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GERMINATION AND GROWTH RESPONSE OF VACHELLIA NILOTICA AS AFFECTED BY MOISTURE AND THICKNESS OF SEED PALLETIZATION

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Abstract

Low rainfall and high temperatures hinder successful tree plantation establishment in arid and semi-arid regions. Poor soil fertility and seed predation limit seed germination and seedling development. One protective and moisture-retaining technique is seed pelletization (seed balls). This study attempts to improve early plant establishment through seed ball technology. The seed ball technology and moisture combination's impact on the germination and growth of *Vachellia nilotica* was examined in this study with control (T_0), 1.0 cm (T_1), 1.5 cm (T_2), 2.0 cm (T_3), and 2.5 cm (T_4) seed ball thickness, along with 5, 10, and 15 mL of irrigation. This study was conducted at the Department of Forestry and Range Management, University of Agriculture, Faisalabad, Pakistan, using a completely randomized design (CRD) with factorial arrangements. The plant growth parameters were analyzed using two-way ANOVA. The study evaluated the effect of irrigation levels and the use of seed balls of different thicknesses on seedling growth and biomass production. The results show that shoot length, root length, stem diameter, and dry biomass were significantly influenced by these factors ($p < 0.05$). Treatment T_3 (2.0 cm seed ball thickness and 10 mL irrigation) had the highest values of shoot length (10.52 cm), root length (23.98 cm), stem diameter (0.138 cm), and total dry biomass (0.337 g). However, combining thicker (2.5 cm) seed balls and greater amounts of irrigation led to poorer growth. Among the treatments, T_3 was the best, and thus, it is concluded that a seed ball thickness of 2 cm with irrigation of 10 mL is best for enhancing the germination, seedling growth & biomass of Vachellia nilotica. The study demonstrated that seed ball technology has potential for use in tree planting and ecological restoration in dry and degraded areas.

Key Words: Biomass, Deforestation, Germination, Irrigation, Limiting, Multipurpose, Seed pallet

INTRODUCTION:

Arid lands are ecosystems characterized by extremely low precipitation (typically <250 mm annually), high evapotranspiration, and scarce vegetation cover, which collectively result in water scarcity and fragile soil structures. Such areas originate primarily due to persistent climatic conditions such as high temperature, low rainfall, strong solar radiation, and are augmented by human-induced pressures like overgrazing, deforestation, and poor farming practices, etc. (Cherlet *et al.,* 2018). Arid lands are increasingly significant in global climate change discussions as they are highly vulnerable to desertification and land degradation, which directly threaten the food security and livelihoods of millions of people (Shukla *et al.,* 2019). Converting arid lands into woodlots with seeds can be tough due to several obstacles, including insufficient precipitation, long-term water shortage, seed scavenging, and nutrient-deficient soil. Seed pellets (also called seed balls and seed bombs) have appeared as an encouraging solution to overcome these hurdles and facilitate successful tree planting in dry/hot areas (Madsen *et al.,* 2016).

The low-cost technology known as "seed balls" is unique, allows for controlled dispersal, and produces new plants in areas with limited vegetation, having a high deforestation rate, in deserts, and grasslands, etc. In any kind of lithosphere or biosphere on Earth, seed balls are highly effective in growing forests, legumes, oil seeds, flower crops, vegetables, and fruit crops. They're an inexpensive and efficient way to get plants without drilling or ploughing, during germination, as the balls' organic material provides vital nutrients during early growth stages (Tamilarasan *et al.,* 2020).

Additionally, seed balls can be dispersed over damaged areas and left dormant until germination is triggered by rainfall and appropriate conditions, as observed for different crops and trees (Fukuoka, 1985). This method allows spontaneous regeneration, which makes seed balls a useful tool for reviving desolate areas with minimal moisture levels. In addition to offering a minor nutritional boost for early growth, seed balls, a mixture of soil, seeds, clay, and water, protect seeds against adverse environmental conditions like wind, animal ingestion, and dehydration etc. (Gornish *et al.,* 2019).

Seedball technology has been shown to effectively enhance germination and early seedling growth, especially in arid and semi-arid regions. The study found that optimizing seed ball thickness and implementing moderate irrigation can significantly improve root development, biomass, and overall seedling vigor. These characteristics are vital for plant establishment and survival in water-limited environments. Due to its low cost and high effectiveness, this technique presents a practical solution for ecological restoration in degraded drylands. Therefore, adopting seedball technology can greatly support reforestation and land rehabilitation efforts in harsh arid to extremely arid climates (Saleem *et al.,* 2025).

To improve the green cover of forests through natural regeneration, direct seeding is often employed, but seed predation and dispersal issues can hinder seedling establishment. To address these challenges, techniques like seed balls and improved sowing methods are used to protect seeds and enhance germination rates. Aerial seeding is both expensive and leads to poor plant survival. One major reason for the high death rate of directly sown seeds is that the roots from the sprouted seeds can't get through the top layer of soil. In Illinois, the most common reason for direct seed planting failure is that predators eat the seeds (Farlee, 2013).

Pods, pellets, or seed bombs are other names for seed balls, which are pressed or rolled balls composed of different proportions of binder and other substances that typically contain one to several seeds of desirable species. The use of seed balls to improve crop plant establishment, restore native species at inaccessible locations, and promote wildflower establishment has gained significance in recent years. Seed balls are effective against seed predators, desiccation, and pre-emergence herbicides, which are used to manage weeds before ecological restoration. Small seeds can also be dispersed more effectively because of the ball's additional weight, and ball additives may enhance seed germination and seedling establishment (Farlee, 2013; Overdyck *et al.,* 2013).

An economical method for afforesting huge stretches of parched terrain is seed balls, as vegetables, wildflowers, trees, and bushes can be grown through this technique quite effectively. For large-scale, successful forest restoration, the techniques employed need to be economical, environmentally benign, and must engage local stakeholders. Thus, seeds can be buried with seed balls instead of digging a hole for each one (Shoo *et al.,* 2016). Seed pelleting is widely recognized as a technique to enhance germination and early seedling establishment, especially under suboptimal environmental conditions. For *Vachellia nilotica*, the moisture level and thickness of seed pellets can play a critical role in regulating water uptake and oxygen diffusion, both of which are vital for successful germination. Studies have indicated that optimal pellet thickness allows for adequate moisture retention without impeding radicle emergence, while excessive thickness may delay germination due to restricted oxygen flow, etc. Similarly, appropriate moisture conditions ensure the activation of metabolic processes necessary for seedling growth. Understanding these interactions is essential for improving the establishment and growth performance of *Vachellia nilotica*, particularly in arid and semi-arid environments (Lopez *et al.,* 2011).

Vachellia nilotica is a member of the Fabaceae family, which includes more than 1350 species of the genus Vachellia (Seigler, 2003). It is a decorative and therapeutic plant that reaches heights of 14-17m and a circumference of 2-3m and is found throughout the Indian subcontinent, the Middle East, and tropical and subtropical portions of Africa, etc. This species has great economic significance due to its multiple uses in all developing countries across the globe (Bargali and Bargali, 2009; Lopez *et al.,* 2011).

For seeds to germinate, there are several conditions that must be met, including the presence of moisture and oxygen, along with the right environmental conditions. The presence of oxygen is critical as it allows for respiration, which provides the energy for further metabolic processes and the growth of the embryo. However, if the seed has a particularly thick seed coat, it may be difficult for oxygen to become available to the embryo, and as a result, germination may be delayed or fully inhibited (Gorim and Asch, 2017). Previous studies indicated that seed coverings may inhibit the germination process by regulating the diffusion of oxygen and the absorption of water (Corbineau, 2022).

The technology of seed pelleting involves coating seeds in a protective outer layer. This protects the seed from the environment and makes it easier to handle, but if the coating is too thick it may restrict the diffusion of water and oxygen, leading to a more negative germination environment. The coating is also responsible for maintaining the right conditions for seed imbibition and for the emergence of the seedling. However, if the coating is too thick, it may delay germination because of inhibited gas exchange (Durgadevi *et al.,* 2025).

Species within the Fabaceae family often show physical dormancy due to seed coats that are hard and impermeable to water and gas exchange. Dormancy, even with smoke stimulation, often requires an additional treatment to increase the likelihood of germination. This can be done by breaking the impermeable seed coat barrier through scarification, soaking, or mechanical means. Lack of understanding of dormancy barriers can lead to the misinterpretation of germination behavior of *Vachellia nilotica*, a seed with a hard seed coat that inhibits early seedling establishment.

From these considerations, the hypothesis is that a seed pellet with a specific thickness (optimal at some point) and moisture content will improve germination and growth of *Vachellia nilotica* by balancing water availability with the ability to diffuse oxygen to the embryo.

Keeping in view the significance of the species, the current study was designed to explore the germination and growth response of *Vachellia nilotica* under varying pellet thickness and moisture levels, aiming to explore optimal seed ball size and irrigation levels for maximizing germination and seedling vigor.

MATERIALS AND METHODS

Experimental Site

The experimentation was carried out in the research field of the Department of Forestry and Range Management, University of Agriculture, Faisalabad, Pakistan (31°N, 74°E, 184 m above sea level). The area experiences a semi-arid subtropical climate, receiving 350 - 400 mm of rain annually, with 25 - 26 °C as the mean yearly temperature and a relative humidity of 45 - 65%.

Physicochemical Properties of Soil

The soil used for the experiment was collected from the nursery site and characterized before the experiment. The soil was sandy loam with a pH of 7.6, an electrical conductivity (EC) of 1.2 dS m^{-1}, and an organic matter content of about 0.9%.

Seed Source, Age, and Viability

Vachellia nilotica seeds were acquired from healthy, mature trees in the plantation area of the University of Agriculture, Faisalabad. During the last growing season, seeds were collected and kept in dry lab storage until the time was to be used. As a germination test was conducted to determine seed viability, only seeds that were healthy and had a high potential for germination were chosen for the experiment.

Preparation of Seed Pellets

Seed pellets were made by mixing sandy soil and clay in a 1:5 ratio (1 part clay, 5 sandy soil). The binding agent, sodium alginate (1.5%), was added to make pellets more stable. Water was added to the mixture incrementally until a homogeneous and moldable mixture was formed. The desired moisture content for pellet formation was achieved with the addition of approximately 230-250 mL of water per kg of dry mixture. The clay component was locally sourced fine-textured natural clay. Two seeds were placed within the structure of the pellet on each of the four diameter sizes (1.0 cm, 1.5 cm, 2.0 cm, and 2.5 cm), which were prepared by hand. The pellets were shade air-dried for 24 - 36 hours until dry enough to handle.

Control Treatment

The control treatment (T0) involved direct sowing of dry seeds with no seed coating in order to evaluate the differences in performance of pelleted seeds against dry seeds.

Irrigation Regime

Irrigation treatments were applied manually at 3-day intervals. The water levels were adjusted to represent three different moisture conditions that approximated 40, 60, and 80% of soil field capacity, which were 5, 10, and 15 mL of water applied to each pot, respectively.

Experimental Design

The experiment was conducted under a Completely Randomized Design (CRD) with factorial arrangements to evaluate the effect of pellet thickness and irrigation levels on the germination and growth of *Vachellia nilotica* under controlled conditions. Five treatments of seed pellet thickness were applied: T_o (control), T_1 (1.0 cm), T_2 (1.5 cm), T_3 (2.0 cm), and T_4 (2.5 cm). Each treatment was replicated ten times across three irrigation levels (5, 10, and 15 mL) to ensure the accuracy and reliability of the results. This factorial design facilitated the examination of both the main effects and the interaction between pellet thickness and moisture availability on seedling establishment and early growth performance.

Germination and Growth Measurements

Germination was recorded daily, and a range of indicators such as the percentage of seeds germinated, mean germination time (MGT), and the germination rate were calculated to analyze performance of seeds in germination. Growth parameters were also recorded 30 days after germination, including the lengths of shoots and roots, diameter of the stem, and the biomass of the seedlings.

Data Collection Parameters

Shoot length (cm), root length (cm), and stem diameter (cm) of each seedling were measured using a measuring scale and a digital caliper. The root-to-shoot ratio was determined by dividing root length by shoot length. Shoot fresh weight (g), root fresh weight (g), and total fresh biomass (g) were recorded immediately after harvesting using an electronic weighing balance (JJ3000B). For dry biomass estimation, shoots and roots were placed in labelled paper bags and initially sun-dried to remove surface moisture. Samples were subsequently dried at 75 °C for 24 hours in a thermal electric drying oven (DGH-9202 Series) until a constant weight was achieved. Following drying, shoot dry weight (g), root dry weight (g), and total dry biomass (g) were measured with an electronic weighing balance. All measurements were conducted at regular intervals, and data were systematically recorded.

Determination of Biomass

At the conclusion of the experimental period, seedlings were collected and divided into shoots and roots. The roots and shoots were then dried in an oven at 70 °C until constant weight was achieved, and their oven-dry weights were measured to determine the biomass.

Statistical Analysis

The collected data were subjected to analysis of variance (Two-Way ANOVA) to determine the significance of treatment effects at a probability level of $P < 0.05$.

RESULTS:

Shoot Length, Root Length, and Root Shoot Ratio

Seed ball thickness and irrigation levels exhibited a statistically significant effect on the shoot length of *Vachellia nilotica* seedlings ($p < 0.05$). The maximum shoot length (10.52 cm) was recorded in treatment $T_{3,}$ under 10 mL irrigation, whereas the minimum shoot length (6.77 cm) was observed in treatment T_4 under 15 mL irrigation (Figure 1-a). Root length was also significantly affected by seed ball thickness and irrigation levels, as the longest root length (23.98 cm) was measured in treatment T_3 under 10 mL irrigation, and the shortest root length (15.25 cm) was observed in the control treatment T_o with 5 mL irrigation (Figure 1-b). Furthermore, the root-to-shoot ratio was significantly influenced by the interaction of treatments and irrigation levels. The highest root to shoot ratio (2.41 cm) was obtained in treatment T_3 with 10 mL irrigation, while the lowest ratio (1.8 cm) was observed in treatment T_3 under 15 mL irrigation (Figure 1-c).

Stem Diameter

Stem diameter exhibited significant variation in response to seed ball thickness and moisture levels ($p < 0.05$). The maximum stem diameter (0.138 cm) was observed in treatment $T_{3,}$ under 10 mL irrigation, whereas the minimum stem diameter (0.078 cm) was recorded in treatment T_1 with 5 mL irrigation (Figure 2-a).

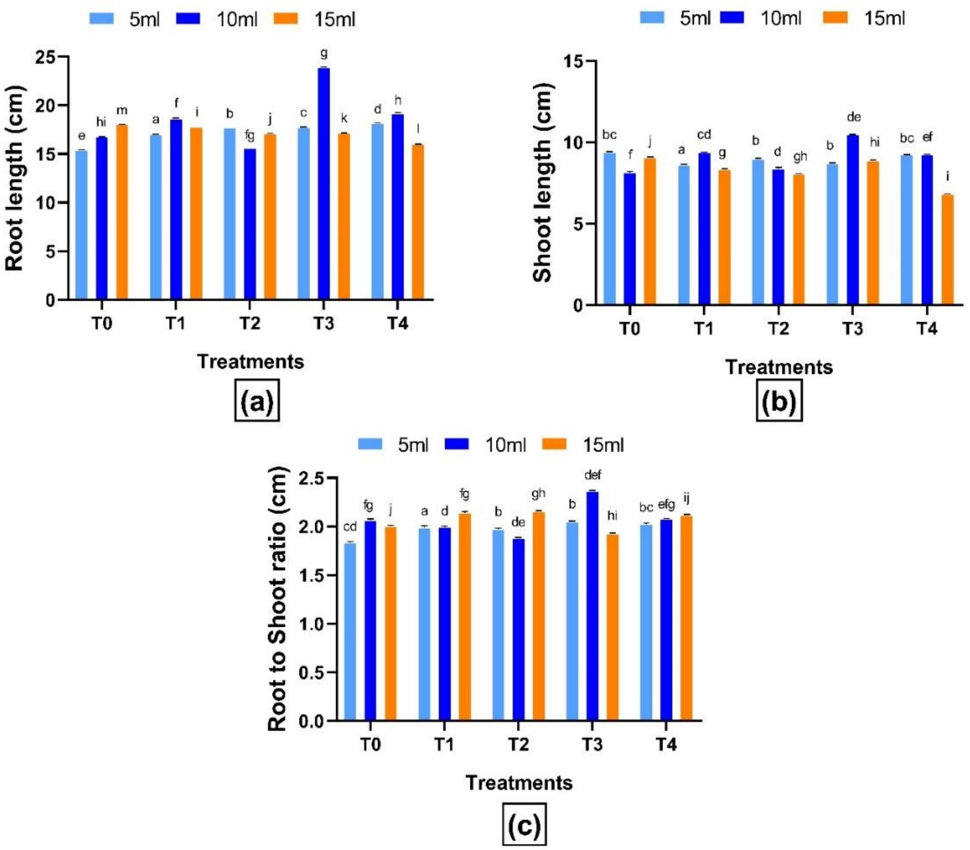

Figure 1: Effect of different levels of irrigation and size of seed ball on (a) root length (cm), (b) shoot length (cm) (c) root to shoot ratio (cm)

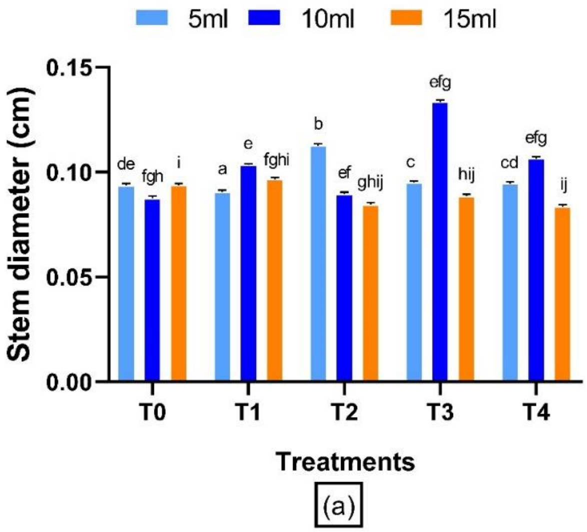

Figure 2: Effect of different levels of irrigation and size of seed ball on (a) stem diameter (cm)

Biomass distribution pattern

Shoot fresh and dry weights were significantly influenced by seed ball thickness and irrigation levels ($p < 0.05$). The maximum shoot fresh weight (0.28 g) and shoot dry weight (0.115 g) were obtained under treatment T_3 with 10 mL irrigation, while the minimum shoot fresh weight (0.14 g) and shoot dry weight (0.057 g) were recorded in treatment T_4 with 15 mL irrigation (Figure 3- a and b).

Root fresh and dry weights also exhibited significant variation in response to seed ball thickness and irrigation levels ($p<0.05$). Maximum root fresh weight (0.546 g) and root dry weight (0.222 g) were recorded under treatment T_3 with 10 mL irrigation, whereas the minimum root fresh weight (0.285g) and root dry weight (0.107 g) were observed in treatment T_4 with 15 mL irrigation (Figure 4- a and b). Overall, moderate irrigation (10 mL) consistently enhanced root biomass production across treatments, with treatment T_3 demonstrating the most favorable response.

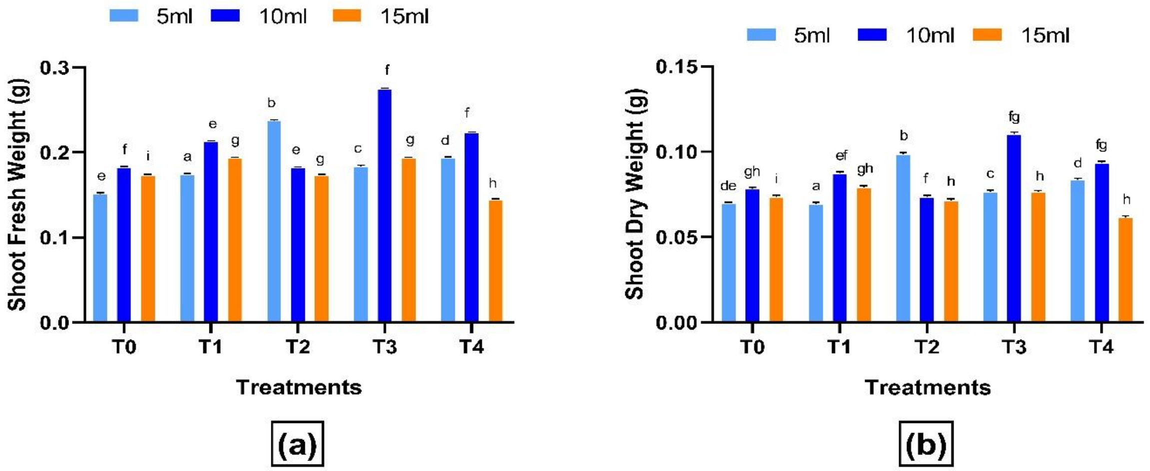

Figure 3: Effect of different levels of irrigation and size of seed ball on (a) shoot fresh weight (g), (b) shoot dry weight (g).

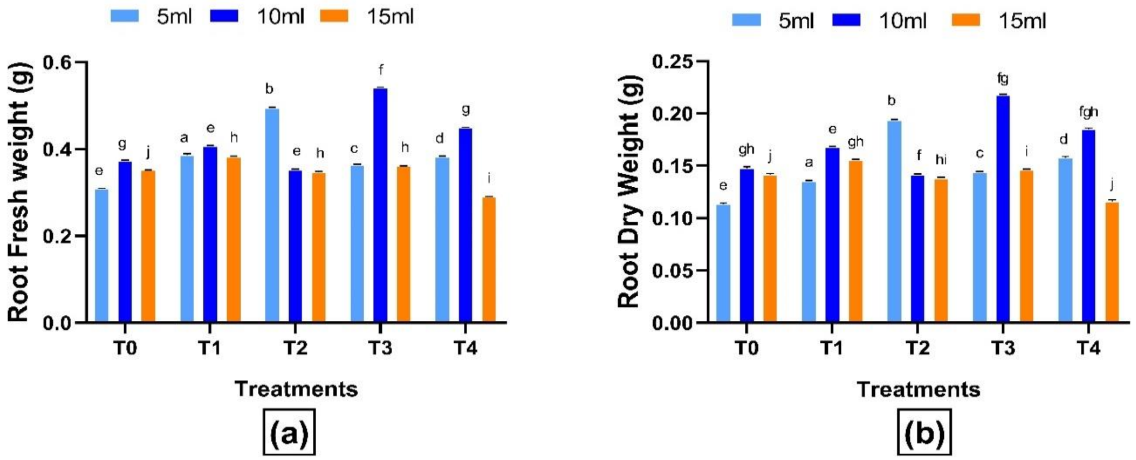

Figure 4: Effect of different levels of irrigation and size of seed ball on (a) root fresh weight (g), (b) root dry weight (g).

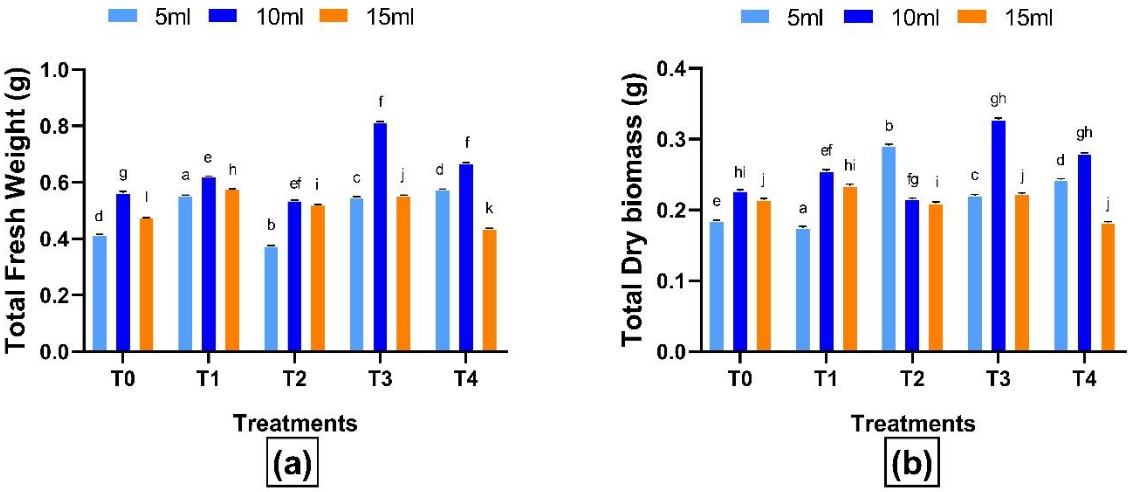

Figure 5: Effect of different levels of irrigation and size of seed ball on (a) total fresh weight (g), (b) total dry biomass (g).

Total fresh and dry biomass were also significantly influenced by seed ball thickness and irrigation levels ($p < 0.05$). The highest total fresh biomass (0.822 g) and total dry biomass (0.337g) were obtained under treatment T_3 with 10 mL irrigation, whereas the lowest total fresh biomass (0.37g) and total dry biomass (0.166 g) were recorded in treatment T_4 under 15 mL irrigation (Figure 5- a and b). These findings highlight the interactive effect of seed ball size and irrigation levels on overall biomass accumulation, with moderate irrigation combined with intermediate seed ball thickness T_3 producing the most favorable outcomes.

DISCUSSION

Arid lands have become a focal point in global climate change discourse due to their heightened vulnerability to desertification and land degradation, both of which pose direct threats to food security and the livelihoods of millions of people (Shukla *et al.,* 2019). Establishing woodlots in these regions through direct seeding presents significant challenges, including inadequate precipitation, prolonged water scarcity, seed predation, and nutrient-poor soils. Seed pelleting, also referred to as seed balls or seed bombs, has emerged as a promising technique to mitigate these constraints and enhance tree establishment in arid and semi-arid environments. This method has shown potential in improving germination success and seedling survival for various xerophytic species (Madsen *et al.,* 2016).

Seed balls have demonstrated considerable potential in improving productivity within arid environments, as prior studies have reported that their application enhances both shoot and root development in crops such as pearl millet (Nwankwo *et al.,* 2019). These improvements in root and shoot systems directly contribute to early seedling establishment and overall growth performance (Zhang *et al.,* 2022). Aligned with these earlier findings, the present study indicates that an optimal combination of seed ball thickness and irrigation regime can significantly improve the early shoot and root growth of *Vachellia nilotica*.

Pelleted seeds must demonstrate sufficient mechanical strength to withstand handling, transport, and sowing processes, thereby minimizing weight loss and maintaining viability (Sarker *et al.,* 2023). Seed balls further contribute to improved root development by ensuring consistent moisture availability and enhancing the soil seed interface, which supports germination and seedling establishment (Bainbridge, 2007). The findings of the present study are consistent with these observations, as appropriate seed ball treatments were shown to enhance the root-to-shoot ratio. A higher root-to-shoot ratio reflects relatively greater root development as compared to shoot growth, a characteristic that is particularly advantageous under water-limited or nutrient-deficient conditions, as it promotes seedling survival and early establishment.

Seed coatings can alter the size, shape, and surface characteristics of seeds, thereby improving their handling and ease of planting (Sohail *et al.,* 2022). Seed treatments combined with adequate irrigation can significantly influence stem development by enhancing water uptake and nutrient availability (Yadeta *et al.,* 2019). Seed balls help to retain moisture and nutrients for the seed to germinate, providing a stable growth environment that supports greater stem elongation and thickness (Abd El-Wahab, 2006; Yadeta *et al.,* 2019). Consistent with these observations, the present study suggests that an optimal combination of seed ball size and irrigation level can enhance stem thickness, which reflects improved seedling health, mechanical strength, and efficient transport of water and nutrients.

Seed balls have been demonstrated to enhance shoot fresh and dry weights in seedlings, largely due to improved nutrient availability and sustained moisture retention, which together create a favourable microenvironment for early growth (Nwankwo *et al.,* 2018a; Jarrar *et al.,* 2023). The regulation of irrigation levels further strengthens this effect by ensuring adequate water supply for metabolic processes and tissue development (Jarrar *et al.,* 2023). Comparable results have been observed in pelleted *Amaranthus* seeds, where the application of coating materials significantly increased seed length and width, reflecting the beneficial influence of seed enhancement technologies on early plant vigour (Kangsopa *et al.,* 2018). In line with these findings, the present study indicates that an optimal combination of seed ball size and irrigation volume can substantially improve shoot fresh and dry biomass, thereby supporting overall plant establishment and development.

Numerical simulation technology for seed pelletizing offers a valuable tool to model the pelletization process for small or irregularly shaped seeds, enabling the identification of optimal operational parameters tailored to each seed type and thereby supporting enhanced plant growth (Zheng *et al.,* 2024). Previous studies have shown that seed balls contribute to increased root biomass, with notable improvements in root fresh and dry weights compared to untreated controls. These effects are largely attributed to improved soil seed contact and the creation of a favourable microenvironment that supports root elongation and nutrient absorption (Nwankwo *et al.,* 2018b; Abhishek *et al.,* 2024). In agreement with these findings, the present study indicated that the combination of suitable seed ball size with moderate moisture levels can significantly enhance root development and below-ground biomass by maintaining consistent soil moisture and facilitating efficient nutrient uptake in the root zone.

The observed increases in fresh and dry weights indicate enhanced seedling biomass, which can be attributed to improved nutrient absorption and utilization (Rocha *et al.,* 2019). Similar findings have been reported in pearl millet, where seedlings established from seed balls demonstrated greater total fresh and dry biomass compared to controls. This improvement was linked to enhanced seed contact, superior moisture retention, and localized nutrient availability within the seed ball, which collectively promoted better root and shoot development (Nwankwo *et al.,* 2018b; Rawat *et al.,* 2024). Consistent with these studies, the results of the present research suggested that an optimal combination of seed ball size and irrigation volume can significantly improve total seedling biomass during the early stages of growth.

CONCLUSION

The objective of this research was to examine the effects of seed ball thickness and irrigation levels on germination and early seedling growth of *Vachellia nilotica* under semi-arid conditions. Both factors influenced growth parameters such as shoot length, root length, stem diameter, and biomass accumulation. A seed ball thickness of 2.0 cm (T_3) and irrigation of 10 mL showed the highest shoot and root growth and maximum fresh and dry biomass. Conversely, the greatest seed ball thickness (2.5 cm) and excessive irrigation showed reduced growth, suggesting that consideration of seed pellet thickness and irrigation is necessary to achieve desired levels of seedling growth. Overall, this study proves that seed ball technology improves germination and early growth of *Vachellia nilotica* under controlled irrigation conditions. Better seed protection through seed ball technology improves roots environment, structure, and moisture retention, and costs. For this reason, seed ball technology is a viable option for widespread use for afforestation and ecological restoration of arid and degraded areas. Future research is needed on long-term survival and field performance under unaltered natural conditions of seedlings established via seed ball technology. Also, studies on the incorporation of nutrient amendments, microbial inoculants, or biodegradable coatings could help establish and grow seedlings. Testing the methodology on a broader scale across multiple tree species and climatic conditions would create numerous opportunities for the large-scale application of restoration and sustainable land management strategies.

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COMPETING INTERESTS

Authors have no conflict of interest

AUTHOR’S CONTRIBUTION

Authors have contributed equally

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