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Adaptation of Grain Legumes to Terminal Drought after Rice Harvest in Timor-Leste

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Abstract: In Timor-Leste, most paddy fields are abandoned after rice harvest due to limited water resources for another rice production cycle, particularly in lowland coastal areas. There is substantial scope for including legumes and other crops in the rice–fallow system in Timor-Leste. This study investigated the adaptation of grain legumes to terminal drought. The experiment was undertaken in 2018 and 2019 at field sites in Vemase and Laleia, respectively, on the northeast coast of Timor-Leste. The experiments used a split-plot design with two factors (water treatment and species) and three blocks (Vemase site) or four blocks (Laleia site). In 2018, the water treatments were well-watered control (W0), water withheld from flower initiation to maturity (W1), and water withheld after seedling establishment to maturity (W2). In 2019, the water treatments were well-watered control (W0) and water withheld from flower initiation to maturity (W1). Grain legumes were mungbean and soybean tested against grass pea (cv. Ceora), a well-known drought-adapted grain legume. The measured parameters included soil water content, crop phenology, plant growth and development, yield and yield components. The experiments revealed that mungbean is the most suitable grain legume crop after rice harvest under moderate drought conditions, while soybean is the preferred option under severe drought. Grass pea could be the best adaptive grain legume under severe drought in Timor-Leste when combined with the worsening conditions of climate change.

Keywords: terminal drought; grain legumes; growth and development; yield and yield components

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1. Introduction

Food insecurity in Timor-Leste continues during the lean period between November and February/March, particularly for agricultural-dependent farmers in rural areas [1]. Farmers sow maize and other crops at the onset of rain in November, with harvest in February/March. As a result, most farm families have limited food available during this time, with some relying on wild plants and honey [2]. However, the availability of wild produce can be unreliable, resulting in continuous hunger during this critical period [3].

Conventional cropping systems produce insufficient food for the lean period, resulting in food shortages. Maize harvested in late-February or March is consumed mainly during rice production activities between February and July [4]. The harvested rice is consumed during traditional/cultural events, usually in the dry season (May–October).

One strategy to reduce food insecurity during the lean period is to produce more crops after rice harvest, ensuring food access for all Timorese. At present, most paddy fields (38,701 ha) are abandoned after rice harvest until the following rice season [5]. Crops grown during the transition into the dry season are at risk of terminal drought, as water availability dramatically declines due to high temperatures that increase water loss from the soil surface [6]. Drought stress reduces crop growth, development, yield, and yield components [7]. The extent of yield losses depends on the duration and intensity of the stress [8] and varies between species and cultivars and climatic variations, as reported for mungbean [9]. In grass pea (cv. Ceora), the seed yield declined by up to 87% under severe water deficit during the reproductive stage [10] and 24% under moderate water deficit [11]. In soybean, long-term drought stress during the reproductive period reduced stem biomass by 35–52.1% and seed production by 57–69% [12]. In Timor-Leste, limited studies have shown that grain legumes with a short growing season can be grown after rice harvest [13].

This study investigated the adaptation of grain legume species after rice harvest under field conditions in the east-north of Timor-Leste.

2. Materials and Methods

2.1. Research Site and Design

The experiment was conducted in Vemase, Baucau Municipality, in 2018 (hereafter 'Vemase site') and Laleia, Manatuto Municipality in 2019 (hereafter 'Laleia site') on the northeast coast of Timor-Leste; the distance between the two sites was 2–3 km. The experiment was undertaken in paddy fields after rice harvest from July to October (Vemase site) and from August to November (Laleia site). At both sites, irrigation water is drawn from the Laclo River during the rainy season for rice cultivation from February to May. Figure 1 shows the long-term average rainfall in Vemase, representing the Vemase and Laleia sites. The soil at both sites is heavy clay that is hard and deep cracked when dry, with low soil organic matter (1.5%) and soil P (Olsen P) (5.6 mg P/kg) and pH 7.8.

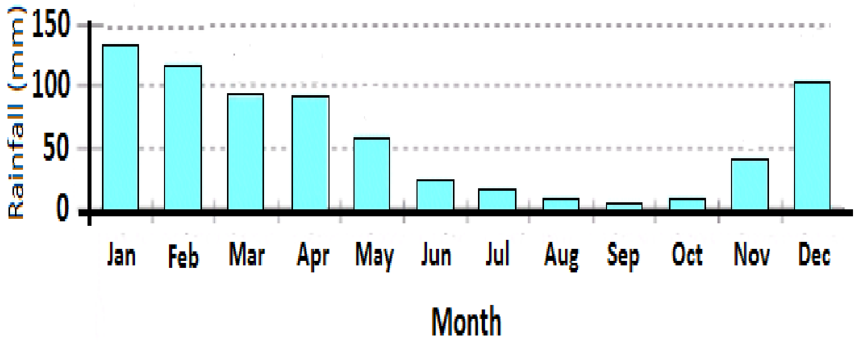


Figure 1. Long-term average rainfall in Vemase, representing the Vemase and Laleia sites. Source: Adapted from Defense Meteorological Support Unit, Australian Bureau of Meteorology.

The experiment used a split-plot design with two factors (water treatment and species) repeated in three blocks (Vemase site) and four blocks (Laleia site). The Vemase site had three water treatments: well-watered control (W0), water withheld from flower initiation to maturity (W1), and water withheld after seedling establishment to maturity (W2). The Laleia site had two water treatments: well-watered control (W0) and water withheld from flower initiation to maturity (W1). Mungbean and soybean were tested against a recently introduced drought-adapted grass pea (cv. Ceora). The mungbean and soybean were chosen based on a previous study where they produced relatively high seed yields of 2.1 t/ha (mungbean) and 2.5 t/ha (soybean) under drought conditions during the reproductive stages [14].

2.2. Land Preparation and Seed Sowing

The Vemase site had been used for rice research during the rainy season from January to May 2018. After rice harvest, the land was prepared using a hand tractor to form 2 m × 3 m plots arranged into three blocks. Before sowing, each plot had the equivalent of 5 t/ha of rice husk biochar applied uniformly before being flooded and allowed to drain to approximately field capacity. On 21 June 2018, three seeds per hole of mungbean or soybean were sown 30 cm apart in rows spaced 30 cm apart at a depth of 3 cm and thinned to two plants per hole once established. Grass pea, due to the limited available seeds, were pre-germinated in a sand/soil media covered with rice residue to maximize germination of seeds and transplanted to the field after germination at the same planting distance as mungbean and soybean.

The Laleia site had been used for rice production by local farmers from January to May 2019. After rice harvest, the land was prepared using a tractor to form 2 m × 2 m plots arranged in four blocks. Similar to the Vemase site, each plot had the equivalent of 5 t/ha of rice husk biochar applied uniformly to each plot before sowing. On 24 August 2019, three seeds per hole of mungbean or soybean were sown 30 cm apart in rows spaced 30 cm apart and thinned to two plants per hole once established. Grass pea seeds were pre-germinated in a sand/soil media in small pots made of banana leaves for easy transfer to the field at the same planting distance as mungbean and soybean.

2.3. Drought Treatment and Monitoring of Soil Water Content

At the Vemase site, soil water content measurements occurred at 28, 42, 56, and 70 days after sowing (DAS) at 10 cm and 15 cm depths. At the Laleia site, soil water measurements occurred at 33, 66, and 94 DAS at 10 cm and 15 cm depths. For each plot, a marked stainless-steel pipe was inserted into the soil to a depth of 10 cm, and pulled out to remove the soil sample. The pipe was reinserted into the same hole to a depth of 15 cm for the second soil sample. Samples were weighed for fresh weight (FW) before being oven-dried at 105 °C for 48 h and weighed for dry weight (DW). Average gravimetric soil water content was calculated (g/g) and converted to volumetric soil water content (cm^3/cm^3) as follows:

$$\Theta_m = (FW - DW)/DW \quad (1)$$

$$\Theta_v = \Theta_m \, (\rho_b/\rho_w) \quad (2)$$

where Θ_v is volumetric soil water content (cm^3/cm^3), Θ_m is gravimetric soil water content (g/g), ρ_b is soil bulk density (g/cm^3), and ρ_w is density of water (1 g/cm^3).

2.4. Growth, Yield, and Yield Components

Harvest occurred when plants had reached physiological maturity. Eighteen plants from a 40 cm × 50 cm (0.20 m^2) quadrat in each plot were harvested for yield and yield components. Five representative plants were randomly selected for growth and yield components, including plant height and numbers of nodes, branches, filled pods, and empty pods per plant, and seeds per pod, except at the Laleia site, plant height and the number of nodes and branches per plant were measured on three pre-selected representative plants in each plot at 56 DAS. Seeds were separated from the pods, with the pod walls added to the other plant components, oven-dried at 75 °C for 48 h, and weighed for dry matter production. The seeds remained in the oven for 2 h to ensure that they were dry before weighing for seed yield. One hundred seeds were randomly selected and weighed for seed size.

2.5. Statistical Analysis

Analysis of variance was performed using Genstat Statistical Software Version 18 manufactured by VSN International (VSNi), Hertfordshire, UK to compare data between water treatments and species at each location.

3. Results

3.1. Soil Water Content

At the Vemase site, volumetric soil water content did not differ between species for all measurements ($p > 0.05$). At 28 DAS, the W2 treatment (water withheld after seedling establishment) had lower soil water content (0.40 cm^3/cm^3) than the W1 (12%) and W0 (10.6%) treatments (Figure 2) ($p = 0.007$). The volumetric soil water content of W1 and W2 continued to decline until the last measurement at 70 DAS, when they were 24.7% (W1) and 35.1% (W2) less than W0 (0.34 cm^3/cm^3) ($p < 0.042$).

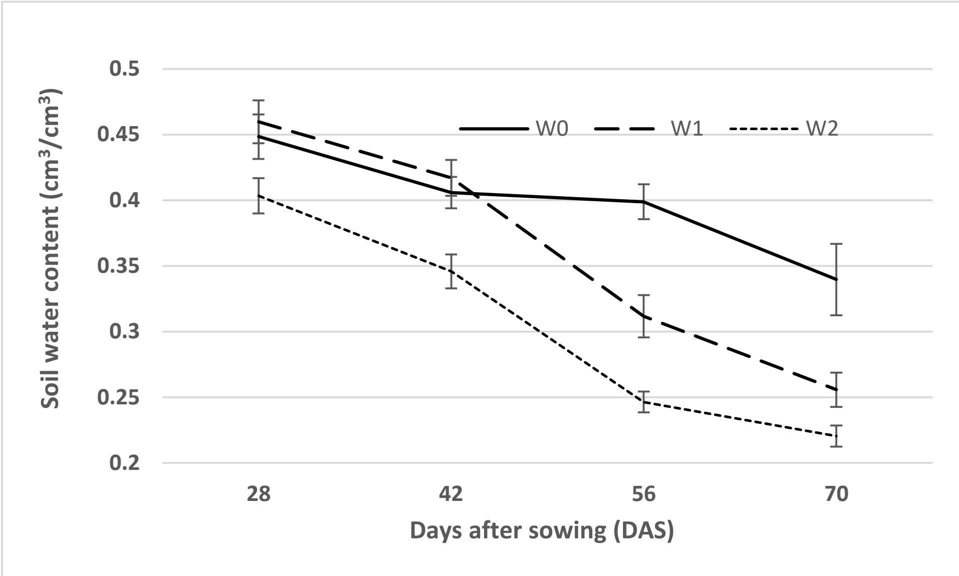


Figure 2. Average volumetric soil water content (cm^3/cm^3) at 28 days after sowing (DAS) (p = 0.007), 42 DAS (p = 0.007), 56 DAS ($p < 0.001$), and 70 DAS (p = 0.042) at the Vermase site in 2018. W0, well-watered control; W1, water withheld from flower initiation to maturity; W2, water withheld after seedling establishment to maturity. Bars indicate the standard error of means.

At the Laleia site, all treatments had similar volumetric soil water contents (0.30 cm^3/cm^3) at 33 DAS (two days after initiating water treatment) (Figure 3). At 66 DAS and 94 DAS, the volumetric soil water content of the W1 treatment had declined significantly by 30.7% and 61.6%, respectively, relative to the well-watered control (W0).

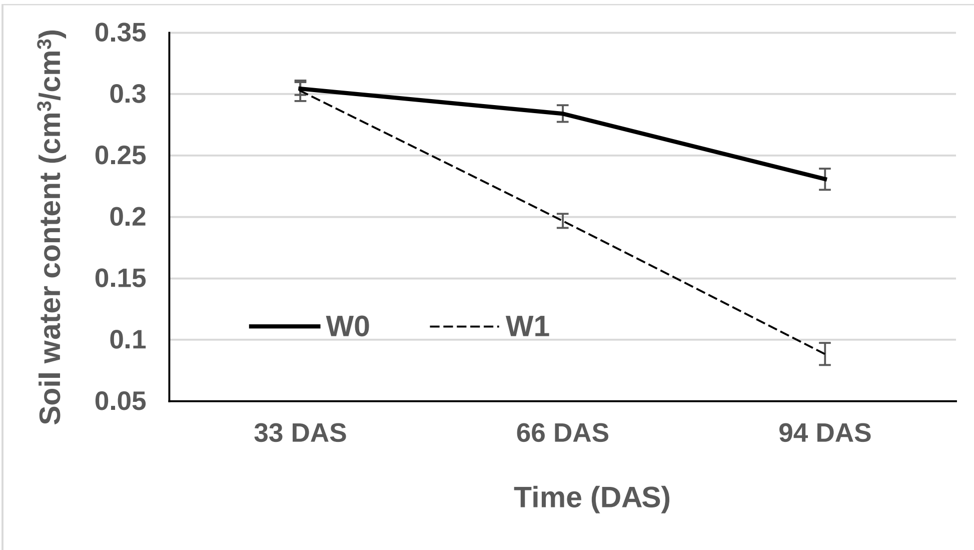


Figure 3. Average volumetric soil water content (cm^3/cm^3) at 33 days after sowing (DAS), 66 DAS ($p < 0.001$), and 94 DAS ($p < 0.001$) at the Laleia site in 2019. W0, well-watered control; W1, water withheld from flower initiation to maturity. Bars indicate the standard error of means.

3.2. Crop Phenology

Figure 4 shows the phenological development of grain legumes across the two experimental years and two locations—Vemase (2018) and Laleia (2019). At the Vemase site, mungbean germinated two days earlier (6 DAS) than soybean (8 DAS) and grass pea (cv. Ceora) (8 DAS). Soybean flowered first (43 DAS), followed by mungbean (52 DAS) and grass pea (57 DAS). Soybean also set pods first (51 DAS), followed by mungbean (56 DAS) and grass pea (65 DAS). Soybean and mungbean reached physiological maturity at the same time (89 DAS), followed by grass pea (91 DAS).

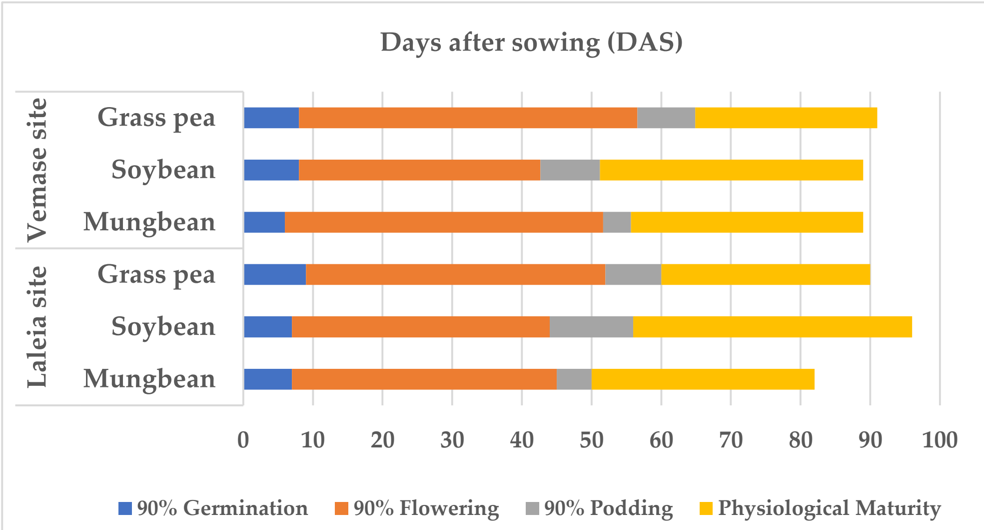


Figure 4. Crop phenology of grain legumes at the Vemase site (2018) and Laleia site (2019).

At the Laleia site, mungbean and soybean germinated two days earlier (7 DAS) than grass pea (cv. Ceora) (9 DAS). Soybean flowered first (44 DAS), followed by mungbean (45 DAS) and grass pea (52 DAS). Mungbean set pods first (50 DAS), followed by soybean (56 DAS) and grass pea (60 DAS). Mungbean reached physiological maturity first (82 DAS), followed by grass pea (90 DAS) and soybean (96 DAS).

3.3. Growth, Yield, and Yield Components

At the Vemase site, there was no water treatment × species interaction for plant height ($p > 0.05$) (Table 1). Terminal drought reduced plant height by 10% (W1) and 16% (W2), relative to the W0 control. Grass pea produced the tallest plants (36.8 cm), followed by mungbean (26.5 cm) and soybean (23.9 cm). For grass pea, control plants were taller (40 cm) than the W1 (36 cm) and W2 (34 cm) treatments. For mungbean, control plants had comparable plant height to W1 (30 cm vs. 27 cm), which was taller than W2 (22 cm). Soybean had similar plant heights across treatments (23–24 cm). At the Laleia site, the W1 treatment reduced plant height by 6.5% in mungbean, 6.9% in soybean, and 18.3% in grass pea, relative to the controls.

At the Vemase site, there was a water treatment × species interaction for node number per plant ($p = 0.024$) (Table 1). Grass pea produced the most nodes, with 23.3 in the control, followed by 19.9 in W1 and 18.5 in W2. The remaining water treatment × species interactions were comparable, except for mungbean in the W2 treatment which had the fewest nodes per plant (7.2). Terminal drought did not affect node number per plant in soybean. However, for mungbean, node numbers declined by 20.6% (1.9 fewer nodes) in the W2 treatment, relative to the W0 control. Grass pea produced the most nodes per plant. Terminal drought reduced node number per plant in grass pea by 14.6% (3.4 nodes) in the W1 treatment and 20.6% (4.8 nodes) in the W2 treatment, relative to the W0 control. At the Laleia site, control plants of grass pea produced the most nodes per plant (208.3), significantly more than the W1 treatment (117.3). Grass pea produced significantly more nodes in the drought treatment than soybean and mungbean in all treatments. Drought did not affect node numbers in mungbean or soybean.

Table 1. Significance of sources of variation for water treatment, species, and their interactions. There were three water treatments at the Vemase site (2018) and two water treatments at the Laleia site (2019), and three grain legumes at each site. n.s. not significant, * $p \leq 0.05$, ** $p \leq 0.01$, *** $p \leq 0.001$. Least significant differences of means (LSD) values at $p = 0.05$ are in parenthesis.

Sources of Variation		Water Treatment	Species	Water Treatment × Species
Plant height	2018	*** (2.2)	*** (2.2)	n.s
	2019	*** (1.6)	n.s	** (2.7)
Node number (/plant)	2018	*** (1.1)	*** (1.1)	* (1.8)
	2019	** (11.0)	*** (7.9)	*** (11.8)
Branch number (/plant)	2018	n.s	*** (0.5)	n.s
	2019	*** (1.0)	*** (0.6)	*** (1.0)
Filled pods (/plant)	2018	* (3.6)	*** (3.6)	n.s
	2019	*** (1.2)	*** (1.4)	n.s
Seeds/pod	2018	** (0.3)	*** (0.3)	**** (0.5)
	2019	n.s	*** (0.2)	n.s
Empty pods (/plant)	2018	n.s	*** (1.4)	n.s
	2019	*** (0.2)	*** (0.3)	*** (0.4)
Dry matter (t/ha)	2018	*** (0.3)	*** (0.3)	*** (0.5)
	2019	** (0.3)	*** (0.4)	** (0.6)
Seed yield (t/ha)	2018	*** (0.2)	*** (0.2)	** (0.3)
	2019	*** (0.2)	*** (0.3)	ns
100-seed weight (g)	2018	*** (0.6)	*** (0.6)	*** (1.0)
	2019	*** (0.3)	*** (0.3)	n.s
Harvest index	2018	n.s	*** (0.1)	* (0.1)
	2019	*** (0.02)	n.s	** (0.03)

At the Vemase site, there was no water treatment × species interaction for branch number per plant ($p > 0.05$) (Table 1). The water treatment did not affect branch number; however, branch number differed between species ($p < 0.001$). Grass pea produced the most branches (4), followed by soybean (2) and mungbean (1). At the Laleia site, there was a water treatment × species interaction for branch number at 59 DAS ($p < 0.001$). Control plants of grass pea produced the most branches (24.2), followed by grass pea in the W1 treatment (15.3). Control plants of soybean and mungbean produced similar branch numbers (5–6). The W1 treatment halved the branch number per plant in mungbean but had little effect on soybean.

At both sites, there was no water treatment × species interaction for the number of filled pods per plant ($p > 0.001$) (Table 1). At the Vemase site, grass pea and soybean produced similar numbers of filled pods per plant (16.1 vs. 15.0) and more than mungbean (8.4) ($p < 0.001$). The W2 treatment reduced the average number of filled pods per plant by 34.3% compared to the W0 controls ($p = 0.018$). The W1 treatment had a comparable number of filled pods per plant (13.27) to W2 (10.38) and W0 (15.80). At the Laleia site, soybean produced the most filled pods per plant (18.0), followed by grass pea (11.5) and mungbean (9.0) ($p < 0.001$). The W1 treatment reduced the average number of filled pods per plant by 25% compared to the W0 controls ($p < 0.001$).

At the Vemase site, there was a water treatment × species interaction for seed number per pod ($p < 0.001$) but no interaction at the Laleia site ($p > 0.05$). At the Vemase site, terminal drought reduced seed number per pod in mungbean by 5.8% (W1) and 18.4% (W2), relative to the W0 controls, with a similar trend in soybean (0.9% (W1) and 6.7% (W2)). However, in grass pea, seed number per pod increased by 2.2% in W1 but decreased by 0.9% in W2, relative to the W0 controls. At the Laleia site, the W1 treatment did not affect seed number per pod ($p > 0.05$), but there were significant differences between grain legumes ($p < 0.001$). Mungbean produced the most seeds per pod (10.6), followed by soybean (2.0) and grass pea (1.1).

At the Vemase site, there was no water treatment × species interaction for the number of empty pods per plant ($p > 0.05$), but a significant interaction at the Laleia site ($p < 0.001$)

(Table 1). At the Vemase site, the water treatments did not affect the number of empty pods per plant, but significant differences occurred between species ($p < 0.001$). Grass pea produced the most empty pods per plant (5.8), followed by soybean (0.2) and mungbean (0.1). At the Laleia site, W1 treatment increased the number of empty pods per plant, particularly in grass pea (1.7), followed by mungbean (0.7) and soybean (0.1) ($p < 0.001$).

At the Vemase ($p < 0.001$) and Laleia ($p = 0.014$) sites, there was a significant water treatment × species interaction for dry matter production (Table 1). Control plants of mungbean produced the most dry matter (4.3 t/ha), followed by mungbean in the W1 (3.6 t/ha) and W2 (2.3 t/ha) treatments, and control plants of soybean (1.4 t/ha), which were comparable with soybean in the W1 and W2 treatments and control plants of grass pea. Grass pea in the W1 treatment produced the least dry matter (0.6 t/ha), but this did not differ from the W2 treatment or the W0 control plants. At the Laleia site, control plants of mungbean produced the most dry matter (11.6 t/ha), followed by mungbean in the W1 treatment (9.4 t/ha), W0 control plants of soybean (7.7 t/ha), and soybean in the W1 treatment (6.3 t/ha). Grass pea produced the least dry matter in both water treatments. Terminal drought reduced dry matter in grass pea the most (32.8%), followed by mungbean (19.1%) and soybean (17.5%).

At the Vermase site, there was a water treatment × species interaction for seed yield ($p = 0.005$), but no interaction at the Laleia site ($p > 0.05$) (Table 1). At the Vemase site, control plants of mungbean produced the highest seed yield (1.18 t/ha), followed by W0 control plants of soybean (1.08 t/ha) and mungbean in the W1 treatment (0.8 t/ha). The remaining species and treatment combinations produced similar low seed yields ranging from 0.5 t/ha (soybean in the W1 treatment) to 0.3 t/ha (grass pea in the W1 treatment). At the Laleia site, W1 treatment reduced average seed yield by 27.1% compared to the W0 controls ($p < 0.001$). Mungbean produced the highest seed yield (3.3 t/ha), followed by soybean (2.3 t/ha) and grass pea (0.8 t/ha) ($p < 0.001$).

At the Vermase site, there was a water treatment × species interaction for 100-seed weight ($p < 0.001$), but no interaction at the Laleia site ($p > 0.005$). At the Vemase site, control plants of soybean produced the highest 100-seed weight (15.2 g), followed by grass pea in the control (12.7 g), W2 (12.5 g) and W1 (12.2 g) treatments, soybean in the W2 (10.5 g) and W1 (10.2 g) treatments, and mungbean in the W0 controls (6.1 g), W1 (5.8 g) and W2 (5.4 g) treatments. At the Laleia site, W1 treatment reduced the average 100-seed weight by 7.1% compared to the controls ($p < 0.001$). Soybean produced the highest 100-seed weight (14.7 g), followed by grass pea (12.1 g) and mungbean (5.3 g) ($p < 0.001$).

At the Vemase ($p = 0.044$) and Laleia ($p = 0.002$) sites, there was a water treatment × species interaction for harvest index (Table 1). At the Vemase site, soybean in the W1 treatment had the highest harvest index (0.51), followed by grass pea in the W2 treatment (0.49), soybean in the W2 treatment (0.45), grass pea in the W1 treatment (0.42), and control plants of grass pea (0.42). Mungbean had the lowest harvest indices, being 0.25 in the W1 treatment and the W0 controls, and 0.18 in the W2 treatment. At the Laleia site, control plants of grass pea had the highest HI (0.64), followed by control plants of soybean (0.52). The W1 treatment reduced the average harvest index by 20.3% compared to the W0 controls.

4. Discussion

This is the first study to identify drought-adaptive grain legumes suitable for cropping after rice harvest in paddy fields in the northern coastal areas of Timor-Leste, where paddy fields are typically abandoned after rice harvest. An additional crop after rice harvest will increase grain production from these fields to improve food security. Two field experiments were conducted to investigate the adaptation of the grain legumes after rice harvest conducted in 2018 and 2019.

4.1. Impact of Terminal Drought on Crop Phenology

Two of the recommended grain legumes (mungbean and soybean) were tested against a drought-adapted grass pea cultivar (cv. Ceora) to investigate the impact of terminal drought on growth and development and yield and yield components in the northeast of Timor-Leste after rice harvest. Terminal drought significantly reduced volumetric soil water content at the Vemase and Laleia sites (Figures 2 and 3), which did not affect crop phenology but significantly reduced the growth and yield of all three species. Mungbean germinated earlier, reaching maturity at least two weeks earlier than the other two species (Figure 4). Mungbean's growth cycle (82 DAS at Laleia or 89 DAS at Vemase) was comparable to other studies reported by Gusmao [13,15]. Species with fast germination and the ability to complete the reproductive cycle before severe drought is important in environments prone to terminal drought [16–18]. In the current study, none of the tested species matured earlier due to terminal drought; this may be because there was sufficient soil water for crop development, including seed filling, of droughted plants. Under more severe drought, some species/varieties mature earlier to escape severe drought, as demonstrated for grass pea in a greenhouse study [10,11].

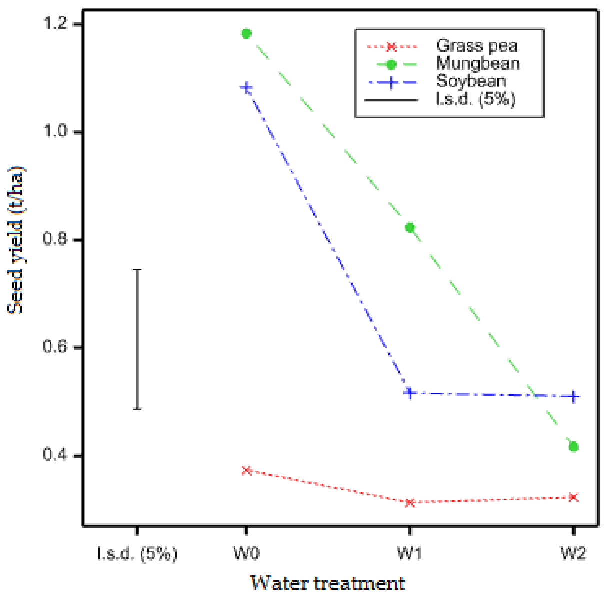
4.2. Impact of Terminal Drought on Growth and Development

Drought stress rapidly reduced growth and development of the grain legumes grown at the Vemase and Laleia sites. Grain legumes sown at the Laleia site had taller plants (41.6%) and more nodes (79.8%) and branches (73.1%) per plant than the earlier-sown grain legumes at the Vemase site. At the Laleia site, at 63 DAS, drought significantly reduced plant height by 6.5%, 6.9%, and 18% for mungbean, soybean, and grass pea, respectively, relative to the control plants (Table 1). At the Vemase site, terminal drought immediately after germination (W2) significantly reduced plant height by 15.8% compared to the control. The impact of terminal drought (W2) in the current study was consistent with a pot study on grass pea (cv. Ceora), where severe drought stress reduced plant height by 23% compared to the controls [10,11].

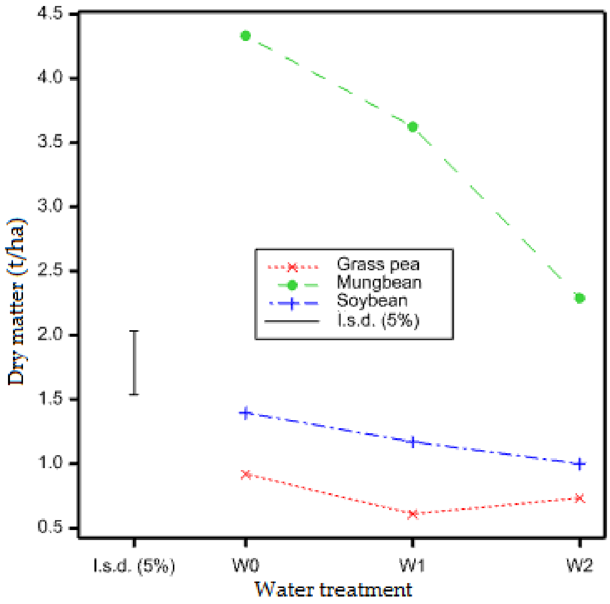
At the Vemase site, grass pea had the tallest plants (36.8 cm), followed by mungbean (26.5 cm) and soybean (23.9 cm). The plant height of control plants of grass pea (40 cm) was consistent with a field study [13], but about one-fifth that in greenhouse studies [10,11]. The drought treatments significantly reduced plant height in grass pea. Control plants of mungbean had similar plant height to the W1 treatment, which was taller than the W2 treatment. Reduced plant height under severe drought (W2) is consistent with a study on mungbean under drought during the vegetative stage [19]. Plant height in soybean in the current study was comparable among all water treatments.

4.3. Impact of Terminal Drought on Yield and Yield Components

Mungbean biomass production at the Laleia site was consistent with another study [15]. Fast-growing species that produce high biomass are important in conditions where water becomes increasingly unavailable toward the end of the reproductive stage. This is true for growing grain legumes after rice harvest, where water resources are increasingly limited after the preceding rice crop, particularly in Timor-Leste [14]. As residual water availability after rice rapidly declines, it is important to sow seeds soon after rice harvest [13], avoiding heat stress during the dry season. Mungbean produced 65.2% and 77.9% more biomass at the Vemase site and 33.2% and 79.0% at the Laleia site than soybean and grass pea, respectively (Table 1, Figures 5b and 6a). The high biomass production of mungbean at the Vemase site is consistent with a study on other mungbean genotypes (BARmung 6, BINA-mung 6, and BUmung-2) [20]. Despite this, the current study produced less aboveground biomass than other studies [13,15]. High biomass production and partitioning to seeds are important for seed yield under terminal drought [21]. In the current study, it is notable that drought had less effect on the biomass production of grass pea than mungbean and soybean. At the Vemase site, biomass production under W1 and W2 declined sharply in mungbean and moderately in soybean but had little or no effect on grass pea (Figure 5b). However, at the Laleia site, biomass production declined by 32.3% in grass pea compared to 17.5% in mungbean and 19.1% in soybean (Figure 6a). Grass pea is a well-known drought-adapted grain legume, reducing its green leaf area and growth rate under drought conditions, enabling the plant to adapt to extremely low soil water contents [10,11].

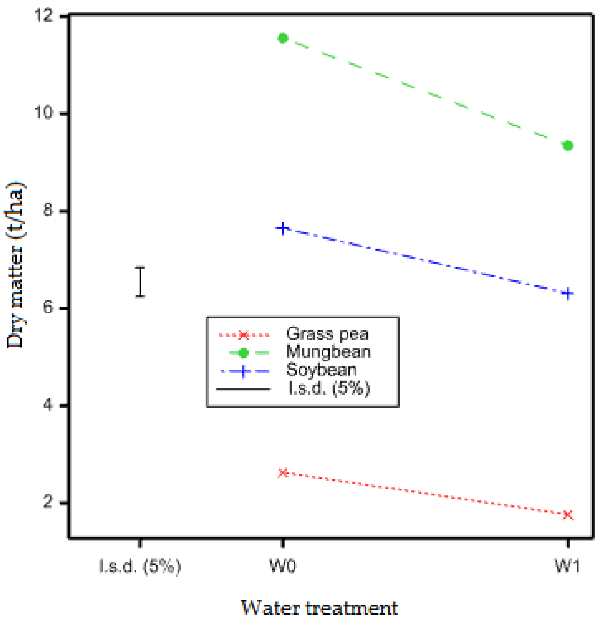


(**a**)

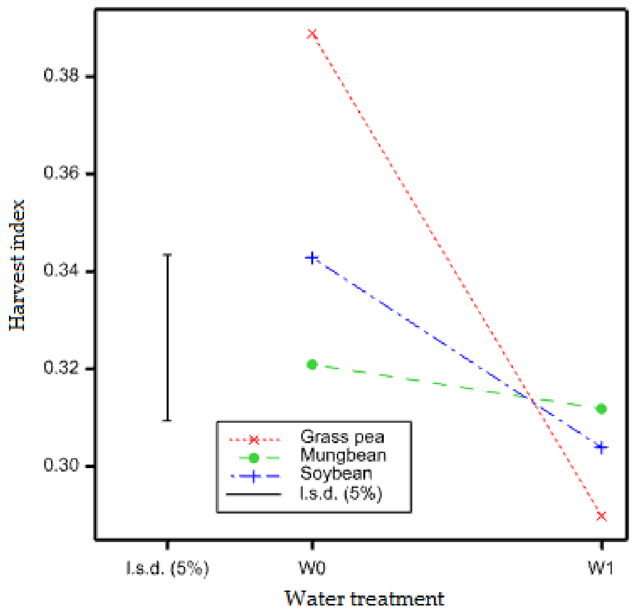


(**b**)

Figure 5. Water treatment × species interaction for (**a**) seed yield (t/ha) ($p = 0.005$) and (**b**) dry matter production ($p < 0.001$) at the Vemase site in 2018.



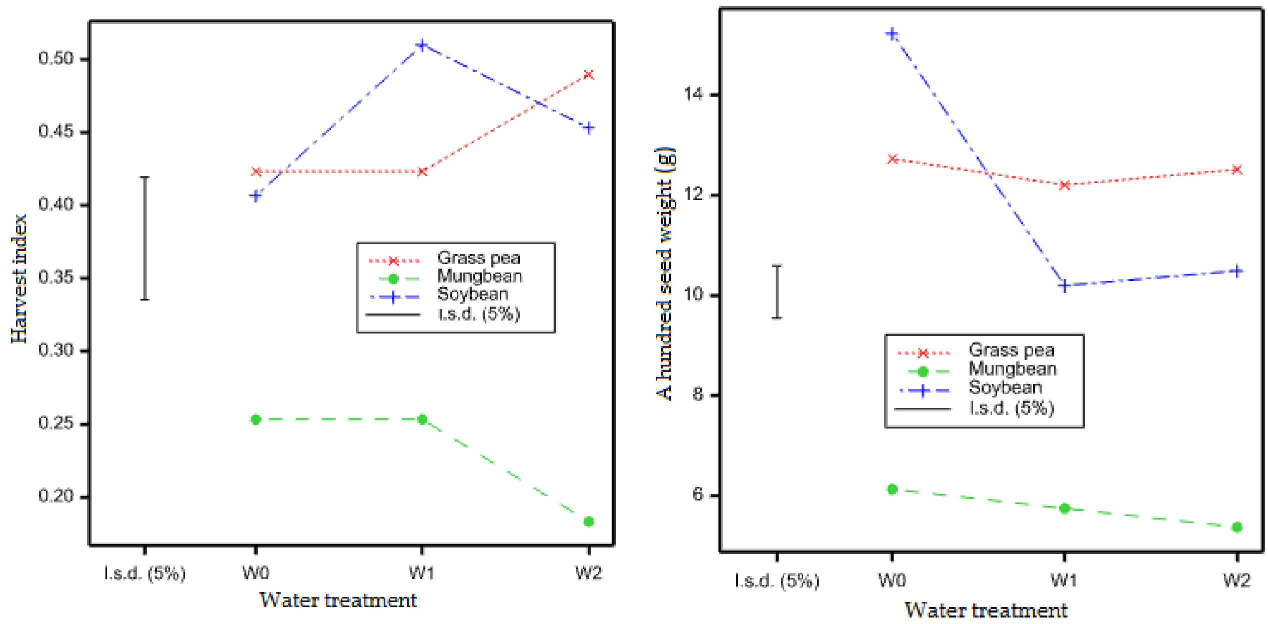
(**a**)



(**b**)

Figure 6. Water treatment × species interaction for (**a**) dry matter production ($p < 0.012$) and (**b**) harvest index ($p < 0.004$) at the Laleia site in 2019.

High biomass partitioning into seeds increases seed yield and, thus, harvest index. At the Vemase site, the harvest indexes of grass pea and soybean were double that of mungbean (Figure 7a), consistent with those at the Laleia site (Table 1, Figure 6b). The harvest index of control plants of grass pea in the current study was double that in a study conducted in Dili [13] and a greenhouse study (0.37) [10,11,15]. Grass pea is one of the most drought-adaptive species [10,22,23], and is well-adapted to Timor-Leste [13–15]. Despite mungbean having the lowest harvest index in the current study, control plants had the highest seed yield (1.2 t/ha), followed by soybean (1.1 t/ha), compared with about 0.4 t/ha in grass pea (Figure 5a) and consistent with an earlier report [24]. Interestingly, the reduction in seed yield of mungbean under moderate terminal drought (0.8 t/ha) was similar to that under severe terminal drought (0.4 t/ha); both treatments produced similar yields, which were about half that of the control. Low soil fertility, soil organic matter, and soil P may also contribute to low seed yield. Increased soil P may enhance grain yield under terminal drought, as reported for soybean [25]. In the current study, terminal drought had less effect on seed yield in grass pea than the other species.



(**a**) (**b**)

Figure 7. Water treatment × species interaction for (**a**) harvest index (p = 0.044) and (**b**) 100 seed weight (g) (p < 0.001) at the Vemase site in 2018.

The high yield in mungbean was mainly due to high seed numbers per pod, four or more times higher than soybean and grass pea. On average, soybean produced two seeds per pod, while grass pea averaged less than two seeds per pod. Mungbean had the lowest seed weight (Table 1). Soybean had the highest average 100-seed weight (>15 g), followed by grass pea (>12 g), despite being significantly affected by terminal drought (Figure 7b). In other studies, drought reduced grass pea yield by 36% compared to the control [11,15]. Grass pea reduces vegetative growth and yield as water becomes increasingly limited [10]. In the current study, grass pea yields did not significantly differ between treatments, which was likely due to the relatively high gravimetric soil water content (0.25 cm^3/cm^3) in W2 eight weeks after sowing that supported growth. Grass pea and soybean had similar and higher harvest indexes than mungbean (Table 1, Figure 7a). In contrast, mungbean was the second-fastest species to reach podding in both droughted and control plants, showing its ability to adapt to terminal drought conditions. Mungbean cultivars with improved harvest index characteristics could be grown after rice harvest, where terminal drought is common.

5. Conclusions

This study revealed that mungbean should be grown after rice harvest when sufficient soil water is available (moderate drought), while soybean is the preferred option under severe drought. Grass pea could be one of the best adaptive grain legumes for severe drought in Timor-Leste when the worsening conditions of climate change trigger grain legume production in the future. Further research incorporating other grain legumes on lowland and upland areas after rice harvest is needed. Further studies should investigate grass pea adaptation to highland areas.

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