

Article

An Integrated Crop Management Strategy Using Wood Chips and Pumice Under Feather Compost for Sustainable Ginger Soilless Production and Endophytic Bacteria Composition in Open Field

You-Hong Zeng , Yu-Zhen Chen and Ming-Chich Hsu

Soil and Fertilization Laboratory, Crop Environment Division, Taichung District Agricultural Research and Extension Station, Ministry of Agriculture (Taiwan), 370 Songhuai Road, Dacun Township, Changhua County 515008, Taiwan; b10627025@gmail.com (Y.-Z.C.); c520e1314@yahoo.com.tw (M.-C.H.)

* Correspondence: zengyh@tcdares.gov.tw

Abstract

This study evaluated the effects of placing wood chips (F-Wood chip) or pumice (F-Pumice) at the bottom of poultry feather compost on open-field ginger soilless media production. Root control bags were prepared with 10 L of wood chips or pumice overlain by 20 L of feather compost, with three ginger rhizomes planted. Crops were drip-irrigated without synthetic fertilization and replenished with compost three times. Results indicated that bottom-placed wood chips or pumice improved water infiltration. Ginger yield was significantly higher in the F-Wood chip treatment than in the F-Pumice, with fresh weights of 3.4 and 2.5 kg, and dry weights of 451.8 and 332.7 g, respectively. Furthermore, F-Wood chip significantly increased rhizome calcium levels. Although no significant differences were observed between treatments regarding leaf and post-harvest media nutrient contents, the F-Wood chip group exhibited higher microbial abundance ($9.5 \pm 4.5 \times 10^5$ CFU⁻¹) and greater endophytic diversity, spanning 7 genera and 11 species with potential plant growth-promoting and stress-resistance functions. Overall, this innovative integrated crop management strategy demonstrates great potential to substitute for fossil-fuel-based chemical fertilizers, this innovative production mode eliminates the need for fossil-fuel-based chemical fertilizers, offering an applicable and sustainable soilless cultivation solution for open-field ginger production under extreme weather conditions like typhoons and heavy rainfall.

Keywords: feather compost; wood chip; pumice; zingiber officinale; endophytic bacteria



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1. Introduction

Ginger is a herbaceous crop cultivated in tropical and subtropical regions that is widely utilized as a spice and traditional herbal medicine. The primary producing nations are India, Nigeria, and China. According to FAOSTAT (2023) data and relevant scientific literature, global ginger production experienced a substantial 366.1% increase over more than two decades, soaring from 1,046,320 tons in 2000 to approximately 4,877,179 tons in 2023 [1,2]. However, global ginger cultivation faces critical socioeconomic and environmental bottlenecks that heavily burden agricultural societies.

Economically, the ginger supply chain is highly vulnerable due to smallholder-dominated structures; empirical stochastic frontier assessments indicate that these systems

suffer from substantial technical inefficiencies and a lack of modern capitalized inputs, preventing actual yields from reaching global market potentials [3]. Biotically, this production burden is severely exacerbated by soil-borne diseases, particularly bacterial wilt caused by *Ralstonia solanacearum*. This resilient pathogen radically disrupts the rhizosphere microbiome and causes devastating yield losses across major global production hubs, inducing severe consecutive cropping obstacles that directly destabilize smallholder livelihoods [4]. Furthermore, climate-driven radiation stress and rising global temperatures present severe physiological challenges; as a semi-shade plant, extreme solar radiation induces heat stress that impairs biomass accumulation, threatening long-term supplies and imposing heavy mitigation costs on the agricultural economy [5].

The rhizome of ginger (*Zingiber officinale*) is widely used as a culinary spice and traditional herbal medicine in Taiwan. The primary cultivation region for ginger is located in Nantou County, spanning approximately 220 hectares. Recently, the severity of ginger rhizome rot caused by *Pythium myriotylum* has rapidly escalated, particularly in poorly drained agricultural soils; consequently, numerous farmers have transitioned toward planting ginger in soilless culture systems. Previous research has demonstrated that coir dust, coarse coconut husk chips mixed with fine coconut fiber, sand mixed with perlite (1:1), and peat mixed with perlite (3:1) can serve as optimal media for ginger production [6–9].

Although various cultivation substrates are inherently suitable for ginger growth, optimizing the physical drainage capacity of open-field substrates remains critical under Taiwan's perennially rainy and humid subtropical climate. Previous investigations have indicated that surface mulching or direct incorporation of wood chips can effectively increase soil infiltration rates and hydraulic conductivity [10]. The efficiency of wood chips in enhancing drainage is closely linked to their lignocellulosic content under varying environmental conditions. At the nanoscale, relative humidity significantly modulates the Young's modulus and adhesion characteristics of these lignocellulosic polymers [11]. Under suitable humidity levels, the liberated lignin acts as a crucial macro-molecular binder that promotes soil aggregation (forming stable aggregate structures). While high concentrations of organosolv lignin can function as a physical binder to decrease the permeability of specific landfill barrier soils [12], its primary role at lower dosages in agricultural wood chip application is to bind fine particles into stable aggregates. This structural optimization increases soil macro-porosity, which ultimately improves soil permeability and drainage rates. Furthermore, wood chips provide a favorable microenvironment and organic nutrients for soil organisms, thereby enhancing bioturbation [13] and potentially stimulating plant development. Concurrently, pumice is recognized for its ability to rapidly drain excess water and is widely utilized to regulate root-zone moisture content. For instance, when pumice was applied as the sole growing medium for grapevine cultivation, its limited moisture- and nutrient-retention capacities resulted in lower fruit quality and yield compared to a coir-based medium [14]. Additionally, mixing pumice with Douglas fir [*Pseudotsuga menziesii* (Mirb.) Franco] bark significantly decreased the overall water-holding capacity and available water content of the substrate [15]. Consequently, these findings suggest that both wood chips and pumice represent highly promising candidates for enhancing substrate drainage and root-zone aeration.

In addition to mitigating climate- and pest-related risks through the structural improvement of substrate drainage, harnessing beneficial endophytic bacteria offers a powerful biological approach to enhance crop resilience. These symbiotic microorganisms can promote plant growth through pathways such as biological nitrogen fixation and enhanced nutrient mobilization, while simultaneously protecting their hosts against phytopathogens and alleviating environmental abiotic stress [16,17]. To date, numerous studies have iden-

tified specialized endophytic bacteria within the ginger endosphere that are capable of stimulating vegetative growth and bolstering systemic resistance to biotic stresses [18–22].

In the context of contemporary net-zero carbon initiatives, reducing the consumption of mineral chemical fertilizers is imperative to lower the greenhouse gas emissions associated with their manufacturing. While poultry feather compost has been validated as a highly viable alternative medium for cultivating tomatoes and melons without supplementary chemical fertilization [23,24], our preliminary attempt to apply this organic matrix to open-field ginger production in 2024 resulted in a total crop failure. Following the heavy monsoon rainy season, the ginger plants sequentially succumbed to devastating soft rot disease induced by prolonged waterlogging, resulting in zero economic harvest. To overcome this critical bottleneck, the present study aimed to investigate and compare the effects of incorporating either a wood chip or pumice basal drainage layer on the vegetative growth performance, nutrient uptake dynamics, and root-associated endophytic communities of ginger cultivated in feather compost. By implementing this integrated crop management strategy through structural media configuration, this research sought to establish a sustainable, low-carbon, and highly resilient soilless cultivation framework tailored for open-field ginger production in challenging hot and humid environments.

2. Materials and Methods

2.1. Feather Compost Production

The composting experiment was conducted at the Taichung District Agricultural Research and Extension Station (TDARES, Changhua, Taiwan), utilizing 850 kg of spent mushroom substrate (SMS) derived from *Pleurotus ostreatus* (oyster mushroom) bag cultivation, 50 kg of duck feathers, 20 kg of palm ash, and 20 kg of bone meal. The physicochemical properties of the primary raw materials were analyzed prior to mixing. The SMS contained 45.8% organic carbon (C), 0.92% total nitrogen (N), 0.45% phosphorus (P), 0.51% potassium (K), 6.6% calcium (Ca), 0.36% magnesium (Mg), and 51.8% moisture. The duck feathers consisted of 44.2% organic carbon, 13.2% total nitrogen, 0.07% phosphorus, 0.01% potassium, 0.28% calcium, 0.06% magnesium, and 10.8% moisture. All dry ingredients were initially blended thoroughly under moisture-free conditions and spread uniformly on a flat surface to prepare for microbial inoculation.

Bacillus megaterium TCPiA was employed as the microbial inoculant for the composting process. The liquid culture medium was formulated with 1% (*w/v*) molasses and 0.5% (*w/v*) rapeseed meal, followed by sterilization via autoclaving. For the starter culture, the bacterial strain was inoculated into a 50 mL medium volume and incubated at 30 °C with continuous shaking at 120 rpm for 3 days. Subsequently, the culture was scaled up by transferring it into a 1 L medium volume under identical incubation conditions (30 °C, 120 rpm) for an additional 4 days. The final bacterial density of the liquid inoculant reached 2.9×10^9 CFU m^{-1} . Prior to application, the 1 L bacterial broth was diluted in 200 L of groundwater and evenly sprinkled over the pre-mixed composting matrix.

Following inoculation, the mixture was piled into a compost heap with a height of approximately 1.5 m using a wheel loader. During the piling process, supplementary water was incorporated to adjust and maintain the overall moisture content at approximately 60%. The composting process commenced on 3 November 2022, and was completed on 24 January 2023, spanning a total duration of 82 days. To ensure adequate aeration, the compost heap was turned on days 44 and 65 of the fermentation process using the wheel loader. The core temperature profiles, specifically the daily maximum temperatures of the heap, were continuously monitored throughout the fermentation period using a bimetal thermometer (Fonchang Electric Co., Ltd., Taichung City, Taiwan).

2.2. Water Filtration in Different Culture Media

The water filtration and leakage rates of the different media configurations were evaluated using a modified 600 mL polyethylene terephthalate (PET) bottle apparatus (~6.5 cm in diameter). For each apparatus, a perforation was drilled through the cap, the bottom of the bottle was removed, and the bottle was inverted and positioned over a 250 mL beaker. To prepare the materials, the feather compost, wood chips, and pumice were thoroughly saturated with water. Excess gravitational water was removed by placing the saturated feather compost on a 0.5 mm sieve, while the wood chips and pumice were drained on a 2 mm sieve. These pre-moistened materials were then layered from the bottom upward to establish three distinct treatment configurations: (1) Feather Compost (FC) control: 360 mL of feather compost (~16 cm in height); (2) F-Wood chip: a 120 mL basal layer of wood chips (~7.5 cm in height) overlaid with 240 mL of feather compost (~9.5 cm in height); and (3) F-Pumice: a 120 mL basal layer of pumice (~7.5 cm in height) overlaid with 240 mL of feather compost (~9.5 cm in height).

The prepared bottles were maintained at room temperature for 2 h to allow for complete gravity drainage. Subsequently, a 50 mL aliquot of tap water was poured onto the surface of each medium, and the volume of filtered water was recorded at specified time intervals. In a parallel vertical drainage experiment, the cap orifice was temporarily sealed, and 250 mL of tap water was added to each column until air bubbles ceased to emerge, ensuring complete saturation. Upon unsealing the orifice, the time required for complete water filtration—defined as the point when no free water remained on the substrate surface—was recorded. All experiments were performed in triplicate.

2.3. Ginger Cultivation

Ten liters of wood chips (1.9 kg/bag, equivalent to a local application rate of 167.55 tons/ha based on container basal area) or pumice (4.9 kg/bag, and 432.10 tons/ha) were respectively placed into root-control bags (38 cm in diameter and 43.5 cm in height) to serve as the basal drainage layer, followed by a surface application of 20 L of the prepared feather compost (12.6 kg/bag, and 1111.11 tons/ha). The resulting depths for the basal layer (wood chips or pumice) and the upper feather compost layer were approximately 9 cm and 13 cm, respectively. Three ginger (*Zingiber officinale*) rhizomes, with an average weight of 55 g each, were planted at a depth of 5 cm beneath the feather compost surface. Each treatment configuration consisted of ten replicates. All root-control bags were arranged on plastic drainage boards in an open field at TDARES. During the entire cultivation period (4 February 2025 to 15 January 2026), no additional basal chemical fertilizer was applied. Irrigation was managed automatically via a drip system, delivering 700 mL of water per bag thrice daily at 08:15, 11:30, and 14:45. Supplementary feather compost (10 L in total per bag) was top-dressed onto the medium surface, split across three dates: 15 May, 14 August, and 28 October. Harvested agronomic data comprised plant height, leaf number, and the fresh and dry biomass of the whole plant, rhizomes, and roots. Additionally, elemental nutrient profiles for both leaves and rhizomes were determined.

The soilless ginger plants were grown under open-field conditions, with the monthly meteorological parameters (average temperature, average relative humidity, average cumulative daily solar radiation, and cumulative rainfall) recorded as follows: 16.2 °C, 82%, 14.6 MJ m⁻², and 51 mm in February; 19.0 °C, 81%, 16.1 MJ m⁻², and 108 mm in March; 23.2 °C, 81%, 17.3 MJ m⁻², and 42 mm in April; 26.2 °C, 85%, 19.2 MJ m⁻², and 217 mm in May; 28.4 °C, 87%, 20.9 MJ m⁻², and 222 mm in June; 28.3 °C, 84%, 15.0 MJ m⁻², and 737 mm in July; 28.8 °C, 79%, 19.2 MJ m⁻², and 258 mm in August; 28.8 °C, 80%, 18.3 MJ m⁻², and 118 mm in September; 27.3 °C, 77%, 16.6 MJ m⁻², and 1.5 mm in October; 22.5 °C, 75%, 14.1 MJ m⁻², and 2 mm in November; and 19.3 °C, 77%, 13.8 MJ m⁻², and

4 mm in December. Notably, the vegetative growth period of the ginger directly coincided with the regional rainy season spanning from May to September. In July, due to the passage of Typhoon Danas, the cumulative rainfall from 5 July to 9 July totaled 500 mm, with an extreme daily precipitation peak of 202 mm recorded on 8 July.

2.4. Cultured Materials and Plant Elemental Nutrient Analysis

The pH and electrical conductivity (EC) of the growing media were determined in a 1:10 (*w/v*) deionized water extract using respective electrodes. Ammonium nitrogen (NH_4^+) and nitrate nitrogen (NO_3^-) were quantified using the micro-diffusion method [25]. Total phosphorus content was measured via spectrophotometric colorimetry [26]. Potassium (K), calcium (Ca), magnesium (Mg), copper (Cu), manganese (Mn), zinc (Zn), and iron (Fe) concentrations were analyzed using a polarized Zeeman atomic absorption spectrophotometer (Z-5000, Hitachi, Tokyo, Japan). Additionally, the total organic carbon (TOC) content of the samples was determined using an elemental analyzer (Soil TOC Cube, Elementar, Stockport, United Kingdom). The organic matter (OM) content was subsequently calculated by multiplying the TOC value by the standard conversion factor of 1.72.

At harvest, ginger leaf and rhizome samples were thoroughly washed with distilled water and dried in a forced-air oven at 70 °C. For macronutrient analysis, the dried tissues were digested with concentrated sulfuric acid (H_2SO_4) and hydrogen peroxide (H_2O_2) at 340 °C for 2 h [27]; the total nitrogen, phosphorus, potassium, calcium, and magnesium contents were then determined according to the analytical methods described above. For micronutrient analysis, the dried samples were extracted with 1 M hydrochloric acid (HCl) for 24 h [28], and the elemental concentrations were quantified using the aforementioned polarized Zeeman atomic absorption spectrophotometer.

The physical properties of the media, including bulk density, water-holding capacity per unit weight, and porosity, were determined following the established methodologies described by Fazlil Ilahi et al. [29].

2.5. Culturable Endophytic Bacteria

Harvested ginger roots were thoroughly washed under running tap water, and excess surface moisture was blotted dry with sterile paper towels. To isolate endophytic bacteria, 10 g root samples were surface-disinfested by sequential immersion in 70% (*v/v*) ethanol for 3 min and 1% (*w/v*) sodium hypochlorite for 5 min under continuous shaking at 90 rpm. To verify the efficacy of the surface sterilization protocol, a 100 μL aliquot of the final rinse water was inoculated onto Nutrient Broth Agar (NA) plates and incubated at 30 °C for 5 days; the absence of any microbial growth validated the success of the disinfection process.

Following successful sterilization, the exodermis of the ginger roots was aseptically peeled off using a sterile scalpel, and the remaining inner tissues were homogenized using a sterile mortar and pestle to obtain the root extract. The homogenate was serially diluted with sterile saline and spread-plated onto NA medium. After incubation at 30 °C, total culturable bacterial colonies were enumerated, and representative isolates were purified and maintained based on distinct colony macro-morphologies.

For taxonomic identification, the 16S rDNA sequences of the isolated bacterial strains were determined by Tri-I Biotech, Inc. (New Taipei City, Taiwan). Genus- and species-level identifications were subsequently performed by aligning the obtained sequences against the National Center for Biotechnology Information (NCBI) database using the Basic Local Alignment Search Tool (BLAST) algorithm (BLAST+, version 2.16.0).

3. Results

3.1. Temperature Profiles During Feather Composting

During the composting process, the core temperature of the compost rapidly increased, reaching 57.8 ± 1.8 °C on day 5 and further escalating to 62.9 ± 0.3 °C on day 9, signaling the onset of a robust thermophilic phase. The maximum temperature was recorded on day 34, peaking at 65.0 ± 0.4 °C. Between days 9 and 63, the heap maintained a sustained thermophilic state with a high average temperature of 62.8 ± 0.2 °C. Thereafter, the core temperature gradually declined, eventually cooling to 40.8 ± 0.5 °C by day 80, which indicated the transition into the maturation stage. The 82-day timescale was selected because the composting mass had achieved fully mature and stable conditions. At this stage, the finished compost exhibited a dark black color and a fluffy texture. Analytical results revealed a carbon-to-nitrogen (C/N) ratio of 11.6 and an organic matter content of approximately 67%, fully complying with the national standards for organic fertilizers in Taiwan.

3.2. Physical Characteristics and Soluble Nutrient Composition of Culture Media

Characteristics of the cultivation media used in this study were analyzed and presented in Tables 1 and 2. All three materials were slightly acidic. Among them, poultry feather compost exhibited the highest electrical conductivity (EC) and bulk density, whereas wood chips showed the lowest bulk density. Regarding water-holding capacity per unit weight of material, pumice recorded the lowest value. Furthermore, as pumice was primarily composed of mineral matter, it possessed the lowest organic matter content. Water-soluble nutrient analysis revealed that the poultry feather compost contained the highest concentration of macronutrients. For micronutrients, pumice had the highest copper content, while wood chips displayed a higher zinc content.

Table 1. The Physical characteristics, pH, EC, and organic matter of the culture medium before the experiment.

Medium	pH	EC	BD	Porosity	WHC	OM
		dS/m	g/cm ³	%	g Water/g Dry Sample	%
Pumice	6.9 ± 0.2 a	0.05 ± 0.01 b	0.49 ± 0.04 b	86.5 ± 2.3 a	121.0 ± 1.4 b	0.6 ± 0.1 c
Wood chip	6.8 ± 0.1 a	0.3 ± 0.0 b	0.19 ± 0.01 c	74.8 ± 3.5 b	162.5 ± 1.5 a	87.6 ± 1.3 a
Feather compost	6.5 ± 0.1 b	5.7 ± 0.3 a	0.63 ± 0.01 a	68.8 ± 4.5 c	163.9 ± 4.7 a	67.2 ± 1.4 b

Note: Different letters indicate statistically significant differences (a, b, c). Significance in comparison at $p < 0.05$ (LSD test).

Table 2. The water-soluble nutrients in a 1:10 water extraction of culture medium before the experiment.

Medium	NH ₄ ⁺	NO ₃ [−]	P	K	Ca	Mg	Cu	Mn	Zn	Fe
	mg/kg									
Pumice	9.0 ±1.7 c	18.0 ±1.7 b	3.7 ±1.2 c	37.3 ±17.6 c	42.0 ±1.0 c	11.7 ±0.6 b	0.9 ±0.4 a	ND	0.2 ±0.0 b	5.3 ±2.4 a
Wood chip	24.0 ±1.7 b	9.0 ±1.7 b	58.3 ±9.7 b	612.0 ±54.6 b	272.3 ±26.6 b	62.0 ±6.2 b	0.4 ±0.1 b	0.2 ±0.1 b	0.4 ±0.1 a	3.5 ±0.3 ab
Feather compost	100.0 ±9.5 a	4032.0 ±811.8 a	308.3 ±19.5 a	13,216 ±320.8 a	1994.7 ±62.4 a	2238.3 ±145.6 a	0.4 ±0.0 b	1.3 ±0.1 a	0.2 ±0.0 b	0.7 ±0.1 b

Note: Different letters indicate statistically significant differences (a, b, c). Significance in comparison at $p < 0.05$ (LSD test). ND: Not Detected (below the instrument detection limit).

3.3. Water Filtration and Vertical Drainage Dynamics in Culture Media

Compared with the pure feather compost control (FC), incorporating a basal layer of either wood chips (F-Wood chip) or pumice (F-Pumice) at the bottom significantly increased the water infiltration rate (Table 3). Within the first minute of application, the cumulative infiltrated water volume reached 24.9 mL in the F-Wood chip treatment and 28.3 mL in the F-Pumice treatment, whereas only 13.4 mL of water filtrated through the FC control. Although the drainage rate of the FC treatment increased after the first minute, its total cumulative volume of filtered water remained substantially lower than that of the other two media configurations throughout the monitoring period.

Table 3. The infiltration water volume via different culture media.

Treatment	0–15 s	15–30 s	30–45 s	45–60 s	60–90 s	1.5–2 min	2–3 min	3–4 min	4–5 min	0–5 min
Infiltration Water mL										
F-Wood chip	13.5 ± 1.3 a	7.5 ± 0.5 a	4.5 ± 0.6 a	2.8 ± 0.3 a	3.2 ± 0.3 b	1.9 ± 0.2 b	2.0 ± 0.4 b	0.9 ± 0.1 b	0.5 ± 0.1 b	36.8 ± 1.1 a
F-Pumice	11.7 ± 1.2 a	6.7 ± 0.7 a	3.9 ± 0.3 a	2.6 ± 0.2 a	3.3 ± 0.3 b	1.9 ± 0.4 b	2.3 ± 0.3 b	1.2 ± 0.4 b	0.9 ± 0.1 b	34.5 ± 1.2 a
Feather compost	3.0 ± 0.1 b	3.5 ± 0.8 b	3.7 ± 0.6 a	3.2 ± 0.7 a	4.8 ± 0.8 a	3.6 ± 0.4 a	5.0 ± 0.8 a	3.2 ± 0.8 a	2.2 ± 0.7 a	32.2 ± 1.3 b

Note: Different letters indicate statistically significant differences (a, b). Significance in comparison at $p < 0.05$ (LSD test).

In a simulation mimicking heavy rainfall that exceeds substrate water retention followed by a sudden cessation of precipitation, the time required to completely evacuate surface water differed significantly among treatments. Specifically, the surface water clearance time was 37.7 ± 5.5 s for F-Wood chip, 44.0 ± 9.6 s for F-Pumice, and 143.3 ± 38.1 s for the FC control.

3.4. Ginger Growth Performance, Yield, and Biomass Allocation

The conditions of the substrate bottom, along with the ginger rhizomes and roots at harvest time, are illustrated in Figure 1. Ginger plants cultivated in the F-Wood chip treatment exhibited significantly higher fresh and dry weights of rhizomes compared to those grown in the F-Pumice treatment (Table 4). Intriguingly, while downward root development within the inorganic pumice matrix led to a higher root dry weight in the F-Pumice group, this increased root biomass did not translate into enhanced rhizome productivity. Furthermore, no statistically significant differences were observed among the treatments for any other evaluated agronomic traits.

Table 4. Ginger plant characteristics and rhizome yield in the two culture media.

Treatment	Plant High	Shoot Number	Leaf Number	Fresh Shoot Weight	Fresh Rhizome Weight	Fresh Root Weight	Dry Shoot Weight	Dry Rhizome Weight	Dry Root Weight
	cm			kg	kg	kg	g	g	g
F-Wood chip	88.4 ± 5.7 a	23.7 ± 3.2 a	369.7 ± 99.6 a	0.7 ± 0.26 a	3.4 ± 0.5 a	0.16 ± 0.03 a	78.5 ± 28.0 a	451.8 ± 63.4 a	7.2 ± 1.1 b
F-Pumice	77.0 ± 6.2 a	19.3 ± 2.5 a	274.7 ± 25.5 a	0.40 ± 0.1 a	2.5 ± 0.2 b	0.20 ± 0.03 a	51.2 ± 8.3 a	332.7 ± 13.6 b	10.4 ± 1.1 a

Note: Different letters indicate statistically significant differences (a, b). Significance in comparison at $p < 0.05$ (LSD test).



Figure 1. Bottom condition of the F-Wood chip (A) and F-Pumice (B) at the harvest time; rhizomes of F-Wood chip (C) and F-Pumice (D); roots of F-Wood chip (E) and F-Pumice (F).

3.5. Endophytic Bacterial Number and Composition in Ginger Roots

The endophytic bacterial density within the roots of ginger cultivated in the F-Wood chip treatment was substantially higher than that observed in the F-Pumice treatment. Following isolation, culturing, and molecular identification via 16S rDNA sequencing against the NCBI database, distinct taxonomic distributions were revealed between the two configurations. Specifically, 7 genera and 11 species were identified in the F-Wood chip treatment, whereas the F-Pumice treatment yielded only 3 genera and 6 species (Table 5). These results demonstrated that incorporating a basal wood chip layer effectively enhances both the population abundance and taxonomic diversity of endophytic bacteria within the ginger root endosphere. Notably, *Pseudomonas* was identified as the most predominant genus shared across both treatments (Table 5).

Table 5. Endophytic bacterial numbers and isolated bacteria in the two media.

Treatment	Endophytic Bacteria Number CFU/g Fresh Root	Identification of Endophytic Isolates
F-Wood chip	$9.5 \pm 4.5 \times 10^5$	1. <i>Acinetobacter radioresistens</i> strain NBRC 102413 (99.71%/1398)
		2. <i>Bacillus stratosphericus</i> strain 41KF2a (100%/1453 bp)
		3. <i>Lysinibacillus fusiformis</i> strain DSM 2898 (99.60%/1485 bp)
		4. <i>Microbacterium resistens</i> strain DMMZ 1710 (98.15%/1381)
		5. <i>Pseudomonas fortuita</i> strain GMI12077 (99.80%/1464 bp)
		6. <i>Pseudomonas glycinae</i> strain MS586 (99.86%/1468)
		7. <i>Pseudomonas laurentiana</i> strain GSL-010 (99.93%/1467 bp)
		8. <i>Pseudomonas plecoglossicida</i> strain FPC951 (99.45%/1457 bp)
		9. <i>Pseudomonas sichuanensis</i> strain WCHPs060039 (100%/1458 bp)
		10. <i>Serratia fonticola</i> DSM 22080 (99.79%/1409 bp)
		11. <i>Staphylococcus ureilyticus</i> strain CK27 (99.59%/1454 bp)
F-Pumice	$1.1 \pm 0.2 \times 10^4$	1. <i>Lysinibacillus fusiformis</i> strain DSM 2898 (99.73%/1456 bp)
		2. <i>Pseudomonas glycinae</i> strain MS586 (100%/1465 bp)
		3. <i>Pseudomonas koreensis</i> strain Ps 9–14 (99.93%/1454 bp)
		4. <i>Pseudomonas laurentiana</i> strain GSL-010 (100%/1427 bp)
		5. <i>Pseudomonas sichuanensis</i> strain WCHPs060039 (99.93%/1464 bp)
		6. <i>Serratia fonticola</i> DSM 22080 strain C1 (99.79%/1407 bp)

3.6. Plant Nutrient Profiles and Post-Harvest Media Properties

No statistically significant differences in leaf nutrient concentrations were observed between the two treatments during the harvest season (Table 6). Conversely, the elemental nutrient analysis of the ginger rhizomes revealed distinct variations between the configurations (Table 7). Specifically, the calcium (Ca) content in the F-Wood chip treatment was significantly higher than that detected in the F-Pumice treatment.

Table 6. Element nutrients of the ginger leaf cultured in two different media.

Treatment	N	P	K	Ca	Mg	Cu	Mn	Zn	Fe
			g/kg				mg/kg		
F-Wood chip	17.9 ± 1.5 a	2.0 ± 0.4 a	15.3 ± 1.0 a	7.0 ± 1.5 a	15.8 ± 2.2 a	6.8 ± 1.0 a	194.3 ± 129.3 a	45.3 ± 4.0 a	177.8 ± 18.7 a
F-Pumice	19.8 ± 1.2 a	2.1 ± 0.3 a	16.6 ± 0.4 a	7.4 ± 0.8 a	15.4 ± 1.3 a	7.0 ± 1.2 a	104.5 ± 34.5 a	40.8 ± 1.7 a	224.5 ± 86.7 a

Note: Different letters indicate statistically significant differences (a). Significance in comparison at $p < 0.05$ (LSD test).

Table 7. Element nutrients of ginger rhizome cultured in two different media.

Treatment	N	P	K	Ca	Mg	Cu	Mn	Zn	Fe
	g/kg			mg/kg					
F-Wood chip	14.6 ± 2.2 a	3.7 ± 0.9 a	22.1 ± 2.4 a	2.3 ± 0.2 a	5.9 ± 0.8 a	7.3 ± 1.0 a	131.3 ± 21.1 a	34.0 ± 9.8 a	43.0 ± 6.8 a
F-Pumice	13.3 ± 1.3 a	3.3 ± 0.3 a	20.1 ± 2.3 a	1.8 ± 0.3 b	5.5 ± 0.7 a	7.3 ± 2.5 a	111.0 ± 14.1 a	27.3 ± 7.6 a	45.3 ± 2.2 a

Note: Different letters indicate statistically significant differences (a, b). Significance in comparison at $p < 0.05$ (LSD test).

Regarding the growing media after harvest, since all ginger plants were cultivated in the identical feather compost matrix and received three sequential top-dressing applications during the active vegetative growth period, the water-soluble nutrient contents of the residual feather compost showed no statistically significant differences between the two treatments at the end of the trial (Table 8).

Table 8. The pH, EC, and water-soluble nutrients in a 1:10 water extraction of culture medium after harvest.

Medium	pH	EC	NH ₄ ⁺	NO ₃ [−]	P	K	Ca	Mg	Na	Cu	Mn	Zn	Fe	OM
		dS/m						mg/kg						%
F-Wood chip	6.7 ±0.1 a	1.0 ±0.4 a	87.0 ±24.4 a	578.7 ±341.7 a	358.7 ±89.5 a	787.1 ±299.3 a	497.2 ±112.7 a	291.3 ±92.1 a	590.7 ±183.5 a	1.5 ±0.8 a	0.5 ±0.0 a	0.5 ±0.1 a	3.8 ±0.7 a	80.2 ±0.7 a
F-Pumice	6.6 ±0.1 a	1.1 ±0.2 a	113.7 ±16.4 a	457.3 ±56.1 a	513.7 ±184.2 a	738.1 ±301.5 a	427.0 ±84.6 a	283.7 ±88.2 a	490.0 ±174.9 a	2.6 ±1.4 a	1.1 ±0.5 a	0.7 ±0.1 a	5.5 ±2.0 a	79.3 ±1.9 a

Note: Different letters indicate statistically significant differences (a). Significance in comparison at $p < 0.05$ (LSD test).

4. Discussion

Previous studies indicated that ginger is suitable to be grown in a medium with a pH of 5.5–7.0, an EC of 0.5–2.0 dS/m, a bulk density of 0.2–0.8 g/cm³, and a porosity of 50–85% to maintain oxygen availability and prevent root rot [30]. In this study, among the evaluated media, only the feather compost had an EC value exceeding the recommended range (Table 1). Although high-EC composts are typically considered unsuitable for crop cultivation, a previous experiment demonstrated that feather compost with an EC of 5.5 dS/m could be applied as a cultivation medium for honeydew melon production without additional fertilization [24].

This high nutrient-carrying capacity was further reflected in our nutrient profile; among the cultivation media used in this study, the feather compost contained the highest abundance of macronutrients. Additionally, the water-soluble phosphorus, potassium, and calcium levels in wood chips were higher than those in pumice, while the micronutrient contents varied among the media. Previous studies have indicated that the optimal nitrogen, phosphorus, and potassium (NPK) fertilizer ratio for ginger production is 2:1:3 [31]. Considering the high K requirements of ginger, the feather compost was formulated with palm ash to increase its water-soluble K concentrations (Table 2).

Developing such nutrient-rich organic media aligns closely with the contemporary net-zero carbon reduction paradigm, wherein the consumption of fossil energy in the production of chemical fertilizers contributes to elevated greenhouse gas emissions [32]. Consequently, decreasing the usage of chemical fertilizers can help lower carbon emissions. Beyond the impacts of chemical fertilization, the extraction and application of widely adopted peat substrates represent another significant source of greenhouse gas emissions [33]. Therefore, utilizing fully substituted feather compost as a growing medium for ginger production presents a promising, sustainable alternative.

Nevertheless, successful substrate cultivation relies not only on chemical nutrient supply but also heavily on optimal physical properties, particularly aeration and drainage.

A 2024 preliminary trial revealed that when open-field ginger was grown entirely in poultry feather compost, poor drainage caused the ginger root system to become waterlogged following the rainy season. This subsequent and progressive root mortality ultimately led to a total crop failure with zero yield. Accordingly, this highlights the critical need to optimize the physical structure of the growth medium—such as through the incorporation of a bottom drainage layer—to realize the feasibility of zero-fertilizer feather compost cultivation without compromising root health.

Implementing a basal layer of pumice or wood chips beneath the feather compost effectively accelerates the rapid drainage of free water from the substrate surface by enhancing vertical hydraulic conductivity (Table 3). Although previous studies primarily focused on surface mulching, their findings regarding physical water movement align with our observations; for instance, wood chip mulching has been shown to increase water infiltration rates, improve soil moisture retention, and reduce surface runoff [10,34–37]. Similarly, applications of pumice across diverse soil orders—including Aridisols, Vertisols, and Inceptisols—have been demonstrated to effectively enhance water infiltration rates and reduce surface runoff [38]. Consequently, in the 2025 experiment where wood chips or pumice were incorporated as a basal drainage layer beneath the feather compost, the plants successfully endured the typhoon and rainy season until harvest.

Notably, the survival rate of the F-Wood chip treatment was 60%, whereas that of the F-Pumice treatment reached 80%. Intriguingly, while the F-Pumice treatment exhibited a higher ginger survival rate, its subsequent rhizome yield, as well as the abundance and diversity of endophytic bacteria, were lower than those in the F-Wood chip treatment (Tables 4 and 5). The higher ginger survival rate in the F-Pumice treatment can be attributed to its nature as a stable inorganic mineral material, which consistently provides reliable drainage and aeration throughout the extended 345-day cultivation period (from 4 February 2025 to 15 January 2026). Although the initial drainage performance appeared similar between treatments, the highly porous pumice (Table 1) maintains its physical structure without collapsing. In contrast, the organic F-Wood chip matrix is highly dynamic; over this long-term 11.5-month production cycle, it undergoes progressive degradation and structural contraction, introducing greater operational variables and physicochemical fluctuations during crop establishment. However, this extended decomposition process is pivotal to the observed yield dynamics. The gradual, year-long degradation of wood chips provides a sustained nutrient influx and likely modulates rhizosphere microbial–plant interactions, ultimately precipitating the substantial increase in final rhizome harvest.

This trade-off between survival rate and yield/microbial recruitment can be attributed to the distinct intrinsic properties of the two materials. In contrast to organic wood chips, inorganic pumice is recalcitrant to degradation and does not provide supplementary nutrients, thereby differentially shaping the microbial diversity and population density in the rhizosphere and the endophytes inside the roots. Previous research demonstrated that three consecutive years of surface mulching with wood chips significantly elevated nutrient levels, increasing available phosphorus, potassium, magnesium, and organic matter by 32%, 66%, 71%, and 49%, respectively [36]. The nutrients and organic carbon released by wood chip degradation could subsequently alter bacterial composition and increase bacterial abundance and diversity, particularly promoting taxa with metabolic functions in carbon and nitrogen cycling [39]. In our experiment, the endophytic genus diversity and bacterial numbers of ginger cultured in F-Wood chip were higher than in F-Pumice (Table 5), which was probably also caused by the elevated influx of nutrients and organic carbon via wood chip degradation.

In this study, five endophytic bacterial isolates of ginger were both found in the two media treatments, among which *Lysinibacillus fusiformis* with phosphate-solubilizing

and IAA-producing ability; co-inoculation with *Bacillus velezensis* can increase the number of soybean root nodules, flowering number, and yield [40]; *Pseudomonas glycinae* had salt tolerated ability up to 6% (*w/v*) NaCl [41]; *Pseudomonas laurentiana* had beneficial abilities in promoting plant growth, antagonistic to plant pathogenic fungi *Bipolaris sorokiniana*, and increasing seed germination such as cucumber, tomato, and cabbage [42]; *Serratia fonticola* with plant growth promoting ability and inoculated in cucumber can increase its salt tolerance via increase in antioxidant enzymes and upregulating the expression of the ion transporter genes, especially co-inoculated with *Pseudomonas koreensis* [43]. The presence of these shared endophytes suggests a baseline of systemic resilience and growth support inherent to both treatments.

Intriguingly, the F-Wood chip treatment recruited a distinct assembly of unique endophytic bacteria that were likely linked to higher rhizome yield. This phenomenon is closely tied to the high EC value of the feather compost; consequently, the enrichment and proliferation of specific endophytes capable of mitigating salinity stress during root development could crucially enhance crop productivity. Among these uniquely recruited taxa, *Acinetobacter radioresistens* can enhance the activity of ACC-deaminase, Proline Dehydrogenase (ProDH), Nitrilase, and the enzyme activity required for IAA production under salinity stress, and improving the resistance of *Cucurbita* sp. to salinity stress [44]; *Bacillus stratosphericus* with multiple functions such as nitrogen fixation, IAA production, phosphate and zinc solubilization, sulfur oxidation, plant growth promotion under conditions of saline stress [45], and reported with antifungal activity against common plant pathogens and plant growth-promoting traits, including ACC deaminase activity and IAA production [46].

In addition to these salinity-mitigating strains, *Microbacterium resistens* was reported to degrade 17 β -estradiol, a complex cyclic compound [47]. This capability suggests that its enrichment in the F-Wood chip matrix might be fundamentally related to the biodegradation of wood lignin—a highly recalcitrant aromatic polymer—thereby selectively promoting bacteria with cyclic compound-degrading functions. The unique endophytic community also included *Pseudomonas fortuita*; although originally isolated from the endosphere of yam leaves [48], its potential applications in sustainable agriculture remain largely underexplored. Furthermore, *Pseudomonas plecoglossicida* has been documented to alleviate drought stress in wheat by increasing leaf chlorophyll (Chl) and root cytokinin concentrations while simultaneously decreasing root abscisic acid (ABA) levels [49]. Finally, *Staphylococcus ureilyticus* exhibits potent silica-dissolving capabilities, which could critically facilitate grapevines' nutrient uptake [50].

Collectively, among the endophytic bacteria identified in ginger roots, the majority possess proven plant growth-promoting functions that enhance host resistance to salinity or drought stress. This ecological phenomenon is likely driven by the high electrical conductivity (EC) and the abundance of water-soluble ions inherent to the feather compost. As these ions progressively leached into the basal layer of wood chips or pumice, they established a localized saline gradient that actively recruited salt-tolerant bacteria, thereby facilitating their subsequent migration into the root endosphere. Furthermore, the number of enriched endophytic bacterial genera was noticeably higher in the F-Wood chip treatment (seven genera) than in F-Pumice (three genera). This enhanced microbial recruitment is closely associated with the ongoing biodegradation of the wood chips, which provides a continuous concomitant supply of organic carbon and additional nutrients to the rhizosphere.

In the plant nutrient analysis conducted during the ginger harvest period (Table 6), the leaves had already undergone yellowing; consequently, the leaf nutrient values were lower than the standard recommended plant tissue nutrient levels [51]. Previous studies have

demonstrated that increasing fertilizer application rates for ginger from N-P-K = 75-50-50 to N-P-K = 125-100-100 significantly elevates the nutrient concentrations in ginger rhizomes. Specifically, phosphorus (P) increased from 3.8 to 4.3 g/kg, potassium (K) from 12.2 to 15.9 g/kg, calcium (Ca) from 2.4 to 11.0 g/kg, magnesium (Mg) from 6.2 to 8.2 g/kg, manganese (Mn) from 80.9 to 118.7 mg/kg, zinc (Zn) from 2.8 to 3.2 mg/kg, and iron (Fe) from 196.2 to 225.7 mg/kg, whereas copper (Cu) remained stable at approximately 1.7 mg/kg [52]. In comparison, the ginger rhizomes in the present study exhibited higher potassium content but lower calcium content (Table 7). This antagonistic effect was likely induced by the excessive water-soluble potassium present in the feather compost, which competitively suppressed the root uptake of calcium. This aligns with previous findings indicating that an excess of competing cations (such as K^+ , Mg^{2+} , NH_4^+ , and H^+) severely suppresses calcium absorption in plants [53]. Regarding other nutrients, the concentrations of phosphorus, calcium, and magnesium in the F-Wood chip treatment were comparable to those observed in the aforementioned N-P-K = 75-50-50 treatment. Conversely, the F-Pumice treatment showed a severe calcium deficiency, which might have acted as the primary limiting factor for its lower rhizome yield. Furthermore, the application of feather compost resulted in a significant accumulation of copper and zinc in the rhizomes, exceeding the levels observed in the soil-cultivated counterparts from the previous literature.

After the ginger harvest, no significant differences in growing media properties were observed between the two treatments (Table 8). Compared to the pre-trial levels (Table 2), the concentration of water-soluble ammonium (NH_4^+) remained relatively stable, whereas nitrate (NO_3^-) decreased significantly. This trend indicated the continuous mineralization and degradation of organic nitrogen in the feather compost, which was accompanied by subsequent nitrification and concurrent nutrient uptake by the ginger plants.

This study establishes an integrated crop management framework for soilless ginger production by synergistically addressing nutrient supply and physical substrate structure. By utilizing feather compost with slow-release fertilizer characteristics as a cultivation medium, the system achieves self-sustained nutrient supply for ginger growth, thereby providing a low-carbon cultivation model. Furthermore, modifying the substrate configuration enhances internal drainage performance, rendering this system highly adaptable to open-field cultivation in regions characterized by heavy rainfall. Ultimately, this research provides a sustainable and resilient integrated application model for open-field soilless ginger production.

5. Conclusions

This study evaluated open-field ginger production under soilless culture using root-control bags. The primary findings are concluded as follows. Primarily, utilizing either wood chips (F-Wood chip) or pumice (F-Pumice) as a basal drainage layer beneath feather compost demonstrated high climate resilience, allowing for successful ginger harvesting even during the heavy rainfall brought by Typhoon Danas. Furthermore, although the plant survival rate in the F-Wood chip treatment (60%) was lower than that in the F-Pumice treatment (80%), the F-Wood chip group achieved a substantially higher rhizome fresh weight of 3.4 kg/pot compared to 2.5 kg/pot in the F-Pumice group. Concurrently, the F-Wood chip treatment significantly enhanced the root microbiome, exhibiting an endophytic bacterial count of $9.5 \pm 4.5 \times 10^5$ CFU/g and colonizing seven distinct genera (*Acinetobacter*, *Bacillus*, *Lysinibacillus*, *Microbacterium*, *Pseudomonas*, *Serratia*, and *Staphylococcus*). In contrast, the F-Pumice treatment yielded a lower bacterial count of $1.1 \pm 0.2 \times 10^4$ CFU/g and harbored only three genera (*Lysinibacillus*, *Pseudomonas*, and *Serratia*). These identified endophytes are widely documented to promote plant growth and fortify resistance against salinity and drought stress. Overall, this integrated crop management strategy using feather

compost systems integrated with basal drainage layers demonstrates great potential to substitute for further chemical fertilizer application, offering a resilient solution, thereby facilitating low-carbon and simplified ginger cultivation. This approach offers a highly promising and sustainable solution for farmers operating in challenging hot and humid environments. Nevertheless, further large-scale trials are warranted to enhance data precision and validate these outcomes. To build upon these promising outcomes, several concrete next action lines have been established. First, long-term, multi-location field trials will be continuously conducted to evaluate the effects of this substrate mode on ginger development, yield, and quality under diverse regional and climatic conditions. Second, future investigations will focus on the recycling and reuse of the spent cultivation substrate post-harvest. Third, the potential endophytic microbial strains isolated and screened from ginger roots within this study will be re-introduced exogenously in subsequent trials to verify their practical bio-stimulatory impacts on plant growth. Finally, a comprehensive evaluation will be performed to assess the economic viability, commercial costs, and carbon emission reduction benefits of transforming agricultural wood waste into high-value ginger cultivation media, thereby establishing a sustainable circular agriculture framework.

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Abbreviations

The following abbreviations are used in this manuscript:

SMS	Spent mushroom substrate
F-Wood chip	Wood chip layer at the bottom of the feather compost
F-Pumice	Pumice layer at the bottom of the feather compost
EC	Electrical conductivity
BD	Bulk density
OM	Organic matter
WHC	Water holding capacity
NA	Nutrient broth agar
FC	Feather compost
LSD	Least Significant Difference

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