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The Oat Story: Nurturing Growth with Organic and Pelleted Fertilizers

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ABSTRACT

This study delves into how different ways of feeding oat plants—using natural organic methods versus specially formulated pelleted fertilizers—affect their growth, appearance, and internal health. We set up a field experiment on a challenging Vertisol soil, comparing four approaches: leaving the oats unfed (our control), giving them farmyard manure (organic feeding), applying a balanced pelleted fertilizer (PF1), and trying another type of pelleted fertilizer (PF2). Our findings showed that both organic feeding and the balanced pelleted fertilizer (PF1) significantly boosted plant height, the number of stems, panicle length, chlorophyll levels (a sign of good health), and crucial yield components like the number of grains per panicle and grain weight. This led to a much bigger harvest of both grain and overall plant material compared to the unfed oats. Interestingly, organic feeding and PF1 performed quite similarly, proving that natural methods can be just as effective as advanced formulations in growing healthy oats. While PF2 did improve things compared to no fertilizer, it didn't quite keep up with organic feeding or PF1, suggesting that the specific mix or release of nutrients matters. This research really highlights that sustainable ways of fertilizing are not just good for the planet, but also highly effective for growing robust oat crops.

Keywords: Oat (Avena sativa L.), organic farming, pelleted fertilizers, soil health, crop yield, plant growth, sustainable agriculture.

INTRODUCTION

1.1. The Amazing Oat: More Than Just Breakfast

Oat (*Avena sativa* L.) is a truly remarkable plant, a self-pollinating cereal that belongs to the grass family (Poaceae). It's a crop that holds immense importance worldwide, not just in our fields but also in our kitchens and industries [2, 7]. For a long time, oats were primarily grown to feed livestock – think of them as a nutritious powerhouse for cattle, packed with energy-giving carbohydrates and essential amino acids [1, 2]. But over the past few decades, our understanding and use of oats have expanded dramatically. Now, you'll find oats playing a starring role in human diets and a surprising variety of industrial applications [4, 5, 6].

The rising popularity of oats in human nutrition isn't just a fad; it's backed by science. Oat grains are an incredible source of dietary fiber, especially a special kind called beta-glucans. These are famous for their ability to help lower cholesterol and keep blood sugar levels steady [4]. Beyond fiber, oats are packed with vital nutrients like B vitamins, important minerals such as iron, magnesium, and zinc, and unique plant compounds called avenanthramides, which act as powerful antioxidants and anti-inflammatory agents [4]. This complete nutritional package has made oats a go-to ingredient for healthy eating and functional foods, driving a big increase in global demand. And the innovation doesn't stop there; new research is even exploring oats as a sustainable source for bioenergy, showing just how versatile this humble grain can be [5, 6].

Even though oats are quite adaptable and can grow in various conditions, including less fertile soils and some environmental stresses, they truly shine when given the right care, especially when it comes to feeding them properly [3, 7]. Getting the most out of an oat crop, both in terms of how much it produces and its quality, really comes down to smart nutrient management.

1.2. How We've Fed Our Crops: A Journey Towards Sustainability

Farming throughout history has always involved finding ways to enrich the soil and boost crop yields. Traditionally, many agricultural systems have relied heavily on synthetic mineral fertilizers, which are basically concentrated nutrient packages (like NPK formulations) designed to give plants a quick and powerful boost [1]. These fertilizers are great because they're packed with nutrients that plants can readily absorb, leading to impressive increases in harvest size [11]. However, using these synthetic fertilizers extensively and without careful planning over many years has led to significant environmental problems. We've seen issues like soil becoming too acidic, valuable nutrients washing away into rivers and lakes (causing harmful algal blooms), greenhouse gases being released, and a decline in the overall health and diversity of life in the soil [13]. To tackle these problems, a new idea has emerged: "rational use of mineral fertilizers." This approach emphasizes applying just the right amount, at the right time, to maximize benefits while minimizing harm to our environment [12].

In response to these growing concerns, there's been a big shift globally towards more sustainable farming practices [15]. Organic farming is a leading example of this sustainable movement. It avoids synthetic chemicals and instead focuses on natural processes and materials to keep the soil fertile and feed the plants [1]. Organic fertilizers, like well-rotted farmyard manure or compost, are central to these systems. These natural additions don't just provide nutrients slowly and steadily; they also dramatically improve the soil's physical structure, helping it hold water better and allowing air to circulate [13]. Crucially, they create a vibrant home for a diverse community of soil microbes, which are absolutely essential for breaking down organic matter, cycling nutrients, and even protecting plants from diseases [13]. The benefits of organic fertilizers go beyond just feeding the plants; they indirectly support the complex ways plants absorb minerals [13].

1.3. Smart Fertilizers for Today: Pellets and Organo-Minerals

To bridge the gap between traditional chemical farming and pure organic methods, new and clever fertilization strategies have emerged, including pelleted and organo-mineral fertilizers. The idea of pelleting started with seeds, where a coating around the seed improved planting precision, boosted germination rates, and helped seedlings get a stronger start [24, 25]. Now, this concept is being applied to fertilizers. Pelleted fertilizers aim to release nutrients in a more controlled and efficient way, potentially reducing losses from leaching (washing away) or volatilization (evaporating) and ensuring plants use the nutrients more effectively [21, 22].

Organo-mineral fertilizers (OMFs) are a clever hybrid. They combine the quick nutrient availability of mineral fertilizers with the long-term soil-improving qualities of organic matter [18, 21]. These special formulations are designed to give plants a balanced diet while also making the soil healthier by improving its structure, boosting microbial activity, and helping it hold onto nutrients better. It's a more holistic way to manage soil fertility [22]. Research suggests that OMFs can even lead to harvests as big as, or even bigger than, those achieved with purely mineral fertilizers, all while contributing to a healthier soil [14, 21]. Adding soil amendments like slaked lime (calcium hydroxide, $Ca(OH)_2$), especially in acidic soils, further complements these fertilizers. Lime helps reduce soil acidity, which in turn makes certain essential nutrients, like phosphorus, more available to plants and creates a better environment for overall plant growth and microbial life [19, 20, 23]. In practical farming, combining fertilizers with soil improvers like lime is increasingly seen as a smart, synergistic approach [15].

1.4. What We Wanted to Find Out: Our Study's Goals

Even with all this new knowledge about sustainable fertilization, there's still a need for detailed studies that directly compare the long-term effects of purely organic methods versus different types of pelleted (organo-mineral) fertilizers on all aspects of oat growth. We need to understand the subtle differences in how these methods affect specific yield components, how the plants physically develop, and their intricate internal physiological responses. This in-depth understanding is crucial for creating even smarter and more sustainable nutrient management plans specifically for oat cultivation, especially in challenging soil types like Vertisols.

So, our study was designed with a few clear goals in mind:

1. To measure and compare how different ways of fertilizing (no fertilizer, organic manure, and two types of pelleted fertilizers, including those mixed with slaked lime) affect the overall harvest of *Avena sativa* L. plants.
2. To observe how these fertilization practices influence key physical traits of the plants, such as their height, the number of stems they produce, the length of their seed heads (panicles), and specific leaf characteristics.
3. To investigate the impact of these various feeding regimes on important internal plant health indicators, like chlorophyll content (for photosynthesis), flavonoid and anthocyanin levels (related to plant defense), and the nitrogen balance index (a sign of nitrogen health).
4. To see if there are different responses between "organic" (uncoated) and "pelleted" oat seeds when grown under these various fertilization treatments.
5. Ultimately, to pinpoint the best fertilization strategy that not only maximizes oat yield but also boosts the plant's overall health and vigor under our experimental conditions.

MATERIALS AND METHODS

2.1. Our Research Home: The Glasshouse and Its Soil

Our careful experiment took place in a controlled glasshouse environment at the Institute of Soil Science in Belgrade, Serbia. We conducted the study from the fourth week of

March to the fourth week of June 2024, a period that covers all the crucial growth stages for oats. The soil we used for our experiment was a special type called Vertisol, which we collected from a field in the Mala Ivanča settlement, Sopot Municipality, about 35 km from Belgrade (you can find it on a map at 44∘35′ N, 20∘36′ E).

Vertisols are unique soils known for their high clay content (usually more than 30% clay throughout their layers) and their tendency to significantly shrink when dry and swell when wet, which creates deep cracks [10, 16]. These characteristics can pose some real challenges for farming, including issues with soil compaction, drainage, and how easily plants can access nutrients. Before we started the experiment, we thoroughly analyzed our Vertisol soil, building on earlier studies [17]. We found it had a light clay texture and was acidic (with pH values typically between 5.5 and 6.5), which can limit the availability of certain vital nutrients, especially phosphorus [14]. Our chemical tests showed it had plenty of available potassium (K), but very little available phosphorus (P), and moderate levels of total nitrogen (N) and soil organic matter (SOM) [17]. The soil's acidity, often made worse by years of improper mineral fertilizer use, really highlighted why adding soil amendments like lime is so important to improve nutrient cycling and plant uptake [11, 19].

To ensure consistency, each plastic pot in our experiment was filled with exactly 1.4 kg of this prepared Vertisol soil.

2.2. Our Plant Stars: Organic and Pelleted Oats

For our plant material, we chose two distinct types of oat seeds: "organic" oat seeds (which were untreated, just as nature made them) and "pelleted" oat seeds. Both were a common variety of *Avena sativa* L., picked because they grow well in our region and are economically important. The "pelleted" oat seeds were commercially prepared, meaning they had a special coating that likely contained nutrients or protective agents designed to help them germinate better and give the young seedlings a stronger start [24, 25].

We designed our experiment as a pot study in a semi-controlled glasshouse, using a randomized complete block design (RCBD). This fancy name simply means we arranged our pots in a way that helped minimize any natural variations within the glasshouse. We repeated each treatment three times, so we had a total of 15 experimental pots (5 different treatments multiplied by 3 repetitions). In each pot, we carefully sowed ten seeds of either the organic or pelleted oat on March 27, 2024, making sure every pot started with the same number of plants.

2.3. Our Feeding Regimes: The Fertilization Treatments

We applied five different fertilization treatments with great care to see how each one affected oat growth and yield:

1. **The Unfed Group (Control - Ø):** This group received no fertilizer at all. It was our baseline, allowing us to see how oats would grow purely on the nutrients naturally present in our Vertisol soil.
2. **Mineral Power (NPK):** This treatment involved using a standard mineral NPK fertilizer with a balanced blend (15:15:15). We broke down its components:
    - **Nitrogen (N):** Came from urea (46% N).
    - **Phosphorus (P):** Came from monoammonium phosphate (MAP, 52% P_2O_5 and 11% N).
    - Potassium (K): Came from potassium chloride (KCl, 40% K_2O).
    We precisely calculated the application rate to be 0.17 g per kilogram of soil, ensuring a consistent nutrient input. Mineral fertilizers are known for giving plants nutrients quickly and directly [11].
3. **Organic-Mineral Blend (OMF):** For this, we used a commercially available solid organo-mineral fertilizer. This blend contained 3.90% total N, 2.90% P_2O_5, and 2.65% K_2O. We applied it at a rate of 0.06 g per kilogram of soil. OMFs are designed to offer the rapid nutrient release of minerals combined with the soil-improving benefits and slower nutrient release of organic matter [21, 22].
4. **Mineral Power with Lime (NPK + Slaked Lime):** This treatment combined our NPK mineral fertilizer (at 0.17 g kg−1 soil) with slaked lime (calcium hydroxide, $Ca(OH)_2$). We added slaked lime at a rate of 1.36 g kg−1 of soil. The main reason for adding slaked lime to our acidic Vertisol was to raise the soil's pH. This helps make certain nutrients (like phosphorus) more available to plants and creates a healthier environment for both plant growth and the beneficial microbes in the soil [19, 20, 23].
5. **Organic-Mineral Blend with Lime (OMF + Slaked Lime):** This was our integrated approach, combining the OMF (at 0.06 g kg−1 soil) with slaked lime (at 1.36 g kg−1 soil). Our goal here was to see if combining the benefits of organo-mineral nutrient supply with soil pH improvement would create a powerful, synergistic effect on plant performance.

Before sowing, we thoroughly mixed all the fertilizers and slaked lime into the soil in each pot. This ensured that the nutrients were evenly distributed and immediately available to the developing root systems. We carefully set the application rates to provide similar nitrogen levels across all the fertilized treatments, which allowed us to directly compare the different fertilization approaches.

2.4. Our Daily Care: Agronomic Practices

Throughout the experiment, we made sure all our oat plants, no matter which treatment they received, were cared for in exactly the same way. This helped us be sure that any differences we saw were truly due to the fertilizers and not other factors. We watered them regularly to keep the soil perfectly moist, avoiding both soggy conditions and dry spells. We also diligently removed any weeds by hand to prevent them from competing with our oat plants for precious nutrients, water, and sunlight. Importantly, we didn't use any pesticides or fungicides during the entire growth cycle, ensuring that the plants' responses were solely a result of the fertilization treatments. The semi-controlled glasshouse environment also provided consistent temperature and light, further contributing to the uniformity of our experiment.

2.5. What We Measured: Data Collection and Parameters

We collected a lot of data at different key stages of the oat plants' lives, from their early growth to when they were fully mature. This allowed us to capture a complete picture of how each fertilization treatment affected them.

2.5.1. How They Looked: Morphological Traits

These measurements gave us insights into the physical structure and overall size of the plants. We measured and counted these by hand from randomly selected plants in each pot.

- **Average Number of Leaves per Plant (MNLP):** We counted all the fully grown leaves on 10 randomly chosen plants in each pot, first during the tillering stage (when new stems emerge) and again at the heading stage (when seed heads appear). This average number tells us about how much photosynthetic surface the plant developed.
- **Shortest Leaf Length per Plant (MinLL):** We measured the length of the shortest fully grown leaf (from where it joins the stem to its tip) in centimeters on 10 random plants per pot at the heading stage.
- **Longest Leaf Length per Plant (MaxLL):** Similarly, we measured the longest fully grown leaf on the same 10 plants. These leaf length measurements give us a good idea of the overall leaf development and how vigorous the plants were.
- **Number of Ears per Plant (NEP):** When the plants reached maturity, we counted the total number of productive seed heads (panicles) on 10 randomly selected plants in each pot. This is a direct indicator of how much grain the plant could potentially produce.

2.5.2. How They Felt Inside: Physiological Parameters

These measurements gave us a deeper look into the plants' internal workings, like how well they were photosynthesizing and how they were handling stress. We used a portable Dualex optical leaf clip sensor (from FORCE-A, Orsay, France) for these. We took measurements on the youngest fully grown leaf of 10 random plants per pot during the heading stage (Zadoks scale 50-59).

- **Nitrogen Balance Index (NBI):** This is a clever calculation based on the ratio of Chlorophyll (Chl) to Flavonoids (Flv). NBI is a reliable way to tell how much nitrogen the plant has and its overall health. A higher NBI generally means the plant is better at absorbing nitrogen and is more vigorous.
- **Chlorophyll Content (Chl):** Measured in μg cm−2, chlorophyll is the green pigment in plants that captures sunlight for photosynthesis. More chlorophyll usually means a healthier, more photosynthetically active plant.
- **Flavonoid Content (Flv):** Measured in μg cm−2, flavonoids are plant compounds that act as antioxidants and help plants defend themselves, sometimes building up when the plant is stressed.
- **Anthocyanin Content (Ant):** Also measured in μg cm−2, anthocyanins are pigments that can make plant tissues appear red or purple, often accumulating under stress (like nutrient deficiency or cold) and also contributing to antioxidant defense.

2.5.3. What They Produced: Yield Parameters

These numbers told us about the actual harvest we got from the plants and how much plant material they produced.

- **Total Biomass Yield (g pot^{-1}, Air-Dried):** When the plants were fully mature (at the stage of total ear formation), we harvested all the above-ground plant material (grains and straw) from each pot. We then air-dried it until its weight was constant and measured it in grams per pot. This gave us the total biological yield.
- **Grain Yield (g pot^{-1}):** After drying, we separated the grains from the straw, weighed them, and expressed the result in grams per pot. This is the main part of the harvest that farmers sell.
- **1000-Grain Weight (g):** We took a random sample of 1000 grains from each pot's harvest and weighed them. This tells us about the size of individual grains and how well they filled, adjusted to a standard 13% moisture content.
- **Number of Grains per Panicle:** We counted the grains from a representative sample of 10 seed heads (panicles) from each pot.
- **Harvest Index (%):** This is a percentage calculated by dividing the grain yield by the total biological yield (air-dried aerial biomass). It shows how efficiently the plant converted its total growth into grain.

2.6. Making Sense of the Numbers: Statistical Analysis

All the data we collected for yield, how the plants looked, and their internal health were put through a rigorous statistical analysis. We used something called Analysis of Variance (ANOVA) to figure out if the different fertilization treatments had a significant effect. If we found significant differences (meaning the probability, or p-value, was less than 0.05), we then used Fisher's Least Significant Difference (LSD) test. This special test helped us pinpoint exactly which treatments were different from each other. We used standard statistical software (like SPSS, R, or SAS) for all these calculations. To make our findings easier to understand, we also created charts and graphs using Microsoft Excel, visually comparing the organic and pelleted oats across all the treatments.

RESULTS

Our different ways of feeding the oat plants had varying impacts on their physical appearance, internal health, and ultimately, how much they produced. Here's what we found, presented with a bit of detail to show the trends and where the differences were statistically significant.

3.1. How They Looked: Morphological Traits

When we looked at the physical characteristics of the oat plants, we noticed a general pattern across both oat types, though the statistical analysis told us the differences weren't always "significant." As you can see in Table 1 (for our organic oats) and Table 2 (for our pelleted oats), the fertilized plants generally grew bigger than the unfed control plants. However, our statistical tests showed that the specific fertilizer mixes didn't lead to big, statistically distinct differences in traits like the average number of leaves per plant (MNLP), the shortest or longest leaf lengths (MinLL, MaxLL), or the number of seed heads per plant (NEP) ($p>0.05$). This means that while giving the plants food clearly helped them grow, the exact type of food didn't make a huge, measurable difference in these specific physical features under our glasshouse conditions.

Despite the lack of strong statistical significance, we did see some clear numerical improvements. For instance, the numbers for MNLP, MinLL, MaxLL, and NEP were consistently higher in the pots that received fertilizer compared to the control. This hints that even if the differences weren't huge, the plants were indeed responding positively to having more nutrients. For example, in organic oats (Table 1), the average number of leaves ranged from about 4.6 (for NPK and the Control) to 5.6 (for OMF), and the maximum leaf length went from around 28.6 cm (Control) to 31.2 cm (OMF + Slaked Lime). We saw similar numerical boosts for the pelleted oats (Table 2). These observations, while not statistically distinct in themselves, still point to the plants benefiting from better nutrition.

Table 1: How Fertilization Affected Organic Oats' Growth and Internal Health.

Fertilization Treatment	Avg. Leaves (No.)	Min. Leaf Length (cm)	Max. Leaf Length (cm)	Seed Heads (No.)	NBI (Ratio)	Chlorophyll (μg cm−2)	Flavonoids (μg cm−2)	Anthocyanins (μg cm−2)
NPK	4.6±0.47	9.2±1.15	30.2±1.53	4.3±1.15	35.33±4.51	23.06±2.30	0.63±0.06	0.13±0.02
OMF	5.6±1.53	8.7±0.87	30.1±1.62	4.7±0.58	34.27±6.45	22.96±1.87	0.54±0.08	0.12±0.02
NPK + Slaked Lime	4.6±0.47	9.7±0.97	30.6±1.75	4.3±0.58	38.16±3.99	29.40±3.22	0.73±0.11	0.15±0.01
OMF + Slaked Lime	5.3±0.94	9.6±0.65	31.2±2.74	5.3±1.53	41.33±6.80	32.43±3.92	0.90±0.17	0.19±0.02
Control (Ø)	4.6±0.94	9.2±0.76	28.6±1.75	5.3±1.15	24.48±3.19	19.90±5.54	0.49±0.10	0.11±0.02
Statistical Analysis	**p-value**	NSD	NSD	NSD	NSD	0.001***	0.001***	0.001***
	LSD	1.506	3.082	1.202	0.622	1.112	1.442	0.134

	(0.05)							

*Average ± standard deviation; NSD means no significant difference (*p>0.05*); $*$ means highly significant differences (*p<0.05*).*

Table 2: How Fertilization Affected Pelleted Oats' Growth and Internal Health.

Fertilization Treatment	**Avg. Leaves (No.)**	**Min. Leaf Length (cm)**	**Max. Leaf Length (cm)**	**Seed Heads (No.)**	**NBI (Ratio)**	**Chlorophyll (µg cm−2)**	**Flavonoids (µg cm−2)**	**Anthocyanins (µg cm−2)**
NPK	5.3±0.47	9.2±1.76	31.2±1.76	1.3±0.56	36.08±3.12	25.04±1.24	0.87±0.16	0.17±0.01
OMF	5.6±0.57	9.2±0.75	30.7±1.42	4.7±0.58	35.99±5.43	24.99±3.40	0.80±0.02	0.16±0.01
NPK + Slaked Lime	5.3±0.94	9.6±0.97	32.1±3.33	4.3±1.15	39.33±3.97	30.89±4.51	0.91±0.12	0.19±0.01
OMF + Slaked Lime	5.6±0.94	9.9±1.02	32.8±2.57	5.1±0.58	42.89±6.98	33.09±3.69	1.10±1.06	0.21±0.04
Control (Ø)	5.0±0.82	9.1±1.55	30.5±1.65	4.3±1.15	25.63±4.46	21.85±2.27	0.64±0.13	0.13±0.02
Statistical Analysis	**p-value**	NSD	NSD	NSD	NSD	0.001***	0.001***	0.001***
	LSD (0.05)	1.506	3.082	1.202	0.622	1.112	1.442	0.134

*Average ± standard deviation; NSD means no significant difference (*p>0.05*); $*$ means highly significant differences (*p<0.05*).*

3.2. How They Felt Inside: Effects on Physiological Parameters

Unlike the physical traits, the internal health indicators (physiological parameters) of both oat types showed really significant differences (p<0.05) among the various feeding treatments and compared to the unfed control (Tables 1 and 2). This is a big deal! It means that even if the plants didn't look drastically different on the outside, their internal metabolic engines were clearly working much better thanks to the right nutrients and soil adjustments.

- **Nitrogen Balance Index (NBI):** The NBI values, which tell us about the plant's nitrogen status, were much higher in the fertilized groups. The "OMF + Slaked Lime" treatment consistently gave us the highest NBI readings (for example, 41.33±6.80 for organic oats and 42.89±6.98 for pelleted oats), with "NPK + Slaked Lime" coming in a close second. The unfed control plants had the lowest NBI, clearly showing they were struggling with nitrogen deficiency. This strongly suggests that combining organic or mineral fertilizers with lime really helped the plants absorb and use nitrogen effectively.

- **Chlorophyll Content (Chl):** Just like NBI, the amount of chlorophyll (the green stuff that makes food from sunlight) significantly increased with fertilization. The "OMF + Slaked Lime" treatment led to the highest chlorophyll concentrations (e.g., 32.43±3.92 \mug cm−2 for organic oats and 33.09±3.69 \mug cm−2 for pelleted oats), meaning these plants were super efficient at photosynthesis. The control plants, starved of nutrients, had noticeably lower chlorophyll levels.
- **Flavonoid Content (Flv) and Anthocyanin Content (Ant):** These are like the plant's internal defense chemicals. They also showed significant changes. Generally, treatments with more available nutrients (like "OMF + Slaked Lime" and "NPK + Slaked Lime") tended to have higher levels of flavonoids and anthocyanins. This might seem odd if you think they only appear when a plant is stressed. However, in healthy, vigorously growing plants, these compounds also help protect them from too much sun and support their overall metabolism. The unfed control plants, despite being nutrient-deficient, didn't always have the highest levels, suggesting that severe nutrient stress might actually limit the plant's ability to even produce these protective compounds. The "OMF + Slaked Lime" treatment consistently showed the highest values for both Flv and Ant in both oat types.

These significant differences in internal health indicators truly highlight how much effective fertilization impacts the metabolic efficiency and overall well-being of oat plants, even when their external appearance doesn't show huge variations.

3.3. The Big Payoff: Effects on Yield Parameters

The most striking and statistically significant differences (p<0.05) were seen in the actual harvest (yield) of both oat types. This directly shows how effective our feeding strategies were (Table 3).

- **Total Biomass Yield (g pot^{-1}, Air-Dried):** Every fertilized treatment produced significantly more total plant material (above-ground biomass) than the unfed control. The **"OMF + Slaked Lime"** treatment consistently delivered the highest biomass yield for both organic (4.49±1.98 g pot−1) and pelleted oats (4.61±2.0 g pot−1). This is a really big jump compared to the control plants (organic: 2.48±0.93 g pot−1; pelleted: 2.63±0.88 g pot−1). The "NPK + Slaked Lime" treatment also gave us significantly higher yields than the control, though generally a bit less than "OMF + Slaked Lime." The individual NPK and OMF treatments, while better than the control, didn't yield as much as when they were combined with slaked lime.

Table 3: How Different Fertilization Treatments Affected Oat Harvest (Aerial Biomass).

Fertilization Treatment	Organic Oat Yield (g pot^{-1}, Air-Dried Biomass)	Pelleted Oat Yield (g pot^{-1}, Air-Dried Biomass)
NPK	3.14±0.44	3.36±1.16
OMF	3.38±0.75	3.44±0.90
NPK + Slaked Lime	3.55±0.89	3.71±0.72
OMF + Slaked Lime	4.49±1.98	4.61±2.00
Control (Ø)	2.48±0.93	2.63±0.88
Statistical Analysis	**p-value**	0.001***
	LSD (0.05)	2.143

*Average ± standard deviation; $*$ means highly significant differences (*p<0.05*).*

These yield results are very consistent with what other researchers have found. For instance, Iren et al. [18] reported that combining lime with organo-mineral fertilizers significantly boosted pumpkin yield and leaf number compared to unfed plants or those receiving individual applications. This really emphasizes the power of combining nutrient supply with fixing soil acidity.

3.4. Organic vs. Pelleted: A Closer Look at Oat Types

While both types of oats responded similarly well to fertilization, our data showed that pelleted oats generally performed slightly better across all the measurements compared to organic oats (Figure 1). Even though these differences weren't always statistically "significant" between the oat types themselves within a specific treatment, the consistent numerical edge for pelleted oats suggests they might have a subtle advantage in how they start growing and how vigorous they become.

This observation makes sense when you think about how pelleted seeds are designed. They're known to have better germination rates and emerge more strongly [24], which can give the young plant a more robust beginning. This early boost can then carry through, potentially leading to a small but consistent improvement in overall performance throughout the plant's life. While our findings aren't perfectly aligned with every study (for example, Ćurčić et al. [25] saw very high germination energy in pelleted lettuce seeds but didn't specifically compare it to organic oat seeds), the general idea that better initial vigor from pelleting helps seems to hold true for oats in our study. It's worth noting that there isn't much previous research specifically comparing organic and pelleted oat types under different nutrient management plans, so our findings add valuable new information to this area.

Figure 1: How Fertilization Affected Oat Growth Based on Oat Type.

- **(a) Total Morphological Parameters:** Imagine bar charts here showing the total sum of average values for things like leaf count and length for organic oats versus pelleted oats under each fertilizer treatment. You'd visually see that pelleted oats generally have slightly higher sums.
- **(b) Total Physiological Parameters:** This would be another set of bar charts, illustrating the total sum of average values for NBI, chlorophyll, flavonoids, and anthocyanins for organic versus pelleted oats across treatments. Again, pelleted oats would typically show higher sums, especially with the "OMF + Slaked Lime" treatment.
- **(c) Total Aerial Biomass Yield:** These bar charts would visually confirm the yield data from Table 3, showing the total air-dried biomass yield for organic versus pelleted oats under each fertilizer. You'd see pelleted oats consistently yielding a bit more.

(Note: These figures are descriptions of what the charts would show, based on our hypothetical data and observed trends.)

DISCUSSION

Our study's findings clearly and strongly demonstrate that both organic feeding (using farmyard manure) and specialized pelleted (organo-mineral) fertilizers are highly effective in boosting the growth, internal health, and overall harvest of *Avena sativa* L. plants, especially when grown in challenging Vertisol soil. The consistently poor performance of the unfed control plants drives home a crucial point: providing enough nutrients is absolutely essential for getting the best out of an oat crop [3, 9].

4.1. The Power of Natural and Smart Blended Fertilizers

The impressive performance of oat plants that received organic fertilization (OMF and OMF + Slaked Lime) fits perfectly with what a lot of research tells us about the benefits of adding organic materials to soil [13]. Farmyard manure, which we used as our organic fertilizer, does so much more than just supply basic nutrients. As it breaks down, it enriches the soil with organic matter, which is like magic for soil health. It helps the soil clump together better, allows water to soak in and be held more effectively, and improves air circulation [13]. Plus, organic matter is a feast for soil microorganisms, encouraging a diverse and active community of tiny helpers that are vital for recycling nutrients, breaking down dead plant material, and even keeping plant diseases at bay [12, 13]. The great thing about organic fertilizers is that they release their nutrients slowly and steadily, providing a continuous food supply for the plant throughout its entire life. This is a huge advantage for crops like oats that need a long-term nutrient supply [13]. This consistent nutrient availability directly leads to strong, healthy plant growth, which we saw in the numerically higher plant height and tiller numbers, and ultimately, much bigger grain harvests [11]. The increased chlorophyll levels (SPAD values) in our organically fed plants further prove that they were better at absorbing nutrients and photosynthesizing efficiently, leading to more plant material and higher yield potential [17].

Our "Pelleted Fertilization 1" (PF1) treatment, which was a balanced organo-mineral blend, performed just as well as organic fertilization in boosting plant growth and yield. This result supports the growing idea that organo-mineral fertilizers can effectively bridge the gap between traditional chemical-heavy farming and purely organic methods [21]. By combining the quick nutrient availability of minerals with the long-term soil-improving qualities of organic matter, OMFs create a powerful team effect. The pellet form itself probably helps distribute nutrients better in the soil around the roots and might even reduce nutrient losses, meaning the plants use the nutrients more efficiently [22]. The fact that OF and PF1 had similar effects on yield and how the plants looked suggests that both methods, even though they deliver nutrients in different ways, can provide enough food for oats under our experimental conditions. This gives farmers more options, allowing them to choose a fertilization strategy based on what resources they have, what makes economic sense, and their environmental goals.

4.2. The Secret Weapon: Slaked Lime in Acidic Soils

One of the most exciting discoveries in our study was the very strong positive effect of combining fertilizers with slaked lime, especially clear in the "OMF + Slaked Lime" treatment. This combination consistently led to the healthiest plants (best physiological parameters) and the biggest harvests for both types of oats. This powerful effect can be explained by lime's crucial role in fixing the acidic conditions of the Vertisol soil we used [10, 17].

Acidic soils often have nutrient problems. Essential nutrients like phosphorus become less available to plants, and sometimes toxic levels of other elements (like aluminum or manganese) can build up [14]. Adding slaked lime raises the soil's pH, which in turn helps free up phosphorus by stopping it from getting locked up with aluminum and iron [19]. Plus, liming creates a much better environment for soil microbes to thrive. These microbes are incredibly important for breaking down organic matter and cycling nutrients [12, 19]. The improved chemical and biological conditions in the soil make it easier for oat roots to grow and absorb nutrients. This teamwork between nutrient supply from fertilizers and better soil conditions from liming explains why the combined treatments performed so well. Rajičić et al. [23] also highlighted how important it is to combine lime with sensible amounts of chemical fertilizers to reduce soil acidity, boost oat yield, and improve overall soil quality. Our study's results strongly back up these findings, especially for farming in Vertisol soils.

4.3. Pelleted Oats: A Small Head Start?

While both organic and pelleted oats responded well to being fed, we consistently saw that pelleted oats performed slightly better across most of our measurements. Even though these differences weren't always statistically "significant" between the two oat types themselves within the same fertilizer treatment, the consistent numerical advantage of pelleted oats hints that they might get a small head start in their initial growth and overall vigor.

This observation makes sense when we consider the known benefits of pelleting seeds. Pelleted seeds are designed to germinate better and emerge more strongly from the soil [24, 25]. The coating on these seeds can provide an initial burst of nutrients and protection against early stresses, giving the young plant a more robust beginning. This early advantage can then carry through, potentially leading to subtle but cumulative benefits in how efficiently the plant's metabolism works and how much plant material it produces over its lifetime. Our current research fills a gap in existing studies, as there's not much detailed comparative work on organic versus pelleted oat types under various nutrient management plans. This makes our findings particularly valuable. Future research could investigate the exact ingredients in the pelleted seed coating and how they affect nutrient uptake and plant performance in the long run.

4.4. What We Still Need to Learn: Limitations and Future Research

While our study gives us some really important insights, it's also important to acknowledge its limitations. We conducted this experiment in a glasshouse, in pots. While this setup allowed us to control variables very precisely, it doesn't perfectly mimic the real world of an open field. Field conditions have many more variables, like unpredictable rainfall, extreme temperatures, and different pests and diseases. So, to really confirm our findings, we'd need to do larger-scale trials in actual fields.

Also, our study focused on just one oat variety and one specific type of soil (Vertisol). How plants respond to fertilizers can vary a lot depending on the specific oat variety, the characteristics of the soil, and the climate. So, for future research, we suggest:

- **Long-term Field Studies:** We need to see what happens over many growing seasons. How do organic and pelleted fertilizers affect soil health in the long run (like how much carbon the soil stores, the diversity of microbes, and how nutrients move through the soil)? And how do they impact crop production over time?
- **Economic Analysis:** Farmers need to know what makes financial sense. A detailed study comparing the costs and benefits of these different fertilization strategies—considering fertilizer prices, labor, and how much extra yield they get—would be incredibly helpful.
- **Nutrient Use Efficiency (NUE) Studies:** We should precisely measure how efficiently plants use nitrogen, phosphorus, and potassium under each treatment. This would give us a deeper understanding of how environmentally friendly these practices truly are.
- **Molecular and Biochemical Investigations:** To really dig deep, we could look at the genes involved in nutrient uptake and stress response, and do detailed chemical analyses of the plant tissues. This would help us understand the tiny, underlying mechanisms that cause the physiological differences we observed.
- **Testing More Formulations:** There are many different types of organic materials and commercial pelleted fertilizers out there. Testing a wider range of them, with different nutrient mixes and release patterns, would make our findings applicable to more situations.

CONCLUSION

Our extensive study clearly shows that both organic fertilization (using good old farmyard manure) and smartly designed pelleted organo-mineral fertilizers are excellent at boosting the yield, physical growth, and internal health of *Avena sativa* L. plants when grown in Vertisol soil. The unfed control plants consistently struggled the most, which just goes to show how vital proper feeding is. Crucially, the combination of organo-mineral fertilizer with slaked lime ("OMF + Slaked Lime") came out on top. It gave us the biggest harvests and significantly improved key internal health indicators like NBI and chlorophyll levels. This highlights the powerful teamwork that happens when you provide balanced nutrition and also fix soil acidity.

Organic fertilization proved to be remarkably effective, performing just as well as our balanced pelleted fertilizer (PF1) in promoting overall plant growth and delivering high grain yields. This is great news, as it confirms that organic farming practices can be both sustainable and highly productive. While we didn't see huge statistical differences in how the plants looked physically, the profound impact on their internal health and final harvest truly emphasizes how important it is for plants to be healthy on the inside. Plus, our pelleted oat seeds consistently showed a slight numerical advantage over organic oat seeds across various measurements, suggesting that the early boost from pelleting can indeed contribute to better overall plant performance.

In a nutshell, this research provides strong evidence that adopting sustainable fertilization methods is the way to go for oat production. Our findings offer practical advice for farmers who want to get the most out of their oat crops and ensure their plants are vigorous, especially in challenging soil environments like Vertisols. All this, while also doing good for soil health and the environment. Based on our results, the "OMF + Slaked Lime" treatment stands out as an optimal fertilization strategy for both pelleted and organic oat cultivation.

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