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Morphological and Biomass Assessment of *Musa paradisiaca* Plantation Wastes at Different Growth Stages

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Abstract:
The Musa paradisiaca plant undergoes various morphological changes throughout its lifecycle. The study of the morphological characteristics of banana plant parts proved to be a guide for comparing the biomass of different parts. During each growth stage, one of these parts is generated as waste; hence, the details of morphological changes and biomass generated at each stage can be of importance. During the life cycle of the banana plant, some parts of the plant become waste. These waste parts can be utilized and may contribute to the circular economy of the banana plantation and the Sustainable Development Goals of the United Nations. According to the morphological evaluation, it is evident that the banana pseudostem and leaf foliage are the major waste remnants that pose a disposal problem and can be substantially utilized for sustainable utilization of plantation wastes. From a detailed comparative evaluation of the pseudostem, it is evident that there is variation in the thickness and weight of each leafsheath layer as well as the meristem. This indicated a possible phytochemical variation; hence, understanding the discrete ways of utilization of leafsheath layers and meristem is needed. Banana roots and the inflorescence account for the least waste biomass generated from the plantation. The root waste remaining after harvesting can be rolled over with the soil is an easy way of disposal. The inflorescence is edible and hence consumed as a vegetable; only a small portion goes to waste. The detailed study of the utilization prospects of pseudostem should be focused on, due to its highest waste biomass generated, followed by the utilizable outcomes of leaves.
Keywords: *Musa paradisiaca, Biomass Assessment, Morphological Evaluation, Waste Remnants, Growth Stages, Banana Pseudostem*

INTRODUCTION:

Banana plantation accounts for the highest amount of plantation waste globally, being the largest cultivated crop and the highest waste-generating crop in Asia, as it bears fruits only once. The statistics obtained from the National Horticultural Board showed that bananas are India's second-largest fruit crop. The annual world production of bananas was 86 million tons, with India accounting for more than 14.2 million tons from 2001 to 2002.[1] World banana production hiked from 1994 to 2023, with 57.4 million tons in 3.6 million hectares in 1994 to 139 million tons in 5.9 million hectares by 2023. Asia became the top banana producer, showing 52% of the world's total banana production, followed by America with 28.3% and Africa with 17.8%. India is in the top position, producing more than 20 million tons from 1994 to 2023.[2]

Banana plantation waste, if not managed, can cause environmental problems due to being dumped in wet conditions or burned, and thus producing greenhouse gases. The pseudostem of the banana plant is the stem of the banana plant that transports nutrients from the soil to the fruits. From the plantation to the harvest, it takes a maximum period of 28 to 30 months. After the harvesting of bananas, the banana plant is not usable for any further harvests. Around 60% of a banana plant's mass is due to the banana pseudostem, which is usually trashed away after the fruit harvest, thus accounting for a significant waste fraction in banana farms. These banana wastes, if utilized sustainably, could be a suitable way of preventing such environmental pollution.[1]

The banana plant belongs to the herbaceous plant family and has an apparent trunk, also known as the pseudostem. The root system has an underground stem modification that has adventitious roots and is also known as a sucker. The suckers develop into new plants that can be further grown for propagating the banana plant. During the growth phase, the banana plant has large leaves closely rolled

over each other to form the pseudostem. The bud of the plant develops after 7 to 8 months to produce flowers. The inflorescence consists of small spikes or finger-like male and female flowers, present in clusters covered with a large boat-shaped outer covering. After flowering, the female flowers open up in the form of clusters and further form the banana fruit, whereas the male flowers are present in the red bud at the tip of the spike. The bananas of the whole spike are called a bunch, and the clusters of bananas are called a hand. Several hands of bananas form a bunch.[3]

A banana plant goes through different stages of growth. According to the Earth Observing System (EOS) - data analytics, the main stages of the banana plant growth are Vegetative Growth, Crop Development, and Fruit Growth, with the plantation-to-harvest time ranging from 9 to 12 months. The growing timeline of the banana plant is depicted in Fig. 1. Overall, a dwarf variety of banana grows through these phases with an average period of 11-14 months, whereas a taller variety grows in 14-16 months. The bunch of bananas is harvested once fully developed on the plant, which takes around 3-4 months. The most common stages are the Vegetative Growth Stage, the Crop Development Stage, the Fruit Growth Stage, and the Fruit Ripening Stage, as explained in Fig. 2. [4]

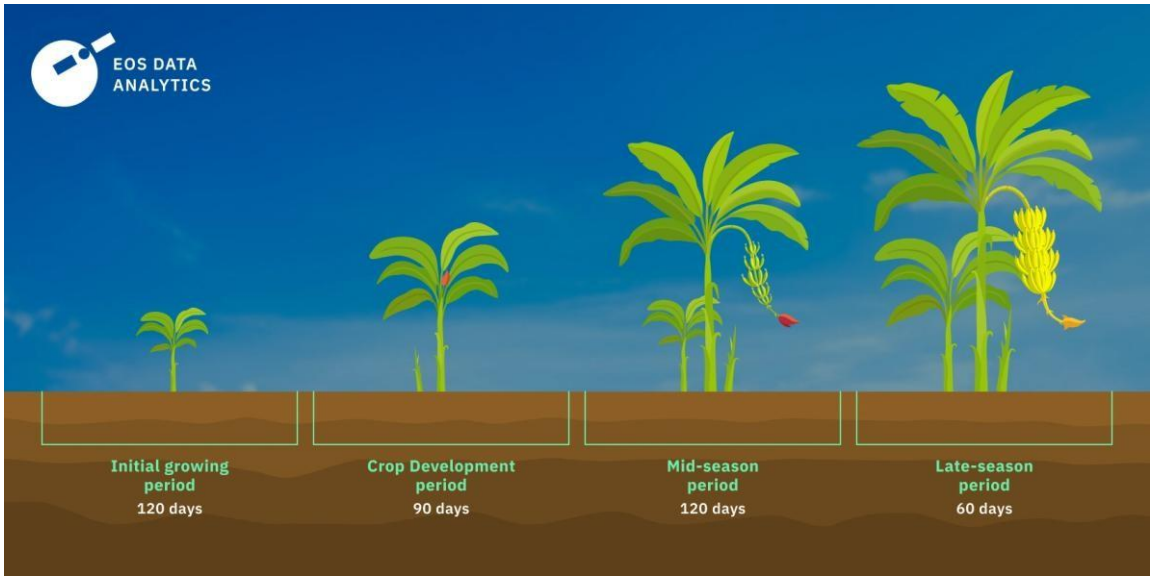

Figure 1: Banana Plant Growing Timeline

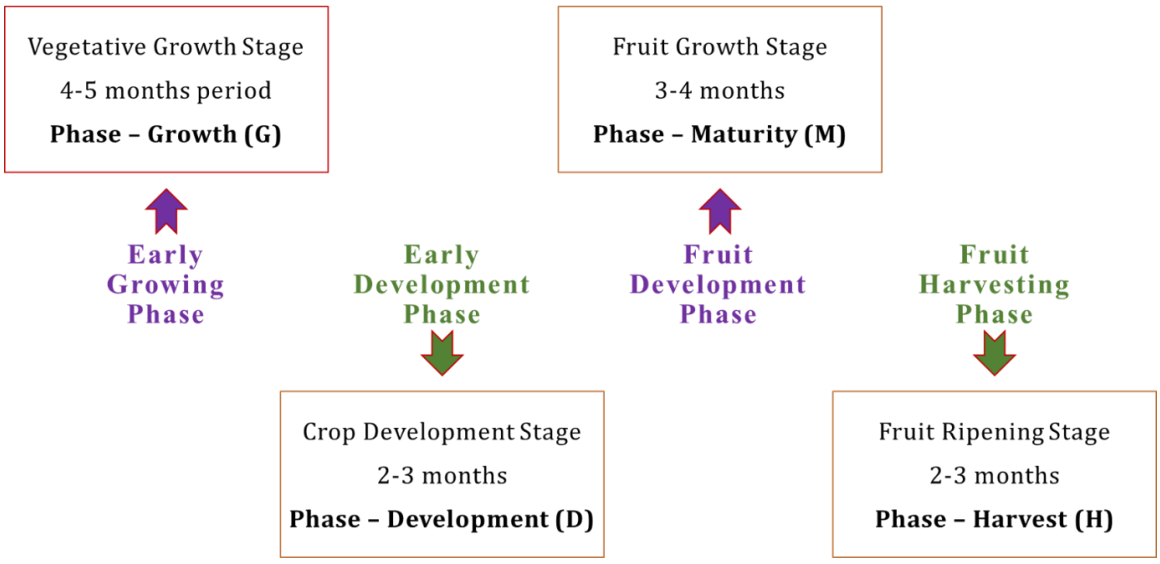

Figure 2: Growth Stages of Banana Plantation

The major post-harvest waste remnants include the pseudostem, leaves, rhizomes, and inflorescence. These wastes are generated even before the harvesting of bananas in minor quantities. The wastes that are generated during the initial three phases of the banana plant lifecycle are of variable average biomass and maturity level. During the banana plant's growth, some parts of the plant become waste during some intermediate stage of growth, but the major plantation wastes are generated only after the harvest of bananas. These waste parts can be utilized and may contribute to the circular economy of the banana plantation and the Sustainable Development Goals. Not all of these parts form waste remnants at the given stage; only some parts fall off or are wasted during the farming process. The wastes generated at different stages of banana plant growth need to be identified.
As multiple products can be isolated or produced from banana plantation wastes, there is a need to choose the best way to utilize these wastes sustainably. This project focuses on evaluating all the waste remnants at various growth stages based on morphology and biomass generated so as to understand the need and prospects for utilization of the maximum components of the plantation wastes.

MATERIAL AND METHODS:

Banana plant varieties were identified that are grown on a large scale at local places near Satara. The commonly called '*the deshi banana*' variety was found to be most widely cultivated in Satara. The Banana plant material was collected from a local private farm at Bhatmarali, Satara, Maharashtra-India. Different common varieties of banana, summarized by the local farmer of Bhatmarali, that are cultivated in the farm include '*Harisal*', '*Safed-velchi*'. Out of this, the '*Harisal* variety' was more widely cultivated at the farm and hence was selected for the final work and was collected. The photograph of the collection of the *Musa paradisiaca* L. with Geo-location has been shown in Fig. 3.

Figure 3: Photograph of collection of the Plant: *Musa paradisiaca L.* with Geo-location

As the growth of a plant affects the phytochemical composition and the structural make-up of its parts, the sampling of plant material was carried out at different growth stages of the life cycle of banana plant. As the plant life cycle progresses through the four phases of growth, different parts are developed to different extents, and some wastes are generated at each phase during the farming process.
Sampling of the parts is done for the preliminary evaluation of the parts based on the development of that part at the particular phase and depending on the availability and abundance of the parts. The details of Growth Phases and sampling details of banana plant parts are given in Table 1.

Table 1: Growth Phases and Sampling Details of Banana Plant Parts

Phase	**Growth (G) Phase**	**Development (D) Phase**	**Maturity (M) Phase**	**Harvest (H) Phase**
Description	Early Growing Phase	Early Development Phase	Fruit Development Phase	Fruit Harvesting Phase
Duration	4-5 months	2-3 months	3-4 months	2-3 months
Progress at the phase	Vegetative Growth	Crop Development	Fruit Growth	Fruit Ripening
Parts Developed at the Phase	Immature Rhizomes, Immature Pseudostem, and Immature Leaves	Rhizomes, Pseudostem, Immature Leaves, and Immature Inflorescence	Rhizomes, Pseudostem, Leaves, Immature Inflorescence and Fruits	Fully Mature Rhizomes, Pseudostem, Leaves, Inflorescence, and Fruits
Wastes generated during the Phase	Immature Leaves and few Psuedostem	Immature Leaves, and few Pseudostem	Mature Leaves and few Inflorescence	Fully Mature Rhizomes, Pseudostem, Leaves, and few Inflorescence
Sampled parts at the Phase	Leaves, Rhizomes, Pseudostem,	Leaves, Rhizomes, Pseudostem,	Leaves, Rhizomes, Pseudostem, Inflorescence	Leaves, Rhizomes, Pseudostem, Inflorescence

The sampling was done at four different growth phases of the banana plantation life cycle, namely: Growth (G), Development (D), Maturity (M), and Harvest (H) Phase. Different parts of a banana plant include leaves, pseudostem, rhizomes, inflorescence, and fruits. Of these, the fruits are completely utilized, and the banana peels are not generated at the farm but at the user's end. Hence, banana peels are not considered for this study. The sampling for subsequent tests was conducted based on the results of previous tests and the availability, need for utilization, and abundance of the part of the plant at that stage.

Morphological Evaluation of Banana Plantation Wastes:

The morphological characteristics of banana plantation wastes were evaluated in terms of the colour, odour, shape, and features as qualitative parameters, and dimensions, and fresh weight/ biomass of the parts as quantitative parameters. The sensory evaluation of the parts was performed by proper observation in triplicate. The colour and the shape or features were recorded by careful observation in the daylight. The odour was recorded by crushing and rubbing a small sample between the fingertips and noting the smell.

The dimensions of the parts were considered in terms of the depth and horizontal diameter of the banana root, the length and width of the banana leaf, the height and horizontal diameter of the banana pseudostem, and the length and width of the banana inflorescence bunch. The weight of each part was recorded. Readings were taken in a set of six.

In addition to these observations, the volume and density were determined by calculations using the observed readings. The volume was calculated using formulae based on the shapes of the part of the plant. The density was calculated using the weight and volume by the formula: Density = weight/volume.

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Each part of the plant was compared to an approximate shape as given in the figure below, and the formula for calculating the volume was considered accordingly. The comparison of the shapes of roots, leaves, pseudostem, and inflorescence is given in Figure 4. The tests were performed in a set of six and expressed as: $R \pm \sigma$; where R is the mean and σ is the standard deviation.

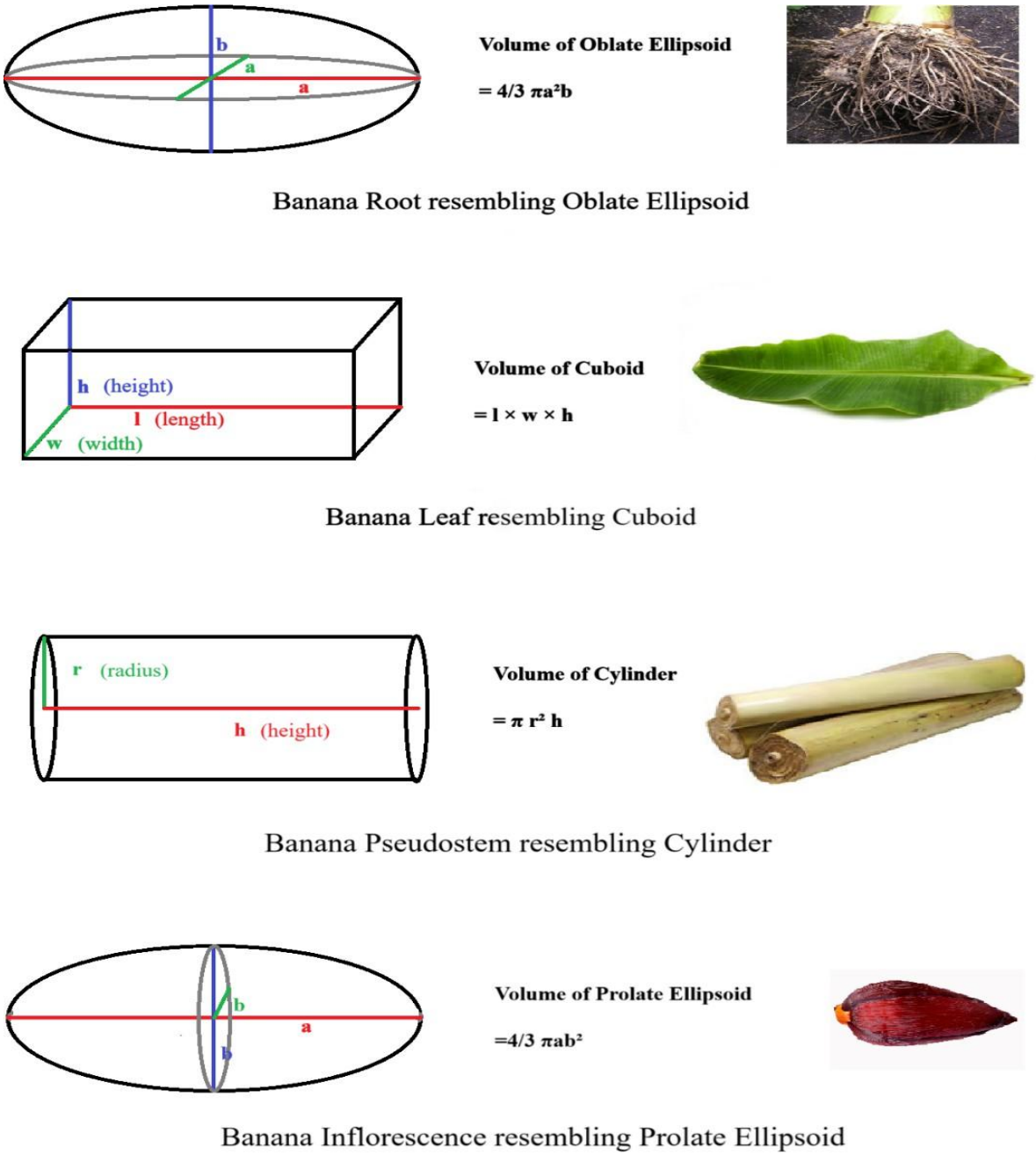

Figure 4: Shape Comparison for Volume Calculations of the Parts of the Banana Plant

The banana root was considered to have an oblate ellipsoid shape, which can be considered to resemble a flattened sphere with two longer axes (a) and one short axis (b). Hence, the volume calculation was done using the formula: $4/3\pi a^2 b$.

Volume of Banana Root = $4/3\pi w^2 d$

Where w = width of the root and
d = depth of the root

The banana leaf is about cuboidal in shape; hence, the volume is measured considering an average thickness, and using the formula: (length) × (width) × (thickness), considering an average thickness of 0.5 cm for calculation purposes.

Volume of Banana Leaf = (l) × (w) × (t)

Where l = length of the leaf,
w = width of the leaf, and
t = thickness of the leaf

As the banana pseudostem is cylindrical, the volume was calculated using the formula: $\pi r^2 h$, where the radius is obtained from the diameter of the pseudostem.

Volume of Banana Pseudostem = $\pi(d/2)^2 h$

Where d = diameter of the pseudostem and
h = height of the pseudostem

The banana inflorescence bunch was considered to have a prolate ellipsoid shape, which can be considered to resemble a rugby ball with one longer axis (a) and two shorter axes (b). Hence, the area calculation was done using the formula: $4/3\pi ab^2$.

Volume of Banana Inflorescence = $4/3\pi w^2 l$

Where w = width of the inflorescence and
l = length of the root

The tests were performed in a set of six and expressed as:

$R \pm \sigma$; where R is the mean and σ is the standard deviation.

And, $\sigma = \sum (X \pm R)^2 n$,
where X is the individual reading and
n is the number of readings.

The results of qualitative morphological evaluation of waste remnants of the banana plant during the four phases of the life cycle of the banana plantation are given in Table 2, and those of the quantitative morphological evaluation are given in Table 3.

In addition, a detailed dimensional analysis was performed on the outer leaf-sheath layers of the pseudostem and the inner meristem. At different growth stages, the pseudostem undergoes variations in the development of leafsheath layers and the meristem. There exists variation in the makeup of the pseudostem in terms of the development of meristem and the development of the number of leafsheath layers, as well as the thickness of leafsheaths. As we move from the bottom to the top of the pseudostem, the overall diameter reduces, and thus the detailed dimensions will also vary.

The pseudostem was analysed at four growth stages and at three positions of the pseudostem, namely: top, middle, and bottom. At the outer, middle, and inner portions of the leafsheath layers were evaluated for the thickness. In addition, the weights of the outer, middle, and inner layers of pseudostem leaf sheaths and the meristem were recorded. Results of Quantitative Dimensional Analysis of Banana Pseudostem are given in Table 4, and those of the Weight Analysis of Banana Pseudostem are given in Table 5.

RESULTS AND DISCUSSIONS:

The results were expressed as mean ± standard deviation of the given dataset.

4.3.1. Morphological Evaluation of Banana Plantation Wastes:

The observations for qualitative morphological evaluation were performed in triplicate and are given in Table 2. The observations for quantitative morphological evaluation were performed in a set of six and are given in Table 3. The observations for detailed dimensional analysis of the banana pseudostem are given in Tables 4 and 5.

Table 2: Results of Qualitative Morphological Evaluation of Banana Waste Remnants

Plant Part	Phase (Sample Code)	Colour	Odour	Shape and Visual Features
Banana Root	Growth (GBR)	Pearl White to Buff	Characteristic and Faint	Fibrous Rhizome
	Development (DBR)	Pearl White to Buff	Characteristic and Faint	Fibrous Rhizome
	Maturity (MBR)	Buff to Pale Brown	Characteristic and Faint	Thick and Fleshy Fibrous Rhizome
	Harvest (HBR)	Light Brown	Characteristic and Faint	Thick and Fleshy Fibrous Rhizome
Banana Leaf	Growth (GBL)	Light Green	Characteristic	Elongated and Broad
	Development (DBL)	Light Green	Characteristic	Elongated and Broad
	Maturity (MBL)	Dark Green (Upper Side),	Characteristic	Elongated and Broad
	Harvest (HBL)	Dark Green (Upper Side),	Characteristic	Elongated and Broad
Banana Pseudostem	Growth (GBP)	Light Green	Faint	Cylindrical and layered
	Development (DBP)	Light Green	Characteristic	Cylindrical and layered
	Maturity (MBP)	Buff to Cream	Characteristic	Cylindrical and layered with inner meristem
	Harvest (HBP)	Buff to Brown	Characteristic	Cylindrical and layered with inner meristem
Banana Inflorescence	Maturity (MBI)	Buff - Flowers Purple - Bracts	Faint	Clusters of spiked flowers with bracts
	Harvest (HBI)	Buff - Flowers Purple - Bracts	Characteristic	Clusters of spiked flowers with bracts

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Table 3: Results of Quantitative Morphological Evaluation of Banana Waste Remnants

Plant Part	Phase (Sample Code)	Depth/ Length / Height (cm)	Diameter/ Width (cm)	Fresh Weight (g)	Calculated Volume (cc)	Calculated Density (g/cc)
Banana Root	**Growth (GBR)**	4.17±0.41	11.25±0.76	228.33±33.12	2232.36±439.15	0.103±0.008
	Development (DBR)	9.92±0.74	16.50±0.89	808.33±28.58	11381.55±1793.47	0.073±0.012
	Maturity (MBR)	13.75±0.52	26.17±1.17	1768.33±58.45	39583.37±4764.98	0.045±0.005
	Harvest (HBR)	14.42±0.58	28.83±1.94	2403.33±61.54	50555.21±8546.71	0.049±0.007
Banana Leaf	**Growth (GBL)**	30.42±1.53	16.17±1.25	83.33±8.76	246.50±29.14	0.339±0.021
	Development (DBL)	84.17±7.36	35.83±5.85	313.33±51.64	1518.75±352.47	0.209±0.022
	Maturity (MBL)	147.5±7.58	75.00±4.47	595.83±48.83	5533.33±462.24	0.108±0.011
	Harvest (HBL)	151.67±8.16	75.83±5.85	561.67±37.64	5737.50±323.17	0.098±0.011
Banana Pseudostem	**Growth (GBP)**	60.83±5.85	13.83±0.82	2421.67±89.31	9218.45±1801.19	0.269±0.042
	Development (DBP)	132.50±9.35	24.17±0.75	6645.00±191.91	60870.98±6055.02	0.11±0.01
	Maturity (MBP)	159.17±13.2	34.25±0.94	10821.67±258.88	147172±19120.48	0.075±0.008
	Harvest (HBP)	157.50±11.73	36.50±0.71	9296.67±245.9	165112.29±16940.13	0.057±0.005
Banana Inflorescence	**Maturity (MBI)**	36.83±0.93	17.00±0.95	1105.00±24.29	44806.01±6136.66	0.025±0.003
	Harvest (HBI)	25.33±0.88	13.25±0.69	629.17±32.47	18644.48±1733.43	0.034±0.004

*All the values are expressed as Mean ± SD, where n = 6

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Table 4: Results of Quantitative Dimensional Analysis of Banana Pseudostem

Plant Part	Focused Portion (Sample Code)	Number of Layers	Thickness of Outer Layers (cm)	Thickness of Middle Layers (cm)	Thickness of Outer Layers (cm)	Diameter of Meristem (cm)
Growth Phase	**Top**	9.17±0.75	1.37±0.08	1.28±0.04	1.2±0.09	--
	Middle	8±0.89	1.92±0.08	1.82±0.08	1.77±0.08	--
	Bottom	7.67±0.82	2.15±0.1	2.05±0.05	1.98±0.08	--
Development Phase	**Top**	13±0.89	1.9±0.11	1.8±0.11	1.75±0.15	--
	Middle	12.67±1.21	2.15±0.1	2.02±0.08	1.95±0.1	--
	Bottom	12±0.89	2.38±0.08	2.27±0.1	2.18±0.08	--
Maturity Phase	**Top**	15.33±1.03	1.72±0.08	1.62±0.08	1.53±0.1	5.83±0.12
	Middle	13±0.89	2.3±0.09	2.23±0.12	2.13±0.08	6.62±0.12
	Bottom	12.5±0.55	2.72±0.08	2.58±0.12	2.38±0.08	7.08±0.15
Harvest Phase	**Top**	17.17±0.75	1.9±0.15	1.83±0.12	1.65±0.1	6.07±0.19
	Middle	14.67±1.21	2.6±0.09	2.43±0.1	2.3±0.09	6.72±0.08
	Bottom	13.83±0.98	2.87±0.08	2.7±0.09	2.58±0.08	7.13±0.15

*All the values are expressed as Mean ± SD, where n = 6

Table 5: Results of Weight Analysis of Banana Pseudostem

Plant Part	Growth Phase	Development Phase	Maturity Phase	Harvest Phase
Weight of Meristem (g)	--	--	1243.33±365.82	1002±485.41
Weight of Outer Layers (g)	368.33±19.41	561.67±14.72	798.33±11.69	633.33±20.66
Weight of Middle Layers (g)	330±12.65	548.33±24.83	765±16.43	591.67±21.37
Weight of Outer Layers (g)	295±10.49	523.33±28.05	725±13.78	578.33±11.69
Average Weight of Leafsheath (g)	330.37±5.72	547.87±11.71	761.9±3.87	599.54±7.73
Overall Weight of Leafsheaths (g)	2534.26±288.4	6575.28±527.7	9903.01±652.87	8290.28±541.2

*All the values are expressed as Mean ± SD, where n = 6

The Morphology of Banana Roots:

The banana plant roots were fibrous, and the propagation of a new plant was through a corm. The development of a new plant occurs from the underground stem modification of the mother plant, called the corm, that is capable of developing into a new sucker.

The banana plant roots were pearl-white to buff in colour at the growth stage, which darkened as the plant progressed from the development phase to maturity phase to a buff/ pale brown colour and further darkened till the harvest phase to light brown. It possessed a characteristic and faint odour throughout its lifespan. The fibrous root showed thin thread-like rootlets spread horizontally and shallow near the ground level, hence the shape of the root cannot be well defined, but can be regarded on the basis of width horizontally and depth vertically below ground level, to be considered with approximation.

The roots were found to be negligible in weight at the initial growth phase of the daughter plant. At the growth phase, the roots were 4.17±0.41 cm in depth and 11.25±0.76 cm in width. At the development phase, the plant attained a depth of 9.92±0.74 cm and a width of 16.5±0.89 cm. At the maturity stage, the root depth was found to be increased to 13.75±0.52 cm with a rise in width to 26.17±1.17 cm. At the harvest phase, the roots are fully grown with a depth of 14.42±0.58 cm and a width of 28.83±1.94 cm. According to the practical aspects of banana plantations, the roots are removed only when the plants are uprooted after the harvest of bananas. There is no root harvest at any intermediate growth phase of the banana plantation. Also, the roots carry a lot of mud and soil on account of their fibrous adventitious root system, posing a difficulty in its cleaning process. The weights of the roots in this experimental study were recorded after possible removal of all the adherent mud and soil. The weight of roots was found to be increased from 228.33±33.12 g at the growth phase, to 808.33±28.58 g at the development phase, and 1768.33±58.45 g at the maturity phase, and finally increased to 2403.33±61.54 g at the harvest phase. As the plant progressed through the growth phases, there was an increase in the weight of the roots, an increase in volume occupied, but a decrease in the density of the roots.

The Morphology of Banana Leaf:

Banana leaves were wide and elongated, somewhat rectangular, with a round apex and a wide, rounded base. Each plant possesses around 8 to 12 leaves that show morphological changes as the plant progresses through its life cycle. The leaves are green in colour and possess a lighter colour on the lower side compared to the upper side, which is dark green with a glossy appearance.

The leaf surface was found to be lighter during the growth phase and the development phase. At the maturity phase, the upper side of the leaf surface became darker and progressed in this manner till the harvest phase. Throughout its life cycle, the leaf had a characteristic shape which can be described as an elongated lanceolate shape with a wider base. The leaves have a thick midrib that protrudes on the lower surface and is depressed at the upper surface of the leaf with parallel venation. The leaf also possessed a characteristic odour throughout its lifecycle.

The weight as well as the dimensions of leaf foliage undergo changes from the growth phase to the harvest phase. At the initial stage, when the corm develops into a new daughter sapling of the banana plant, the plant starts developing one or two leaves of negligible mass and dimensions. At the growth phase, the leaf dimensions approximated 30.42±1.53 cm in length and 16.17±1.25 cm in width, with a fresh weight of approximately 83.33±8.76 g. At the development phase, the weight of the leaf was intermediate with dimensions of 84.17±7.36 cm length and 35.83±5.85 cm width, and the fresh weight approximated to 313.33±51.64 g. At the maturity phase, the plant achieved its highest dimension with 147.5±7.58 cm length and 75.00±4.47 cm width, and the fresh weight was increased to 595.83±48.83 g. Further, as the plant entered the harvest phase, there was a slight decline in the fresh weight to 561.67±37.64 g, but the dimensions remained similar, with a length of 151.67±8.16 cm and a width of 75.83±5.85 cm. Along with an increase in the weight of the leaves during the growth phases, there was an increase in the volume occupied and a decrease in the density of the leaves.

The highest readings at the maturity phase were found to be on account of the need for the plant to nourish its fruits that are developing at this stage. Further, as the plant approaches the harvest phase, the slight decline could be on the account of a lower need for nourishment of the fruits after their complete development and the start of the process of senescence. The highest readings are at the maturity state of the plant, but the waste remnants are obtained only at the harvest phase and not at the maturity phase, since there is no cutting of the plant before the harvest of a healthy fruit bunch.

The calculation for the overall leaf foliage can be considered based on the average number of leaves present on the banana plant.

The Morphology of Banana Pseudostem:

Banana pseudostem is known as the false stem and is a vital part of the banana plant. It is structurally composed of leaf sheaths in a tightly packed fashion extending from the base through the height of the plant, and at the tip of the plant, they turn into leaves. The new leaf development occurs from the innermost layer of the pseudostem.

The banana pseudostem is green in colour at the birth of a new daughter plant. The colour of the pseudostem remains light green at the growth phase and the development phase, and further, the colour lightens and appears cream to buff in colour at the maturity phase and harvest phase. It possesses a characteristic and faint odour throughout the lifespan of the plant, which is milder at the initial phases of its life. The pseudostem shape can be considered as cylindrical with a wider base that narrows up along its height.

As observed with the banana leaves, the pseudostem also shows a similar trend in development through its life cycle. When a new plant emerges from a corm, the pseudostem is of negligible weight. As the plant reached the growth phase, the height and diameter of the pseudostem were 60.83±5.85 cm and 13.83±0.82 cm, respectively, and a fresh weight of 2421.67±89.31 g. Further, as the plant reached the development phase, the height and diameter of the pseudostem approximated to 132.50±9.35 cm and 24.17±0.75 cm, respectively, with a fresh weight of 6645.00±191.91 g. At the maturity phase, the banana pseudostem showed an increase in height, diameter of 159.17±13.2 cm, 34.25±0.94 cm, respectively, and a fresh weight of 10821.67±258.88 g. The maturity phase marked the highest fresh weight of the pseudostem. Further reaching the harvest phase, there was a little decline in the fresh weight of the pseudostem, though there was not much change in the height and the diameter of the pseudostem. The height and diameter were approximated to 157.50±11.73 cm and 36.50±0.71 cm, respectively, with a fresh weight of 9296.67±245.9 g. Along with an increase in the weight of the pseudostem during the growth phases, there was an increase in volume occupied but a decrease in the density of the pseudostem.

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The highest biomass of pseudostem waste was found to be obtained at the maturity phase, but at this phase, there is the start of fruiting and fruit development, and hence, the waste is practically not usually generated at this stage, but is only obtained after the harvest of the fruit bunch. Decline in the fresh weight at the harvest phase could be a result of the start of the process of senescence after complete maturation of the fruit. The earlier the harvesting is done, the higher the weight of the pseudostem obtained as the senescence process is not progressed more as compared to a later harvest time.

The Morphology of Banana Inflorescence:

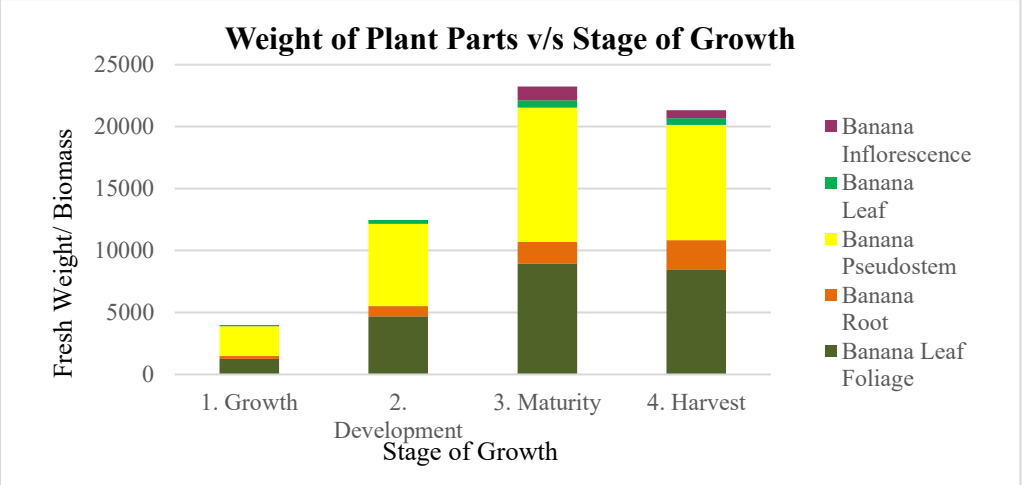
Banana inflorescence consists of a complex structure with finger-shaped flowers covered in boat-shaped, brightly purple-red coloured bracts. The inflorescence rises from the tip of the pseudostem with a branched arrangement of flowers along with the bract, arranged on the central axis in a bunched form. The flowers are of three types: the female flowers that emerge at the beginning and develop into fruits; the bisexual flowers in the middle of the inflorescence; and the male flowers arising at the last and are found at the tip of the bunch of fruits covered with bell-shaped bracts at the time of harvest. Banana inflorescence develops at a later stage of the development phase when the innermost part of the banana pseudostem outgrows and develops into an inflorescence containing bunch finger-shaped flowers covered with boat-shaped bracts on a central core.

At the maturity phase, the dimension as well as the weight of the inflorescence is highest as the fruit development from the flower has not begun, and all flower spikes that can further develop into fruits are present within the bract layers of the inflorescence. The length of the inflorescence bunch was found to be 36.83±0.93 cm with a diameter of 17.00±0.95 cm, and a fresh weight of 1105.00±24.29 g.

As the plant approaches the harvest phase, the outer bracts of the inflorescence bunch roll out, exposing the flowers that develop into fruits further. The flowers and bracts are arranged on an inner central axis. The start of harvest is marked when the fruits are completely developed and no further fruits are obtained from the flowers. At this point, the outermost layers of the flowers start to dry out, and the bunch of inflorescences remains at the tip of the banana fruit bunch. The inflorescence showed a higher value for length, diameter, and weight at the maturity phase, which decreased till the harvest phase. The length of the inflorescence bunch was reduced to 25.33±0.88 cm with a diameter of 13.25±0.69 cm and a fresh weight of 629.17±32.47 g. It was found that the volume of the banana inflorescence was decreased while the density was increased as the plant growth took place from the maturity phase to the harvest phase.

The banana plant morphological results were analysed and could be concluded as follows:

- The weights of the parts of the banana plant during the four phases of the life cycle of the banana plantation were compared graphically and are shown in Graph 1. The highest weights were obtained for the pseudostem and overall leaf foliage was generated at maturity and the harvest phase.



Graph 1: Graph of Weight of Plant Parts v/s Stage of Growth

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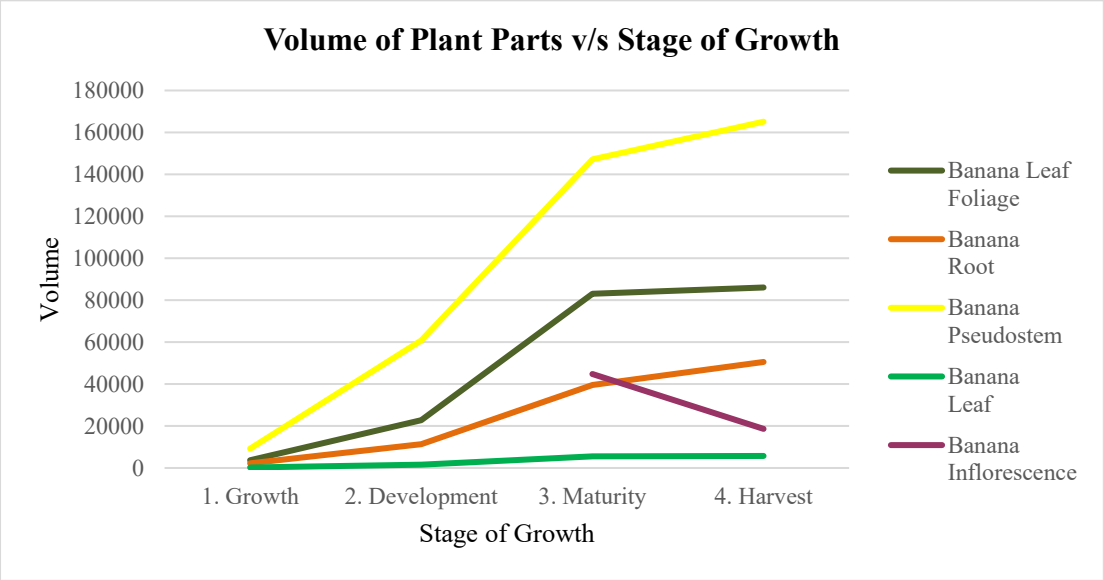
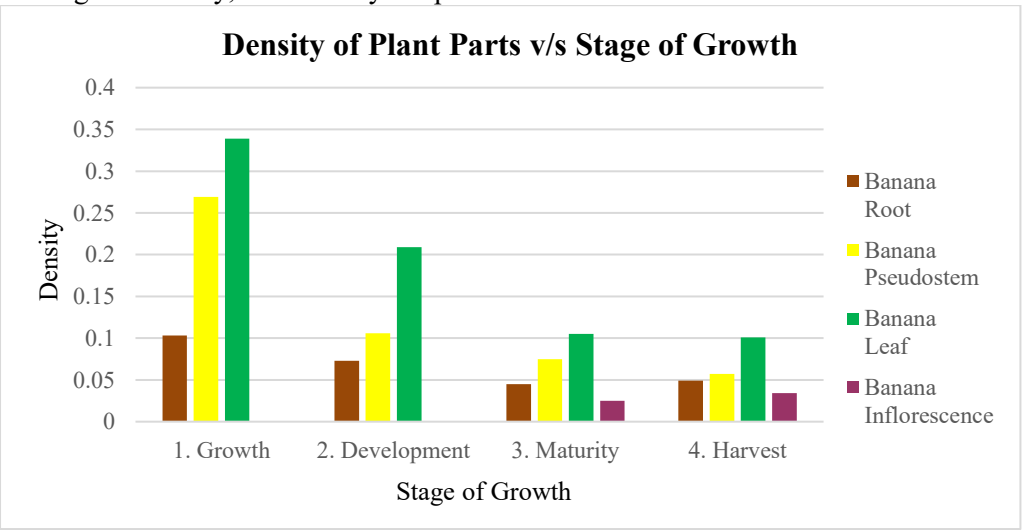
- The volumes of each part were also compared as shown in Graph 2, which revealed that the pseudostem and total leaf foliage showed the highest volume.



Graph 2: Graph of Volume of Plant Parts v/s Stage of Growth

- The comparison of the density of each part, as shown in Graph 3, indicated that the leaf showed the highest density, followed by the pseudostem.



Graph 3: Graph of Density of Plant Parts v/s Stage of Growth

Detailed Dimensional Analysis of the Pseudostem:

The cut section study at each phase revealed that the pseudostem has a difference in morphology in the initial and the later growth stages. At the growth phase and development phase, there is no development of meristem, and the layers of leafsheaths are arranged in a concentric fashion from its centre. At the start of the maturity phase, when the inflorescence starts to form, the inner core, called the meristem, starts developing at the centre of pseudostem. The meristem is cylinder-like, extending from the base to the height of the pseudostem, and extends out as the inflorescence.

In the detailed analysis, the number of leafsheath layers, the thickness of layers at the outer, middle, and inner parts along the top, middle, and bottom of the pseudostem, and the diameter of the meristem were studied. In addition, the weights of the leafsheath layers at the outer, middle, and inner portions and the weight of the meristem were studied at each growth stage.

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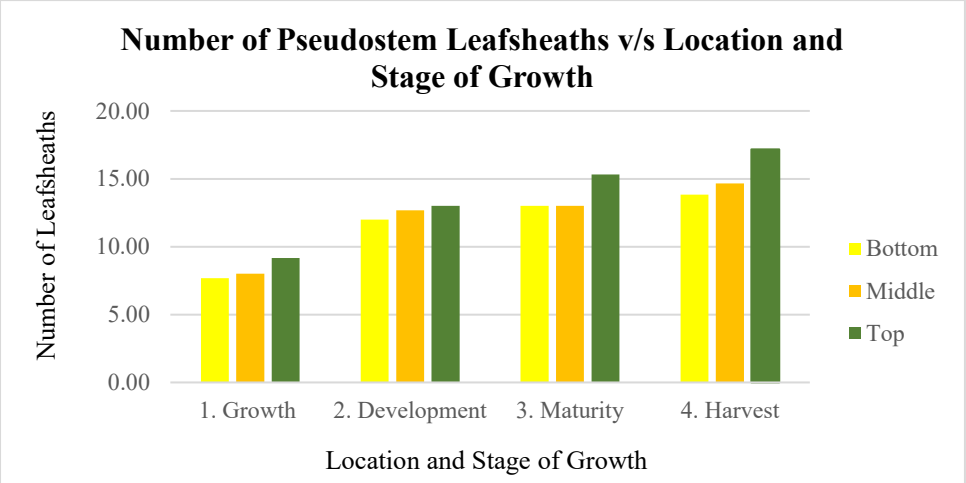
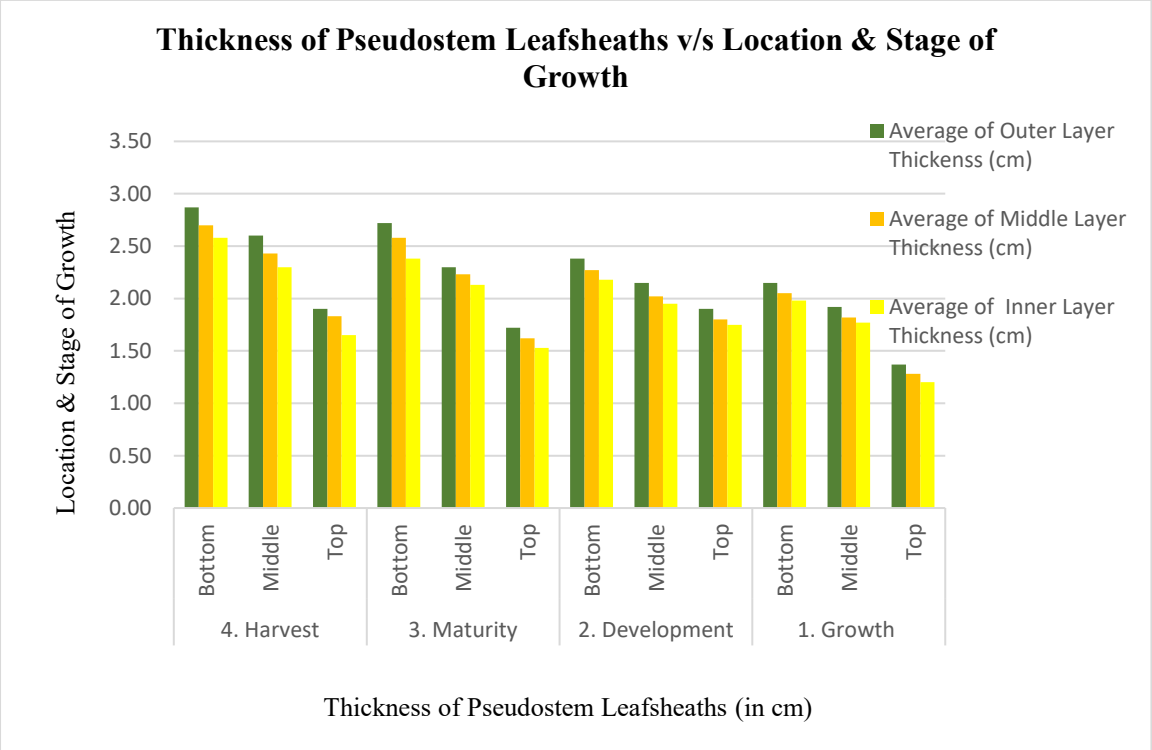
According to the detailed study of the pseudostem as per Tables 4 and 5, it was evident that the number of leaf sheath layers of the pseudostem was found to be increased with progress in the growth of the plant, and also as we move from the bottom to the top of the pseudostem. The number of leaf sheath layers were found to be highest at the top location at the harvest phase, followed by the top portion at the maturity phase, and by the middle and bottom locations of the harvest and maturity phases, respectively, as shown in Graph 4.



Graph 4: Graph of Number of Pseudostem Leafsheaths v/s Location and Stage of Growth

According to Figure 5, the comparison of the thickness of pseudostem leafsheath layers at the top, middle, and bottom locations of the pseudostem showed that the outer layer was thicker as compared to the middle layer and the inner layer at each stage of growth, while the thickness decreased from the bottom to the top location of the pseudostem. The thickest part of the leafsheath layer of the pseudostem was the outer bottom portion. Overall, the outer layer was thicker compared to the middle, followed by the inner layer of the bottom of the pseudostem at maturity and the harvest phase.



Graph 5: Graph of Comparison of Thickness of Pseudostem Leafsheaths at Different Locations and Stages of Growth

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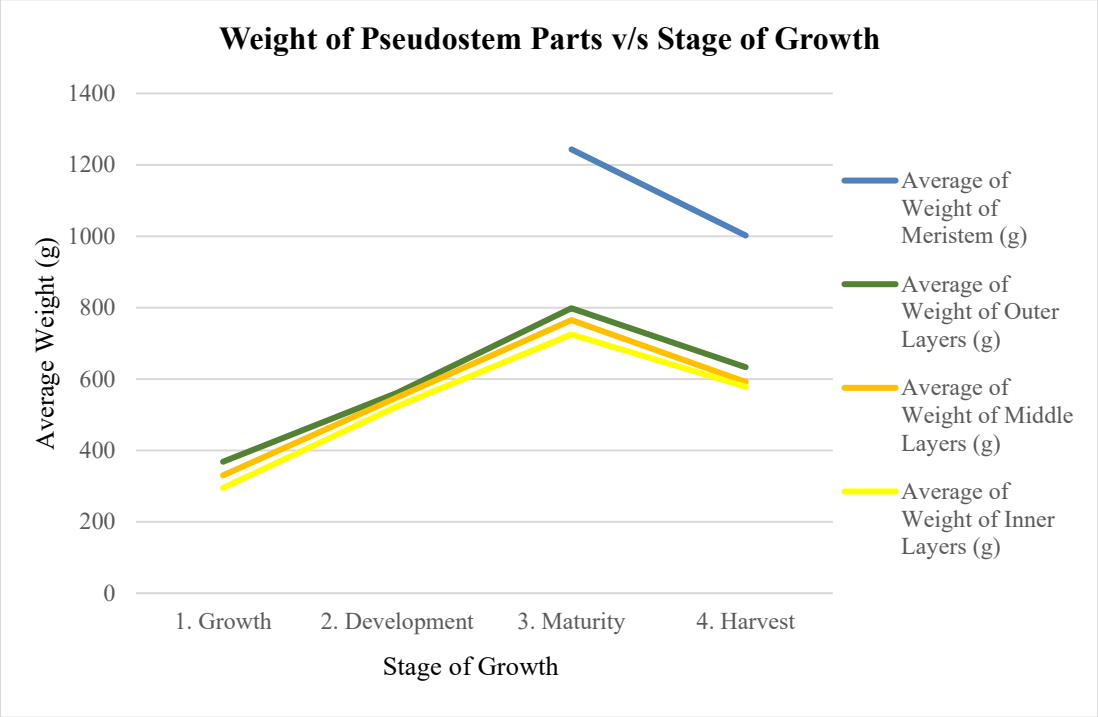
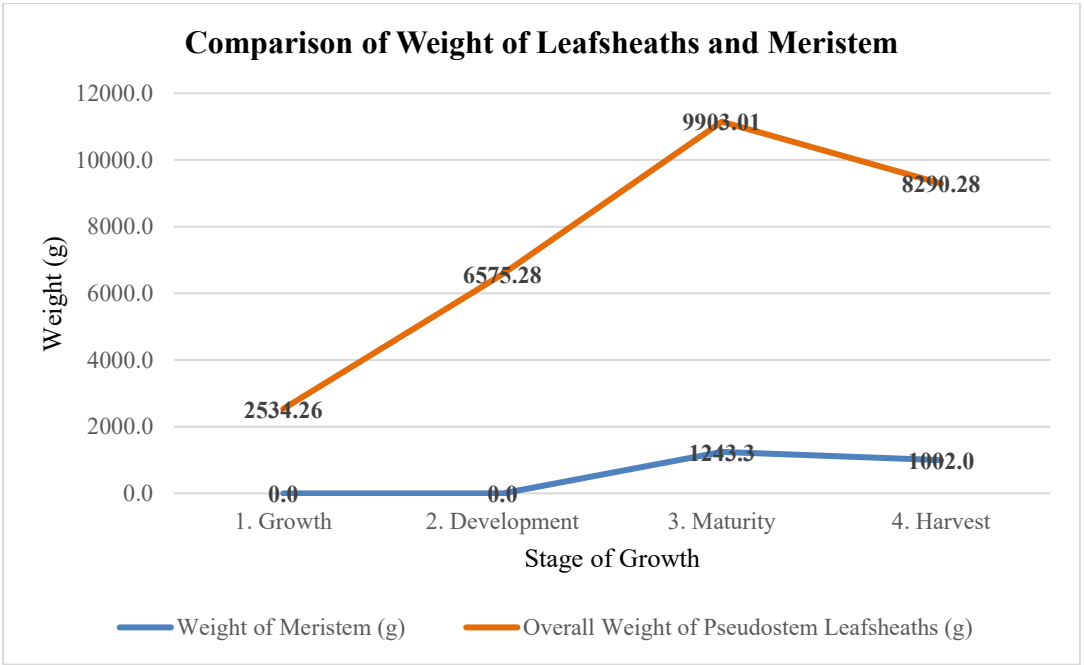
The comparison of the weight of the different layers of the pseudostem leafsheaths and the meristem revealed that, at each stage of growth, the weight of the outer layer was higher compared to the middle and inner layers, and the weight of the meristem is distinctly high compared to that of the individual leafsheath layers, as shown in Graph 6. Also, the weight was increased from the growth stage to the maturity stage and further declined a little at the harvest stage of the banana plant.



Graph 6: Graph of Weight of Pseudostem Parts v/s Stage of Growth

Although the total weight of all the outer layers combined was found to be much more as compared to the weight of the meristem, as shown in Graph 7.



Graph 7: Graph of Comparison of Weight of Leafsheaths and Meristem

Comparison of the Morphology of Banana Plant Parts:

Based on the morphological study carried out, the major amount of waste generated from the banana plantation could be attributed to the banana pseudostem at the maturity phase, followed by the banana pseudostem at the harvest phase. Although this trend was observed experimentally, practically, the pseudostem can be cut only after the harvest phase of the banana plantation. At the earlier stages, the pseudostem is usually not cut, and the highest weight of waste generated could be attributed to the pseudostem after the harvest phase.

The second highest amount of waste biomass is generated from the leaf foliage at the harvest phase. Practically, the fresh leaves are removed only after the fruit harvest, but the plant shed leaves, during the harvest phase and the maturity phase, which can account for the waste remnant that need to be utilized. Banana roots and the inflorescence account for the least waste biomass generated from the plantation. It is a tedious process to clean the root waste, and is mostly rolled over and assimilated in the soil with a rotor instead of being separated and utilized. Banana inflorescences are obtained during or before the harvest phase, and account for the least amount of waste remnants from the plantation. To some extent, banana inflorescence is consumed as a vegetable, and only a small portion goes as waste.

CONCLUSION:

According to the morphological evaluation, it is evident that the banana pseudostem and the banana leaf foliage are the major waste remnants that pose a major problem of disposal and are substantially generated to be considered for a sustainable utilization of plantation wastes. The highest quantity of waste is generated at the harvest phase of the banana plantation. No wastes are generated at the development and the maturity phases during the normal lifecycle of the banana plant. At the growth stage, the banana pseudostem and the banana leaves are generated as wastes to some extent due to the removal of the daughter plants. Hence, the major portion of wastes that need attention for a sustainable utilization of the banana plantation wastes comes at the harvest phase in the form of pseudostem and leaves. These wastes, due to their major biomass, can be used further to meet the Sustainable Development Goals.

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