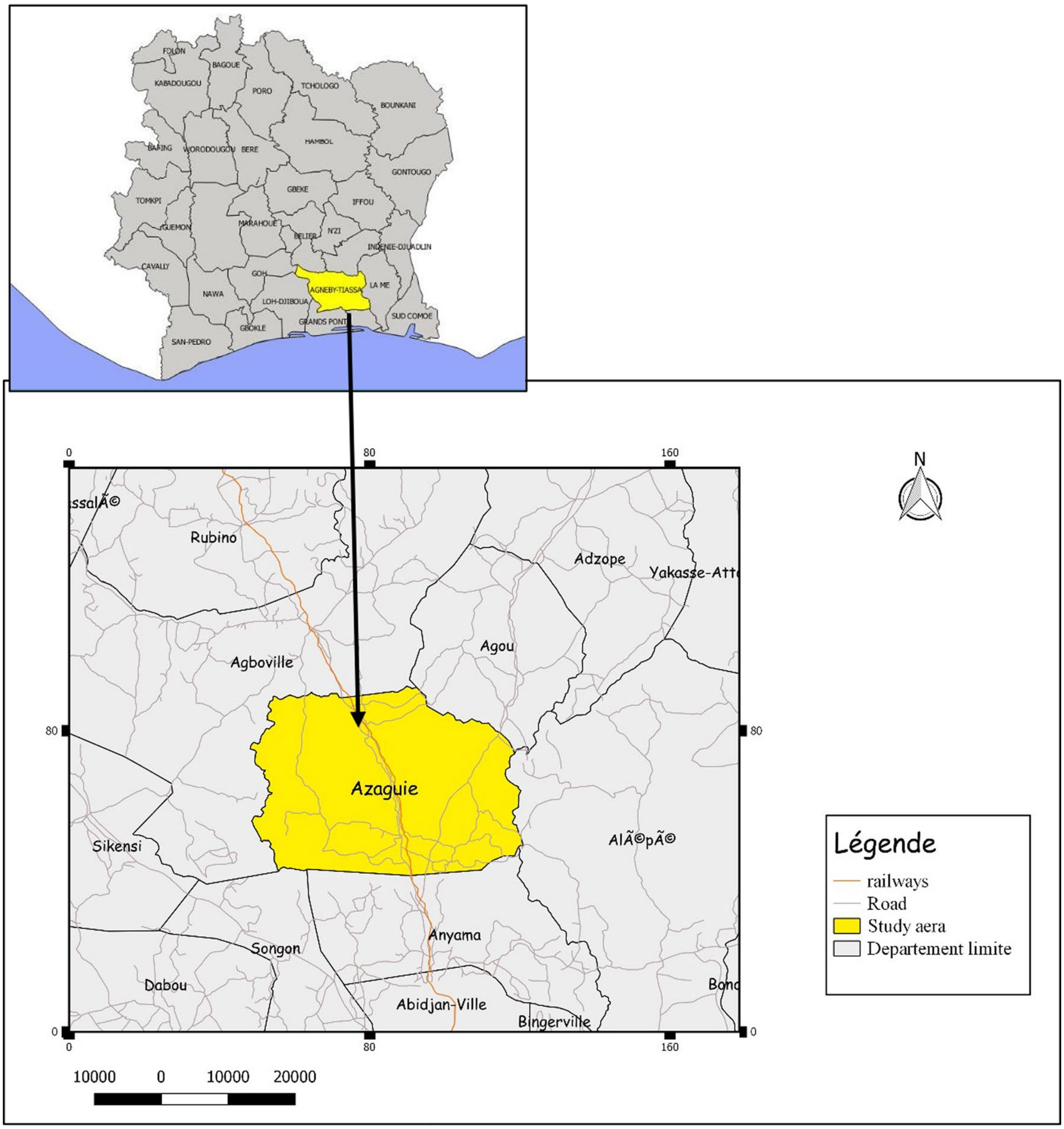

Fig. 1 Localisation of the study area

Plant material

The plant material used consisted of young mangosteen seedlings aged between 1 and 6 years (Fig. 2).

Methods

The study aimed to determine the best conditions for growing mangosteen trees by evaluating the impact of soil type and fertiliser on agronomic parameters. The study was conducted over three years (2019–2021) on two types of soil. There were two experimental plots: one located in a forest understorey and the other in an irrigated lowland.

Physico-chemical soil analysis

The initial fertility status of the two soil types on which the experiments were carried out was determined. The chemical parameters determined were hydrogen potential (pH) and electrical conductivity (EC), organic matter (OM), and total organic carbon (TOC) according to the methods of the Centre of Expertise in Environmental Analysis of Quebec (CEAEQ, 2003). The determination of nitrogen (N) was based on the Kjeldahl method NF V04-407 (AFNOR 2004). For phosphorus (P), potassium (K) and magnesium (Mg) content, the method used was inspired by that described by CEAEQ

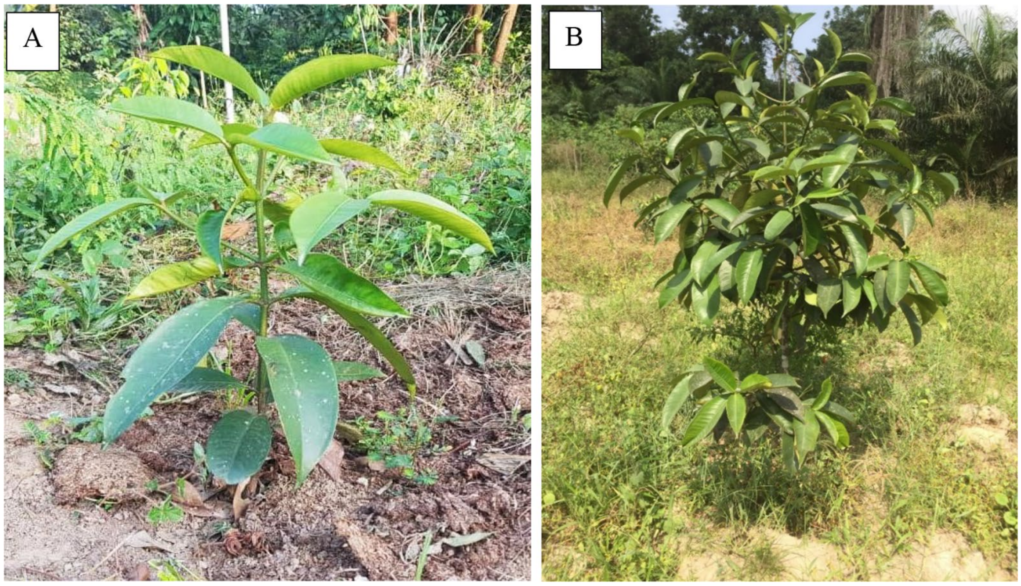

Fig. 2 Plant material. **A** 1-year-old mangosteen seedling; **B** 5-year-old mangosteen seedling

and AOAC (AOAC, 1990; CEAEQ, 2003). For the physical parameters, the particle size, i.e. the sand, clay, and silt content, was determined using the method of Gee and Bauder (1986).

Preparation of experimental plots

All experimental plots were chemically weeded 8 weeks prior to fertiliser application. The herbicide used was glyphosate, sold under the trade name Glycel. After weeding, the plots were cleared of plant debris to facilitate fertiliser application. Finally, the mangosteen trees were selected and marked.

The experimental design used was a complete randomised block with four replicates for each soil type. The factors studied were the effect of fertiliser type as a primary factor and soil type as a secondary factor. A total of 40 elementary plots of 950 m^2 each were formed, divided into eight blocks (four blocks on each soil type). The performance of a single treatment was evaluated on each elementary plot consisting of ten plants. Spaces of 10 and 20 m were observed between the plants of the same plot and between the plots of the same block. The fertilisation treatments applied were:

T1 = NPK mineral fertiliser.
T2 = organic fertiliser.
T3 = foliar fertiliser.
T4 = biostimulant.
T0 = control (plants that received no treatment).

Description, quantity and method of fertiliser application

Fertilisers were applied in accordance with fertiliser recommendations, thereby limiting the risk of loss and soil contamination (FOEN and FOAG, 2012). The quantities and methods of application were in accordance with the manufacturers' recommendations. However, the doses and frequency of fertiliser application varied according to the physiological state of the plants. The choice of fertilisers used was justified by their specific characteristics. The fertilisers differ in their chemical composition, methods of application, and the way in which they are absorbed by the plant.

NPK mineral fertiliser

The mineral fertiliser used was a fully granulated NPK fertiliser with the formula 15–15–15. This fertiliser was purchased from Calivoir CI and its formula was laboratory tested prior to use. The amount of fertiliser applied to the mangosteen trees depended on their physiological state. Thus, 250 g or 25 $kg.ha^{-1}$ and 500 g or 50 $kg.ha^{-1}$ of NPK were applied to the mangosteen trees in rows using a balance. The fertilisers were applied within the limits defined by crowns of 0.5 to 1 m radius (radii of the mangosteen rhizosphere) and then covered with soil to limit the risk of losses (Table 1).

Organic fertiliser: compost

The compost used was produced from poultry manure. This organic fertiliser was produced on the study site

Table 1 Quantities, methods, and frequency of fertiliser applications used for the evaluation of growth parameters

Fertilisers	Formulas	Quantities or doses/age	Application method	Application frequency
NPK Compost Foliar fertiliser biostimulant	Granulated 15–15–15	C1: 25 $kg.ha^{-1}$ C2: 50 $kg.ha^{-1}$	Online localization	3 months
	Poultry manure	C1: 100 $kg.ha^{-1}$ C2: 200 $kg.ha^{-1}$	Online localization	6 months
	12.3 Nitrogen; 6.2 Boron; 0.21 Molybdenum	3 l/ha	Foliar application	C1: 30 days C2: 60 days
	Calcium; Boron	3 l/ha	Foliar application	C1: 30 days -C2: 60 days

Table 2 Physico-chemical characteristics of compost

Settings	Values
pH water	6.4 ± 0.0
pH_{KCl}	5.9 ± 0.0
EC ($\mu S.cm^{-1}$)	281 ± 2.4
OM (%)	50.3 ± 1.2
TOC (%)	29.1 ± 0.7
N (%)	4.3 ± 0.0
C/N	6.7 ± 0.1
TP ($g.Kg^{-1}$)	21.6 ± 2.6
K^+ ($g.Kg^{-1}$)	32.4 ± 1.3

pH Hydrogen potential, *EC* Electrical conductivity, *OM* Organic matter, *TOC* Total organic carbon, *N* Nitrogen, *C/N* Carbon/nitrogen ratio, *TP* Total phosphorus, K^+ Potassium

using a heap composting technique. After cleaning the poultry houses, the collected manure was poured into trenches 1 m deep and 2.5 m long and watered regularly. The composting process took 4 months. The mineralogical composition of the compost produced is shown in Table 2. Prior to application, the compost was treated with fungicides and insecticides to eliminate any harmful organisms (fungi and insects) present. The amounts of compost applied to the mangosteen trees were 10 kg or 100 $kg.ha^{-1}$ and 20 kg or 200 kg.ha-1 for each physiological state. The compost was applied in rows in crowns with a defined radius of 0.5 m around each plant. The frequency of application of this fertiliser was 6 months for all classes. (Table 1).

Foliar fertiliser

The performance of an amino acid formula containing 12.3 $g.l^{-1}$ nitrogen, 6.4 $g.l^{-1}$ boron, and 0.21 $g.l^{-1}$ molybdenum was evaluated on mangosteen tree growth. This fertiliser is marketed under the name Codamin and is distributed in Côte d'Ivoire by the AGRO services group. This fertiliser was applied according to the manufacturer's instructions at a dose of 300 ml per 100 l of water, i.e. 3 l/ha. The application method was foliar. A 15 l constant pressure sprayer was used. The amount of spray received per plant was 100 ml every 30 days for the youngest mangosteen trees (1 to 3 years old) and 200 ml every 60 days for the oldest mangosteen trees (Table 1).

Biostimulant

The biostimulant used is a mixture rich in calcium and boron, which is used in fruit growing. This product is distributed in Côte d'Ivoire by the Agritecno West Africa group and is marketed under the name Tecnokel. It was applied with a 15-L constant pressure sprayer. The amount of spray received per plant was 100 ml every 30 days for the youngest mangosteen trees (1 to 3 years old) and 200 ml every 60 days for the oldest. (Table 1**).**

Parameters evaluated

The agronomic growth parameters evaluated were inspired by those described by Castro-Díez et al. (1998).

Height (HP) and growth rate (Gr)

Plant height growth remains one of the most important agronomic performance indicators (Castro-Díez et al. 1998). In this study, height measurement consisted of determining the length of the main axis of the mangosteen trees from the collar to the ends of the last leaves. The measurements were made with a tape measure. The periodic evaluation of the height of the seedlings allowed the growth rate of the mangosteen trees to be determined using the following formula:

$$\mathrm{Gr} = \frac{H\mathrm{P2} \text{ - } \mathrm{HP1}}{\mathrm{HP2}} \times 100 \quad (1)$$

With Gr: as growth rate (%), HP l: as initial height of the plants (m), HP 2: as plant height at last measurement (m).

Span of plants (SP)

Wingspan is a parameter that reflects the level of growth and health of a plant. The measurement of the wingspan of the plants consisted of measuring the diameter of the ends of the leaves of the mangosteen trees using a tape measure, following the north–south and east–west orientations (Castro-Díez et al. 1998).

Collar diameter (Dcol)

The diameter of the space between the stem and the root of the mangosteen tree (the collar) was measured using a calliper gauge on each of the plants used.

Robustness quotient (RQ)

The hardiness quotient is the ratio between the height of the stem and the diameter at the collar of the plants. According to this parameter, the most robust plants have a better chance of survival than the less robust ones (Dong et al. 2020). A plant is considered robust if this parameter is low. This parameter was evaluated using the following formula:

$$RQ = HP/DC \quad (2)$$

With RQ: as robustness quotient ($cm.mm^{-1}$), HP: as stem height (cm), DC: as neck diameter (mm).

Length and width of leaves (Le and wth)

Leaf length and width were measured using a millimetre ruler. The length was measured from the point where the leaf petiole attaches to the upper leaf tip, while the width was determined by measuring the diameter of the leaf blade. For young plants, measurements were taken on five randomly selected leaves, while for older plants, ten leaves from each pair of branches were randomly selected.

Number of branch peers (NPr)

The number of branches, or ramifications, in the plants was also counted. Generally, this parameter increases as the plants grow taller.

Leaf chlorophyll content (Tch)

The levels of chlorophyll pigment in the leaves were measured before and 4 weeks (30 days) after fertiliser applications using the method described by Lrenzen (1967). The leaves were sampled and extracted with ethanol, and the absorbance of the extracts was measured using a visible UV spectrophotometer at wavelengths of 645 and 663 nm against a blank. Chlorophyll concentration was determined using Aron's formula as described by Lrenzen (1967).

$$Tchl = 8,02(Do663) + 20,20(Do\ 645) \quad (3)$$

With Tchl: as total chlorophyll concentration (mg/ml), Do 663: as absorbance at 663 nm Do 645: as absorbance at 645 nm.

Yield (Yd)

The mass of fruit produced per tree was used to assess the yield for each treatment. To calculate the fruit yield, formula 4 was applied, extrapolating the results obtained from the individual plots to the hectare.

$$Yd = PdF/N \times \text{Number of plants/ha}$$

With Yd: yield (*t*/ha); PdF: average fruit weight per treatment (*t*); *N*: number of plants per treatment.

Statistical analysis

The data was analysed using XLSTAT Pro version 7.5 2016 software. To study the effect of the factors on the agronomic parameters of the mangosteen tree, multiple analysis of variance (MANOVA) was used. Once a significant effect of a factor was identified, one-way analyses of variance (ANOVA 1) were conducted for each parameter to determine which contributed to the effect of the factor. Multiple comparisons were made for each discriminant variable identified using the test of the least significant difference (ppds). This test helped to identify which treatment(s) differed significantly from each other.The Student's *t* test and the Mann–Whitney nonparametric test were used to compare the average mineral contents of the different types. The tests evaluated the effect of soil types and treatments on the growth and production of mangosteen trees. The quantitative data was processed using principal component analysis (PCA) to identify homogeneous groups and evaluate correlations between variables.

Results

Physico-chemical parameters of soils

The soil analysis showed that the lowland soil is sandy-loamy, consisting of 47.1 ± 1.4% sand, 32.4 ± 1.3% clay, and 20.4 ± 1.6% silt. The forest floor has a sand-loamy texture, mostly composed of sand (72.6 ± 2.9%) and silt (21.6 ± 1.8%) (Table 3).

There was a significant difference in organic matter (OM) content between the two soil types ($p < 0.001$), with the forest soil being richer in organic matter than the lowland soil. The lowland soil had an average OM value of 4.4 ± 1.3%, while the forest soil had an average OM value of 9.7 ± 2.2%. Both soil types were found to be acidic based on the recorded pH values, with mean pH values ranging from 4.9 ± 0.3 to 5 ± 0.3. The mean

Table 3 Mean values (±standard deviation) of the physico-chemical parameters of the two types of soil

Settings	Lowland soil	forest soil	*F*	*P*
Sand (%)	47.1 ± 1.4	72.6 ± 2.9	15.3	< 0.001
Silt (%)	20.4 ± 1.6	21.6 ± 1.8	2.1	0.061
Clay (%)	32.4 ± 1.3	5.7 ± 0.4	31.4	< 0.001
TH (%)	21.4 ± 0.7	4.9 ± 0.4	36.8	< 0.001
pH water	5.1 ± 0.3	4.9 ± 0.3	1.4	0.069
pH_{KCl}	5.0 ± 0.1	4.53 ± 0.6	10.3	0.042
EC (μS.cm^{-1})	101.4 ± 4.5	98.6 ± 3.2	2.1	0.053
OM (%)	4.4 ± 1.3	9.7 ± 2.2	16.3	< 0.001
TOC (%)	2.5 ± 0.7	5.6 ± 1.3	16.3	< 0.001
N (%)	0.9 ± 0.0	0.7 ± 0.0	15.5	0.021
C/N	3.8 ± 0.9	7.1 ± 1.5	20.1	< 0.001
TP (mg.Kg^{-1})	22.8 ± 3.2	16.4 ± 1.0	16.8	0.038
K (cmol.Kg^{-1})	0.2 ± 0.0	0.08 ± 0.0	31.8	< 0.001

TH Humidity rate, *EC* Electrical conductivity, *TOC* Total organic carbon, *OM* Organic matter, *N* Nitrogen, *C/N* Carbon/nitrogen ratio, *TP* Total phosphorus, K^+ Potassium

EC values were statistically identical for both soil types ($p = 0.053$). The forest soil had a higher mean value of 101.4 ± 4.5 μS.cm^{-1} compared to the lowland soil's 98.6 ± 3.2 μS.cm^{-1} (Table 3).

The results showed a significant difference in the composition of major minerals between soil types. Forest soil had mean values of 0.7 ± 0.0% for nitrogen, 16.4 ± 1.0 mg.Kg^{-1} for phosphorus, and 0.08 ± 0.0 cmol.kg-1 for potassium. In contrast, lowland soil was statistically richer in nitrogen (0.9 ± 0.0%), phosphorus (22.8 ± 3.2 mg.kg^{-1}), and potassium (0.2 ± 0.0 cmol.Kg^{-1}). The carbon/nitrogen (C/N) ratio means differed significantly ($p < 0.001$) between lowland and forest soils. The mean C/N ratio values for lowland and forest soils were 3.8 ± 0.9 and 7.1 ± 1.5, respectively (see Table 3).

Effect of soil type on mangosteen tree growth

The effect of soil type did not induce production in the mangosteen trees. In fact, no plant produced at the end of the tests, even among the oldest mangosteen trees. Overall, the results show that the mangosteen trees grew rapidly from the first to the third year of cultivation, whatever the soil type. However, this growth was faster for mangosteen trees grown on lowland soil. The highest growth rate was obtained with 3-year-old mangosteen trees grown on lowland soil (53.54%). The lowest growth rate was obtained with 6-year-old mangosteen trees grown on forest soil (16.89) (Table 4).

Table 5 presents the growth parameters of the oldest mangosteen trees after 36 months of follow-up. These trees were 6 years old at the time of the experiment. The nonparametric Mann–Whitney test showed a significant effect ($p \leq 0.05$) of soil type on two of the nine growth parameters measured: plant height (HP) and growth rate (Gr). Plants growing on lowland soil were taller than those growing on forest soil, with an average height of 4.2 ± 0.3 m compared to 2.8 ± 0.4 m, respectively. The growth rates for plants on forest soil were 16.8 ± 2.7%, while those on lowland soil were 30.1 ± 73.2%.

Effect of fertilisers on mangosteen growth parameters according to soil type

The experiment showed that fertilisers have a significant effect on the growth of mangosteen trees depending

Table 4 Growth rate of mangosteen trees according to soil type

Age	1 year	2 years	3 years	4 years	5 years	6 years
Gr LS	48.16	36.58	53.54	40.29	28.45	30.12
Gr FS	18.56	25.36	23.62	24.68	20.58	16.89
Statistics (*p*)	0.01	0.04	0.01	0.1	0.09	0.06

Gr Growth rate, *LS* Lowland soil, *FS* Forest soil

Table 5 Mean value (± standard deviation) of growth parameters of 6-year-old mangosteen trees after 36 months of follow-up

Settings		HP (m)	Gr (%)	SP (m)	Dcol (cm)	RQ	Le (cm)	Wth (cm)	Chc (mg.ml^{-1})	NPr
Soil type	Lowland soil	4.2 ± 0.3	30.1 ± 3.2	3.4 ± 0.6	7.12 ± 0.3	0.9 ± 0.1	20.69 ± 2.6	13.45 ± 2.7	24.1 ± 1.6	12.4 ± 1.2
	forest soil	2.8 ± 0.4	16.8 ± 2.7	2.8 ± 0.6	5.45 ± 1	0.7 ± 0.1	21.85 ± 4.2	17.59 ± 1.02	26.6 ± 1.9	12.0 ± 0.9
Statistical	F	5.01	5.01	0.87	0.07	0.92	0.001	0.61	0.06	0.35
	P	0.03	0.03	0.3	0.8	0.2	0.99	0.36	0.9	0.28

HP Height of plants, *Gr* Growth rate, *SP* Wingspan, *Dcol* Diameter at the collar, *RQ* Robustness quotient, *Le* Leaf length, *Wth* Leaf width, *Chc* Leaf chlorophyll content, *NPr* Number of pairs of branches

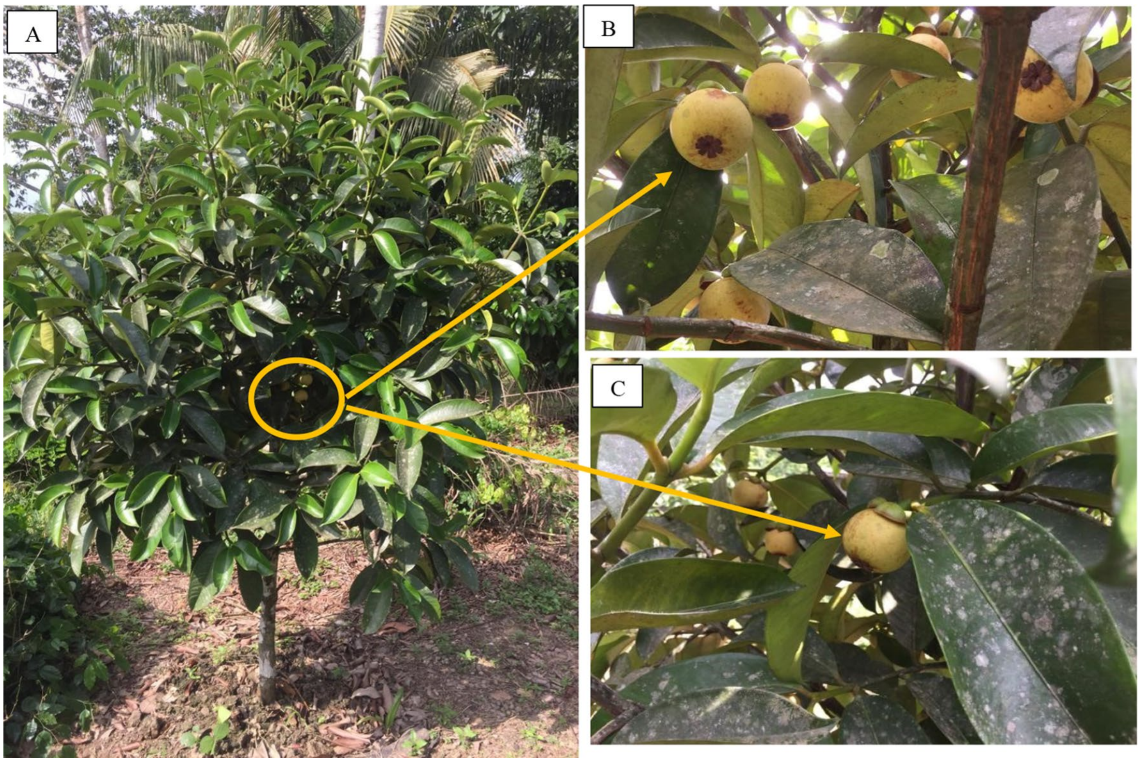

Fig. 3 5-year-old mangosteen plant bearing its first fruits. **A** mangosteen plant; **B** and **C** mangosteen fruits

Table 6 Production (in kg) of mangosteen according to age

Fertiliser	Age	yield 1 (Kg/ha)	yield 2 (Kg/ha)	yield 3 (Kg/ha)	Total (Kg/ha)
NPK	1 year	0	0	0	9.92
	2 years	0	0	2.23	
	3 years	0	0	1.57	
	4 years	0	0	0.86	
	5 years	0	1.08	1.23	
	6 years	0	0.94	2.01	
	1 year	0	0	0	
	2 years	0	0	1.98	
	3 years	0	0	2.58	
EFL	4 years	0	0	2.31	10.05
	5 years	0	0.45	0.98	
	6 years	0	1.02	1.75	

on the type of soil ($p < 0.05$). Foliar and NPK fertilisers caused the trees to bear fruit earlier, with some trees bearing fruit as early as 5 or 6 years old (Fig. 3). Fruit formation was observed in a higher percentage of plants fertilised with foliar fertiliser (11.66%) compared to those fertilised with NPK (6.66%). Mangosteen trees grown on lowland soil fertilised with NPK or foliar fertiliser showed fruit formation, unlike those grown on forest soil. The first fruit formation was observed during the third year of experimentation on plants aged 2, 3, and 4 years for these treatments (Table 6). The plants were 5 and 6 years old at the time of production. Fruit formation was observed in the second year of experimentation for the 5- and 6-year-old plants (Table 6). No fruit formation was observed for the other treatments and controls.

The yields obtained, although low, were, respectively, 9.92 kg/ha and 11.07 kg/ha with plants fertilised with NPK and foliar fertiliser. However, no significant difference was observed between the yields of plants of the same age. The mangosteen trees being of different ages, the productions obtained by age for each of the three years of experimentation are presented in Table 6.

Analysis of variance (ANOVA) showed a difference significant ($p < 0.01$) in the growth parameters, including height (HP), growth rate (Gr), the wingspan (SP) and the diameter of the collar (Dcol), in depending on the type of fertilizer and soil (Table 7). The NPK and organic fertilizers gave rise to the parameters highest growth rates. However, plants growing on lowland soils showed values of higher parameters than those pushing on forest soils. After 36 months of follow-up, the plants no treaties had the lowest growth rate (41.5 ± 13.4%). NPK treatments

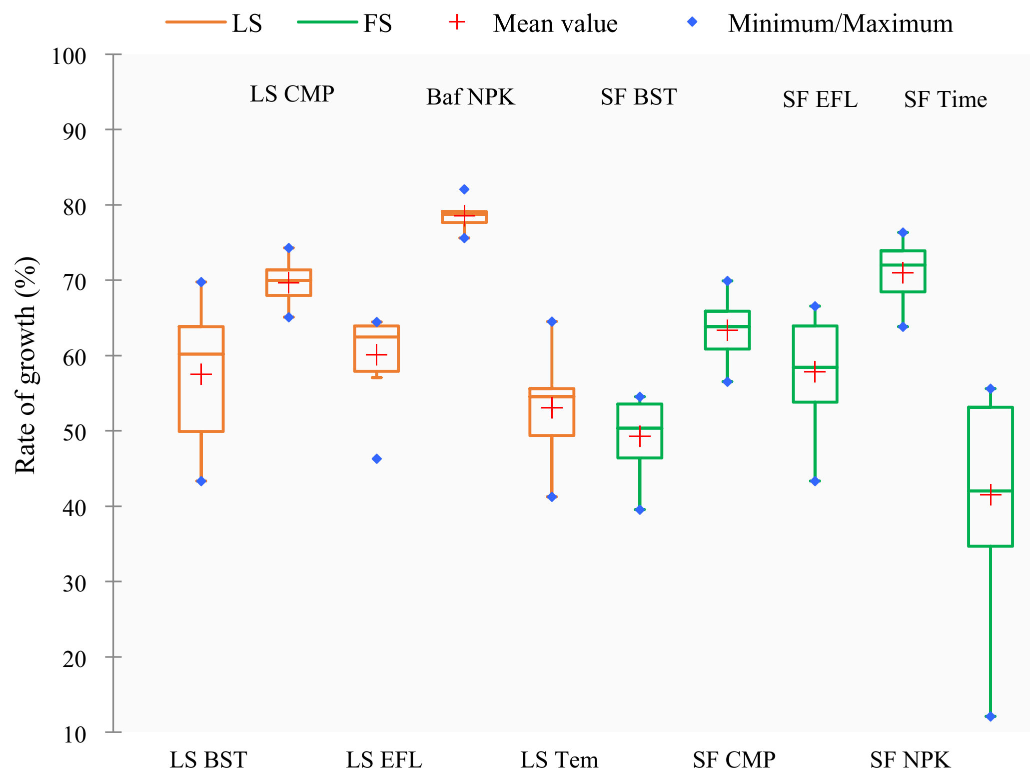

Fig. 4 Descriptive statistics og growth rate according to fertiliser and soil type. *LS* Lowland soil; *FS* Forest soil; *CMP* Organic fertiliser; *BST* Biostimulant; *EFL* Foliar fertiliser; *Tem* Control

Table 7 Average value (± standard deviation) of the growth parameters of the effect of fertilisers on the growth of the mangosteen according to the types of soil

Parameters		HP (m)	Gr (%)	SP(m)	Dcol (cm)	RQ	Le (cm)	Wth (cm)	Chc (mg.ml^{-1})	NPr
Treatments	LS CMP	5.8 ± 0.5b	69.6 ± 2.8b	5.1 ± 0.8b	8.7 ± 0.4e	0.06bc	26.2 ± 0.7a	13.9 ± 1.2a	23.9 ± 1.1a	13.8 ± 0.8ab
	FS CMP	4.8 ± 0.5c	63.3 ± 4.1c	3.7 ± 0.4c	5.3 ± 0.7ab	0.09a	24.7 ± 1.6ab	13.4 ± 1.8a	23.1 ± 0.9a	12.8 ± 1.5ab
	LS NPK	8.3 ± 0.6a	78.5 ± 1.6a	6.9 ± 0.6a	10.3 ± 1.1e	0.08ab	23.3 ± 0.5b	12.1 ± 0.9a	24.4 ± 1.6a	14.5 ± 0.9c
	FS NPK	6.2 ± 0.8b	71.0 ± 3.9b	4.9 ± 0.7b	8.3 ± 1.2 of	0.07bc	22.7 ± 1.2b	11.9 ± 1.3a	24.3 ± 1.8a	13.5 ± 1.8ab
	LS BST	4.3 ± 0.8 cd	57.5 ± 8.6 cd	3.9 ± 0.1c	6.9 ± 0.5 cd	0.06bc	23.3 ± 0.6b	12.0 ± 1.3a	23.8 ± 1.2a	13.6 ± 0.8ab
	FS BST	3.5 ± 0.3d	49.3 ± 5.1d	3.3 ± 0.5c	4.4 ± 0.5a	0.08ab	23.5 ± 1.4b	12.0 ± 1.3a	23.1 ± 1.1a	13.6 ± 0.8ab
	LS EFL	4.5 ± 0.5c	60.1 ± 5.6c	3.4 ± 0.3c	7.2 ± 0.8 cd	0.06bc	23.2 ± 1.1b	12.2 ± 1.3a	23.9 ± 2.3a	13.6 ± 1.1ab
	FS EFL	4.3 ± 0.6 cd	57.8 ± 7.2 cd	3.3 ± 0.5c	6.3 ± 0.7bc	0.06bc	23.1 ± 1.8b	12.0 ± 1.2a	23.5 ± 2.5a	12.4 ± 1.1a
	LS Tem	3.8 ± 0.6 cd	53.0 ± 7.3 cd	3.0 ± 0.6c	5.7 ± 0.7b	0.06bc	22.8 ± 1.3b	12.2 ± 1.6a	24.5 ± 1.4a	11.5 ± 1.8a
	FS Tem	3.1 ± 0.6d	41.5 ± 13.4d	2.8 ± 0.6c	5.7 ± 0.7a	0.05c	22.7 ± 1.1b	13.0 ± 1.3a	24.3 ± 2.0a	12.0 ± 1.8a
Statistical	F	16.91	16.91	26.35	82.35	41.56	35.93	19.14	8.89	33.02
	P	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001	0.054	0.447	0.000

HP Height of plants, *Gr* Growth rate, *SP* Wingspan, *Dcol* Diameter at the collar, *RQ* Robustness quotient, *Le* Leaf length, *Wth* Leaf width, *Chc* Leaf chlorophyll content, *NPr* Number of pairs of branches, *LS* Lowland soil, *FS* Forest soil, *CMP* Organic fertiliser, *BST* Biostimulant, *EFL* Foliar fertiliser, *Tem* Control. The mean values of the same column assigned different letters are statistically different at the 5% threshold (ppds)

(78.5 ± 1.6%) and organic fertilizers (69.6 ± 2.7%) resulted in the rates highest average growth rates (Fig. 4).

The ANOVA test showed a significant difference in leaf length and robustness quotient (RQ) based on fertilisers ($p < 0.001$). However, there was no significant difference in leaf width (wth) and chlorophyll content among the different treatments evaluated ($p \geq 0.05$). Chlorophyll content ranged from 23.1 ± 0.9 to 24.4 ± 1.4 mg.ml^{-1} (Table 7).

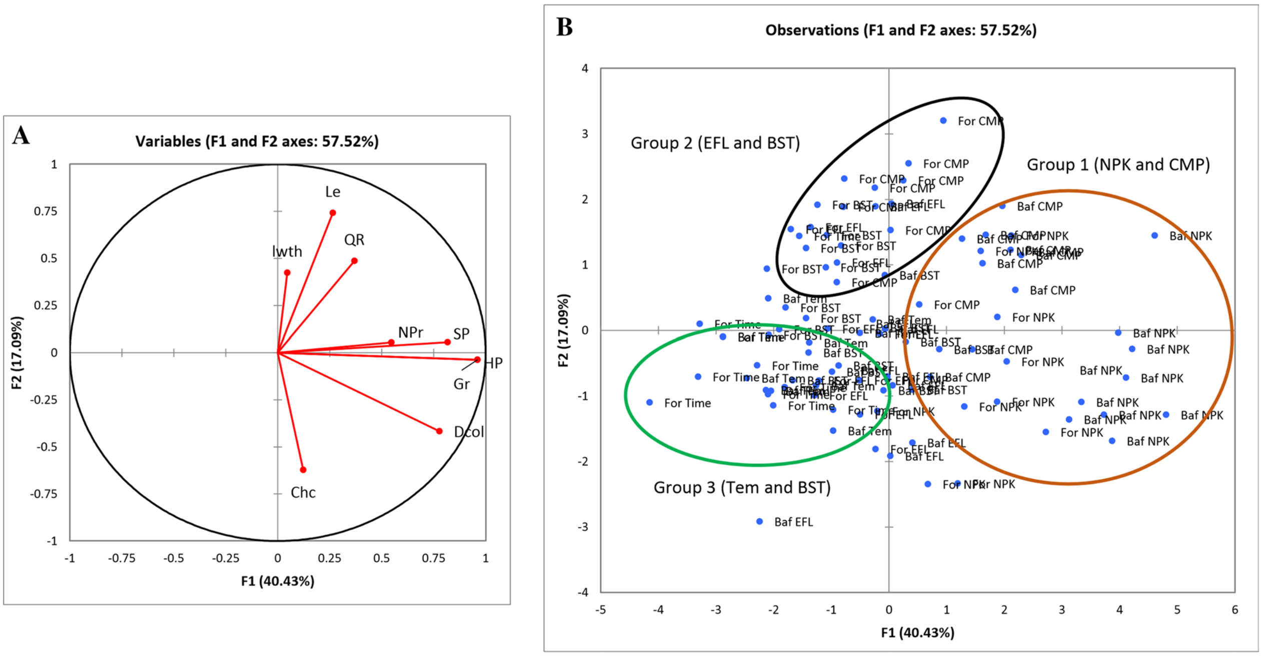

Fig. 5 Principal component analysis (PCA) of growth parameters. **A** Circle of correlation; **B** Projection of individuals in the factorial plane of axes 1 and 2. *HP* Height of Plants, *Gr* Growth rate, *SP* Wingspan, *Dcol* Diameter at the collar, *RQ* Robustness Quotient, *Le* Leaf length, *wth* Leaf width; *Chc* leaf chlorophyll content, *NPr* Number of pairs of branches, *LS* Lowland soil, *FS* Forest soil, *CMP* Organic fertiliser, *BST* Biostimulant, *EFL* Foliar fertiliser, *Tem* Control

Figure 5 presents the results of the principal component analysis (PCA) used to identify groups of similar units and evaluate variable correlations. Factorial axis 1, which accounts for over 40% of the information, shows positive correlations with plant height (HP), growth rate (Gr), wingspan (SP), and collar diameter (Dcol). Axis 2 extracts 17.1% of the information and correlates positively with leaf length, width (Le and wth), and leaf chlorophyll content (Tch) (Fig. 5A).

The individuals are distributed into three distinct groups on the plane of axes 1–2 (Fig. 5B). Group 1 consists of plants fertilised with NPK and organic fertiliser, mainly grown on lowland soil. These plants are characterised by significant growth, wingspan, and collar diameter. Group 2 comprises plants fertilised with foliar fertiliser and some of those fertilised with biostimulant grown on the forest floor. These plants are characterised by significant leaf lengths and widths, as well as a high hardiness quotient. Group 3 consists of plants that have not received any treatment and those fertilised with the biostimulant. They are in contrast to the plants in group I. These plants were grown on both types of soil and are characterised by reduced growth, undeveloped wingspan, and collar diameter.

Discussion

The study found that soil type significantly affects the height growth and growth rate of mangosteen trees. This effect was more pronounced in trees growing on lowland soil compared to those growing on forest soil. The difference in structure, texture, and mineralogical composition of the two soil types likely explains this result. These parameters are important factors that influence mineral bioavailability. When fertilisers are added to the soil, minerals react with soil constituents such as iron and aluminium oxyhydroxides, carbonates, and mineralogical clays. As a result, some minerals may lose their ability to move to plants. This soil property is known as fixing or buffering capacity, depending on the situation. The competition between the soil and the plant for ions is the cause of these facts (Srivastava et al. 2021). The lowland soil's fixing power, clay texture (32.4 ± 1.3%), and mineral composition would have facilitated a consistent supply of necessary mineral elements for the growth of mangosteen trees. The lowland soil's C/N ratio, an indicator of the rate of soil organic matter decomposition, was lower (3.8 ± 0.9) than that of the forest floor (7.2 ± 1.5). Soil carbon and nitrogen are closely linked to soil organic matter. This organic matter gives the soil physico-chemical properties that promote soil functioning and fertility, such as water retention, structure, and a buffer reservoir for nitrogen and other nutrients. It also serves as an energy substrate for microflora. Amit et al. (2021) found that when the C/N ratio is low, significant amounts of ammonium and nitrates are released, making it possible for plants to obtain nitrogen from the soil reserves. The rapid mineralization of organic matter, particularly nitrogen, in lowland soil may explain the greater growth of mangosteen trees in this type of soil.

However, the mangosteen tree is highly sensitive to drought and requires high humidity conditions for optimal growth. The high humidity levels in the lowland soil provide the necessary water and nutrition for photosynthesis, promoting healthy plant growth. The water deficit can lead to a shortage of mineral nutrients, such as nitrogen and phosphate, due to reduced flow of elements to the roots. This can result in stunted plant growth (Boughdiri et al. 2020). The best results on lowland soil are likely due to the combined effects of these factors. These results support the findings of Martias et al. (2021), who reported that soils containing 60–75% clay are favourable for the growth of mangosteen trees. Hapsari et al. (2018) also observed growth disorders in mangosteen trees under water stress.

The study found that fertilisers have a significant effect on the growth of mangosteen trees, depending on the type of soil. Foliar and NPK fertilisers were found to be particularly effective in shortening the time it takes for mangosteen trees to bear fruit. This suggests that fertilisation may help address one of the major challenges in cultivating mangosteen trees: their tendency to bear fruit late. However, they demonstrate the significant role of appropriate fertilisers in plant management and reducing the juvenile phase. The effectiveness of foliar fertilisers and nitrogen-rich NPK is responsible for the positive results achieved.

Nitrogen is a crucial element for plant growth. It is an essential component of proteins, which are built from amino acids that catalyse chemical reactions and electron transport, as well as chlorophyll, which is involved in the process of photosynthesis. Nitrogen promotes rapid growth, enhances fruit quality, increases protein content, and facilitates the absorption and utilisation of other nutrients, such as potassium and phosphorus. Additionally, plant development and yield determination are also influenced by soil texture (Puja et al. 2023).

Soil texture, which refers to the percentage of sand, silt, and clay, plays a crucial role in determining the effectiveness of fertiliser treatments. Clay and silt soils, like the plain soil on which the best performances were recorded, have the capacity to retain nitrogen for plants. The use of nitrogen-rich fertilisers such as NPK and foliar fertiliser could have promoted good growth in the mangosteen trees, thereby shortening their juvenile phase. Research studies have highlighted the importance of nitrogen in plant growth (Sadi et al. 2020). Cashew trees are also sensitive to mineral fertiliser inputs and their growth can be greatly accelerated by nitrogen inputs (N'djolosse et al., 2018). Rawia et al. (2022) found that nitrogen inputs positively affect the growth of mango seedlings.

This may be due to the specificity of the fertilisers used, such as NPK and foliar fertilisers, which shorten the vegetative phase. Mineral fertilisers provide plants with known and constant quantities of minerals in assimilable forms. Access to these minerals would have enabled young mangosteen seedlings to establish the foundations necessary to express their full potential (Choudhary et al. 2023).

In addition to the impressive performance of foliar and NPK fertilisers, organic fertiliser also yielded satisfactory growth results. The treatment was limited to principal component analysis (PCA), which showed that plants fertilised with NPK and organic fertiliser had significant growth, wingspan, and collar diameter. This could be due to the high nitrogen content in poultry manure. Organic fertilisation not only contains minerals but also promotes biodiversity and biological activity in the soil. It accelerates the decomposition of organic matter and increases the availability of minerals to plants, resulting in direct and indirect benefits to crop growth and yield. Numerous studies have demonstrated the crucial role of organic fertilisers in preserving soil fertility and enhancing plant growth. Research has demonstrated that organic matter enhances the physico-chemical properties of soil, leading to improved crop yields and growth (Hafez et al. 2021). This confirms the crucial role of nitrogen in the growth process of mangosteen. However, the slow degradation and gradual release of minerals caused a delayed effect on the fruiting of mangosteen trees when fertilisers were used (Hou et al. 2023).

Conclusions

This study is part of a programme to improve mangosteen production techniques. The study found that soil type and fertiliser significantly affect mangosteen growth parameters. Lowland soil was found to be better suited to mangosteen cultivation, promoting better plant growth. The parameters with a significant influence were growth rate, height growth ($p = 0.028$), and the robustness quotient ($p = 0.021$). After 36 months of monitoring, mangosteen trees grown on plain soil recorded a growth rate of $53.08 \pm 7.30\%$, while those grown on forest soil recorded a growth rate of $41.51 \pm 13.43\%$. The results indicate the significant contribution of fertilisers in managing and shortening the juvenile phase of the mangosteen.

Notably, foliar fertilisers and NPK-based fertilisers performed remarkably well in shortening the onset of mangosteen fruiting to the 5th year.

Although the results were satisfactory, this study is not exhaustive and only covers certain aspects of agronomic research on the mangosteen tree. The results indicate that after the 5th year of cultivation, 6.66% of the plants fertilised with NPK and 11.66% of those fertilised with foliar fertiliser bore their first fruit. Further research is needed to study the effect of fertilisers on yield, fruit health, and soil biology.

However, based on the results obtained, recommendations need to be made to growers and organisations responsible for agricultural extension. The study results have helped overcome most of the obstacles to mangosteen cultivation. Therefore, the following recommendations are proposed:

- When establishing mangosteen plots, it is recommended to choose moist soils with a clay texture, such as clay-sandy, clayey loam, or clayey-sandy loam.
- To promote plant growth, use foliar fertiliser that is rich in amino acids and balanced NPK mineral fertilisers for fertilisation during the growth phase.

Abbreviations

AOAC	Association of Official Analytical Chemists
BST	Biostimulant
C/N	Carbon/nitrogen ratio
CEAEQ	Centre of Expertise in Environmental Analysis of Quebec
Chc	Leaf chlorophyll content
CMP	Organic fertiliser
Dcol	Diameter at the collar
EC	Electrical conductivity
EFL	Foliar fertiliser
FS	Forest soil
Gr	Growth rate
HP	Height of plants
IFAC	Research Institute for Colonial Fruits and Citrus
K^+	Potassium
Le	Leaf length
LS	Lowland soil
N	Nitrogen
NPr	Number of pairs of branches
OFAG	Office Fédéral de l'Agriculture Suisse
OFEV	Office Fédéral de l'Environnement Suisse
OM	Organic matter
PCA	Principal component analysis
pH	Hydrogen potential
RQ	Robustness quotient
SP	Wingspan
Tem	Control
TOC	Total organic carbon
TP	Total phosphorus
Wth	Leaf width

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Author contributions
The authors contributed at all levels, from conducting and carrying out the work to writing the manuscript. All authors read and approved the manuscript. JFH conducted the trials collected the data, analysed the results, and was one of the main editors of the manuscript. NS, EDP and AKL helped carry out the protocol and conduct the trials. AD and KJK were the investigators of the research project and were the artisans of its implementation by creating the carder of its realisation. They also supervised the writing of the manuscript.

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