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Effect of Fertilizer, Sowing Date, and Seeding Rate on Biomass and Yield of Pea (*Pisum savitum* L.) Grown Under Dry Steppe and Steppe Conditions

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Abstract: The impact of different agronomic practices on pea adaptability to terminal drought conditions can provide increased knowledge on optimizing pea yield, biomass, and environmental footprints. Two field experiments in the layout of the split–split plot and a 3-factor (fertilizer × sowing date × seeding rate) design were carried out on pea crops in 2021 and 2022 in Kazakhstan's dry steppe and steppe zones. The objective was to evaluate the significance of these factors and their interactions on biomass and yield based on 12 treatments in the dry steppe and 18 treatments in the steppe. In both zones, fertilizer effect on biomass and yield was significant ($p < 0.05$) and resulted in a biomass increase of 17% and a yield increase of 16% in the dry steppe and 19% and 17.9%, respectively, in the steppe. The sowing date's effect on biomass and yield in both zones was also significant, with maximum yield with late sowing (20 May) and biomass increased by 10% compared to the earliest sowing date (10 May) and yield increase of 9.2% in the dry steppe, and 15.7%, and 30%, respectively, in the steppe. Seeding rate and none of the first- and second-order interactions between these three factors on biomass and yield were significant in either zone. The relationship between factors and final biomass and yield showed that fertilizer application was dominant. Our research also showed that yield was highly correlated (r = 0.8–1.0, $p < 0.05$) with biometric indicators of plants, such as the weight of seeds per 1 m^2 and the weight of seeds per plant. The findings from this study indicate that adaptive crop production to increase the yield of peas can be used for environmental conditions of dry steppe and steppe based on the development of new agronomic practices, especially those that include fertilizer application with a combination of sowing dates.

Keywords: agronomic practice; NPK fertilization; biometric indicator; drought index; legume

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1. Introduction

Field peas (*Pisum sativum* L.) are one of the leading grain legumes for food and forage. Because of their rich and balanced amino acid composition, they are used as a source of protein. Pea seeds contain about 22–24% total protein, 1.5% fat, 55% nitrogen-free extractive compounds, and 6–8% crude fiber. They are an essential source of the amino acid lysine, whose content in 1 kg of pea seeds is 3–4 times higher than in cereal grains [1].

Beyond their nutritional benefits, peas, as leguminous crops, exhibit a unique ability for biological nitrogen fixation from the atmosphere through symbiotic relationships with rhizobia [2]. Symbiotic biological nitrogen fixation is considered a renewable resource crucial for sustainable agriculture. It reduces the need for synthetic fertilizers and contributes to soil fertility without causing environmental harm [3]. This complex process of symbiotic nitrogen fixation is crucial for enhancing soil fertility, particularly concerning soil acidification, rhizospheric processes, and plant CO_2 fixation [4].

Peas can grow in a wide range of agroclimatic zones. According to the Ministry of Agriculture of the Republic of Kazakhstan, the area dedicated to legume cultivation has increased from 23,900 to 446,300 ha during the past 20 years, and the average yield has reached 1220–1350 kg/ha. In northern Kazakhstan's arid to semi-arid climatic environmental conditions, the pea is recognized for its high yield compared to other grain legumes, ranging from 1460 to 1510 kg/ha. Due to the environmental plasticity and responsiveness of pea crops to growing conditions, they have the potential to yield more than the current levels in the dry steppe and steppe regions of Kazakhstan.

For peas, a high yield depends on favorable environmental conditions during their growth and development [5–7]. Pea seeds germinate and actively grow at lower temperatures than many other legumes [8]. A temperature below 15 °C during germination or vegetation slows metabolic processes, leading to seedling emergence issues or reduced pollination compared to 15–20 °C [9]. In general, the lack of soil moisture and high air temperatures lead to a decrease in dry matter accumulation [10,11]. The plant's nutrient condition also greatly impacts the rate and magnitude of aboveground biomass accumulation in crops. With improvement in the nutrient regime, a natural increase in the green mass occurs [12].

The accumulated aboveground biomass in peas is highly correlated with the crop height (r = 0.83) and the vegetation index [13]. It is also closely related to the mass of the root system [14]. A strong and significant correlation was also found between early growth vigor, aboveground biomass, and leaf area [15]. These traits can be important for increasing seed yield, especially during dry years [16]. Many studies have found that the aboveground biomass accumulation by peas depends on the applied agronomic practices, crop rotation, and plant nutrition conditions [17,18].

Fertilizer application is the key method for enhancing the availability of soil nutrients to plants, and its use is considered one of the most vital factors in increasing crop yield [19]. The effectiveness of fertilizers is influenced by weather conditions and the nutrient content in the soil [18]; hence, the recommended fertilizer application rates can differ significantly [20]. Additionally, the response of various pea varieties to fertilization largely varies [21]. Compared with unfertilized peas, NPK fertilizers enhanced the pea seed yield by 10.6–12.9% on average in the Boreal environmental zone [7]. Conversely, another study by Ghodsi et al. [22] found that adding nitrogen to the soil did not significantly improve grain yield and decreased protein content. Mineral fertilizer applied at a rate of 30 kg N/ha was not found to be a significant source of nitrogen for peas [23]. This suggests that avoiding nitrogen treatment could promote sustainable agriculture.

Pea growth and productivity also depend on the interaction of sowing date, variety, and agronomic methods, with the optimal sowing date being essential [24–26]. Choosing an appropriate sowing date means suitable weather conditions for pea varieties, leading to higher yields. Delaying sowing beyond the optimal date gradually reduces pea potential yield [8]. Pea varieties' sensitivity to weather conditions, photoperiod, and sowing dates differs. Temperature, day length, precipitation, and soil moisture differ in crops with different sowing dates, influencing plant growth and yield throughout the growing season [5,24,27].

Plant density is another important agronomic factor affecting the growth, development, and yield of crops [28–30]. The optimal plant density to achieve the highest yield may vary depending on the plant genotype and environmental factors [31]. Findings also show the opposite, that the seeding rate does not significantly affect the formation of pea yield [32].

Several studies have evaluated the impact of different seeding rates on pea emergence, grain yield, and various yield components [33,34]. Seeding rates can also influence the nutrient content of peas [35].

Despite its importance, there is a lack of research examining the interactions between fertilizer, sowing date, and seeding rates on pea crop biomass and yield, particularly in arid environments. Therefore, it is essential to determine whether the interactions among these three factors significantly affect pea crop productivity. The hypothesis of this study is that fertilizer, sowing date, and seeding rates, along with their interactions, significantly affect the biomass and yield of peas in dry steppe and steppe zones. If this hypothesis is confirmed, we aim to quantify the extent of the impact.

Given the significance of fertilizer application, sowing time, and seeding rate, this research aims to investigate their effect on the biomass formation and yield of peas in the dry steppe and steppe zones. The objectives are (a) to determine the effect of fertilizer application, sowing dates, and seeding rates on the formation of plant biomass and yield of peas in dry steppe and steppe conditions and (b) to determine possible correlations between biometric indicators of growth and development during the yield formation.

2. Materials and Methods

2.1. Study Location and Climate

Two field experiments were conducted in rainfed conditions on pea (*Pisum savitum* L.) crops during the 2021 and 2022 growing seasons in Kazakhstan's major grain-producing regions; one in the dry steppe climatic conditions of central Kazakhstan in Karaganda Region at the Limited Liability Partnership (LLP) "Naidorovskoe" (Lat 49.40°; Lon 72.41°) and another in the steppe climatic conditions of the northern part of the country in the North Kazakhstan Region at the LLP "Northern Kazakhstan Agricultural Experimental Station (NK AES)" (Lat 54.17°; Lon 69.53°) (Figure 1).

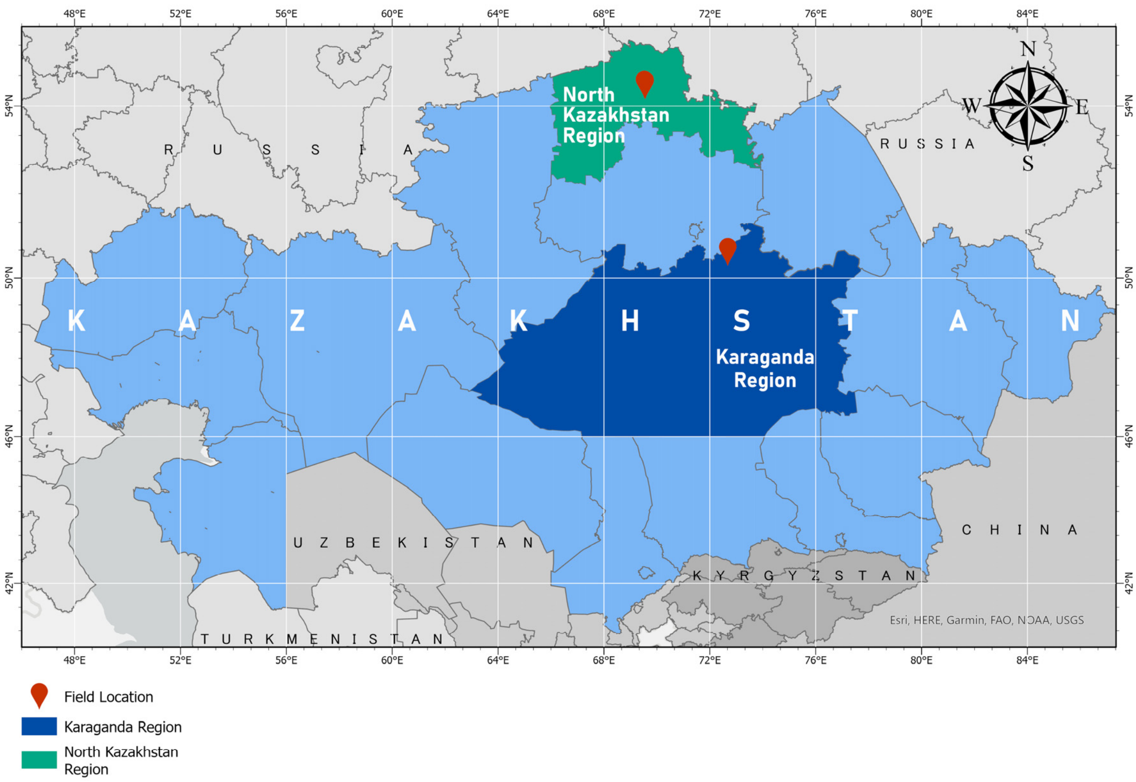

Figure 1. The location of two experimental fields in the dry steppe (the Karaganda Region) and steppe (the North Kazakhstan Region) zones in Kazakhstan.

The "METUS 2015" weather station collected and recorded meteorological parameters (daily average air temperature and total daily precipitation) to estimate environmental conditions during growing seasons. The National Hydrometeorological Service of Kazakhstan provided the long-term average air temperature and precipitation data.

In the experimental field in the dry steppe in 2021, May was warmer (by 3.1 °C) and June cooler (by 1.6 °C) than normal (Table 1). Rainfall was below average, particularly in June (by 13 mm) and July (by 29 mm). In 2022, May and June temperatures were nearly normal, but July (by 1.5 °C) and August (by 1.8 °C) were cooler. Rainfall was also below normal, notably in June (by 23 mm) and August (by 24 mm). Both years experienced drier growing seasons.

Table 1. Air temperature, monthly rainfall, and long-term averages during the growing seasons at two experimental fields in the dry steppe and the steppe zones.

Month	Average Monthly Temperatures, °C			Total Monthly Rainfall, mm		
	Year		Long-Term Average 1991–2022	Year		Long-Term Average 1991–2022
	2021	2022		2021	2022	
			Dry Steppe			
IV	5.7	7.6	5.6	5.5	11.9	22.6
V	16.5	13.6	13.4	29.2	22.3	34.6
VI	17.0	17.8	18.6	25.4	15.4	38.8
VII	20.4	18.3	19.8	18.8	31.7	47.9
VIII	19.0	16.3	18.1	20.0	4.2	28.1
			Steppe			
IV	4.4	8.9	5.4	23.0	18.9	23.3
V	18.4	15.4	13.8	10.1	5.9	26.2
VI	17.9	18.5	18.7	22.0	52.7	48.1
VII	20.7	21.3	20.0	69.8	87.5	66.2
VIII	19.9	19.0	17.9	29.3	34.9	50.6

In the steppe, temperatures were warmer in May and August 2021 by 4.6 °C and 2 °C, while June and July were near normal (Table 1). Rainfall was significantly below average, with deficits of 16 mm in May, 26 mm in June, and 21 mm in August. In 2022, May, July, and August were warmer than normal, while June was nearly normal. Rainfall was below average in May (by 20 mm) and August (by 16 mm) but above average in July (by 21 mm). Overall, both years experienced drier growing seasons, with 2021 being drier than 2022.

2.2. Soil Properties in the Experimental Fields

Layer-wise (0–120 cm) data of the soil's physical and chemical properties were collected in two experimental fields in the dry steppe (LLP "Naidorovskoe") and steppe (LLP "NK AES") zones by the Soil Science Laboratory at the S. Seifullin Kazakh Agrotechnical Research University. Dark chestnut soils in the experimental field in the dry steppe have a clayey texture with predominant fine sand and coarse dust. The humus content in the upper horizons of the soil profile ranges from 2.5% to 3.4% (Table 2). A clayey texture with a clay fraction predominance characterizes carbonate black soils in the experimental field in the steppe zone. The humus content in the upper horizons of the soil profile ranges from 4.5% to 4.7%, indicating a moderate humus content (Table 2).

Soils in these two fields primarily have a clayey texture. The organic matter content is slightly higher in the steppe than in the dry steppe by 1.3–2.0%. The levels of essential macronutrients (N, P, K) in the root zone are high in both fields. Soil pH values in the field generally indicate an alkaline reaction. The pH values are higher in the dry steppe (8.3–8.8).

Table 2. Different soil layers' physical and chemical characteristics at two experimental fields in the dry steppe and steppe zones.

Soil Layers, cm	0–5	5–15	15–30	30–45	45–60	60–90	90–120
Soil properties							
				Dry steppe zone			
Sand, %	72.1	72.6	67.4	72.1	75.1	72.8	75.4
Silt, %	0.0	1.5	11.5	8.8	3.5	5.6	1.5
Clay, %	27.9	25.9	21.2	21.4	21.6	23.6	23.2
Bulk density, g/cm^3	1.01	1.11	1.11	1.13	1.16	1.16	-
Humus, %	3.4	3.3	2.5	1.9	1.8	1.4	0.97
Total N-NO_3, mg/kg	20.0	9.3	8.9	5.3	4.2	1.0	0.7
Total P_2O_5, mg/kg	23.7	12.5	6.4	1.5	1.7	1.4	1.4
Total K_2O, mg/kg	473	376	364	204	166	150	133
pH	8.3	8.5	8.6	8.5	8.5	8.4	8.8
				Steppe zone			
Sand, %	0.8	1.8	0.5	0.4	6.4	4.4	2.0
Silt, %	27.1	27.8	25.1	17.8	19.5	26.7	18.1
Clay, %	72.0	70.4	74.3	81.9	74.2	69.0	80.0
Bulk density, g/cm^3	1.18	1.13	1.17	1.24	1.29	1.48	1.59
Humus, %	4.7	4.6	4.5	3.8	2.8	1.1	0.4
Total N-NO_3, mg/kg	22.9	6.0	7.6	7.8	5.0	13.8	23.4
Total P_2O_5, mg/kg	29.9	38.1	27.9	4.4	3.1	0.1	-
Total K_2O, mg/kg	803	649	392	291	244	226	262
pH	6.9	7.0	7.1	7.2	7.3	7.5	7.6

2.3. Drought Index

Steppes and dry steppes are usually characterized by a semi-arid to arid or continental climate, which means frequent drought conditions. Agricultural drought was estimated with the Hydro-thermal Coefficient of Selyaninov (HTC) [36] as follows:

$$\text{HTC} = \frac{10\sum p}{\sum t} \tag{1}$$

where $\sum p$ is the sum of total daily precipitation (mm) for a period with a daily average air temperature above +10 °C, $\sum t$ determines the sum of daily average air temperatures (t > +10 °C) for the same period. The HTC values and corresponding agricultural drought classes are defined as follows: HTC values less than 0.3—very dry (I), 0.31–0.60—dry (II), 0.61–0.80—moderately dry (III), 0.81–1.00—slightly dry (IV), 1.01–1.20—slightly humid (V), 1.21–1.40—moderately humid (VI), 1.41–1.60—humid (VII), >1.61—very humid (VIII).

2.4. Field Experiment Design and Data Collection

The early-maturing pea variety "Aksaiskii Usatii 55" was selected for this study due to its high yield potential and resistance to drought and shedding. A distinctive feature of this variety is its tendrils, which prevent plants from lodging. This variety effectively utilizes precipitation during the second half of the growing season (from the flowering stage to full maturity).

The two different field experiments were conducted in rainfed conditions in two agro-climatic zones for the 2021 and 2022 growing seasons using a 3-factor design. The experiment layout was established using the split–split plots method. Fertilizer applications were applied to the main plot, sowing dates were the subplot, and seeding rates were the sub-subplot. Factor combinations for the subplots were assigned randomly. Each treatment on a plot size of 36 m × 32 m (~0.115 ha) had 3 repetitions at each site in two climatic zones. The allocation of plots under treatments of the experiment was sequential and according to the predefined order defined during the experiment design process. The plot was fallow before the pea crop.

In the dry steppe zone, the experiment consisted of 12 treatments. Two levels of fertilizer applications (F) were used: the first level was without fertilizer application (F1), and in the second level (F2), an application of 179 kg/ha mono ammonium phosphate (Ammophos) (chemical formula: mixture of ($NH_4H_2PO_4$ + $(NH_4)_2HPO_4$); P_2O_5—46%, N—10%). The two levels of sowing dates were 15 May (SD1) and 20 May (SD2). The three levels of seeding rates were at a rate of 0.8 million seeds/ha (SR1), 1.0 million seeds/ha (SR2), and 1.2 million seeds/ha (SR3). An increased seeding rate was applied within the row. Inter-row spacing of 18 cm was consistent.

In the steppe zone, the experiment consisted of 18 treatments. Two levels of fertilizer applications (F) were used: the first level was without fertilizer application (F1), and in the second level (F2), an application of 179 kg/ha mono ammonium phosphate (Ammophos). The three levels of sowing dates were early sowing on 10 May (SD1), middle on 15 May (SD2), and late on 20 May (SD3). The three levels of seeding rates were 1.0 million seeds/ha (SR1), 1.2 million seeds/ha (SR2), and 1.4 million seeds/ha (SR3) in the steppe zone. An increased seeding rate was applied within the row. Inter-row spacing of 18 cm was consistent. In our study, seed treatment of peas with nodule bacteria was not conducted because, in northern Kazakhstan, where legumes are sown in large areas, the soils already contain specific populations of indigenous forms of these bacteria [37].

The field data collection process included observing phenology stages and measuring yield components. The main stages' dates of pea development, biometric indicators, yield, and yield components were determined following the methodology for the State Varietal Trials of the Republic of Kazakhstan [38]. The development stages were observed throughout the growing season on the same plants. Each phenological stage is distinguished by morphological changes in the plant. The beginning of a phase was marked by the day when at least 10–15% of the plants entered that phase. The full onset of the phase was recognized when at least 75% of the plants were in that phase, and ripeness was defined as the point at which most plants (60–70%) had reached maturity. The following stages of the pea plant development were recorded: emergence (VE), first node (V1), flower bud (R1), beginning bloom (R2), flat pod (R3), full maturity (R7), and harvest.

Biometric indicators including aboveground biomass, aboveground dry biomass (dry weight of the aboveground part of plants, dried to a constant weight), plant height (PH), leaf area index (LAI), number of plants before harvesting per 1 m^2 (PN), lower pod attachment height (LPAH), the average number of pods per plant (ANPP), the average number of seeds per pod (ANSP), the weight of 1000 seeds (WS1000), the weight of seeds per plant (WSp), the weight of straw per 1 m^2 (WStm), weight of seeds per 1 m^2 (WSm), and (seed) yield (BY) were defined and recorded for the same location in each plot where phenological observations were conducted. Harvest index (HI) was calculated as seed yield (kg/ha) divided by straw weight at harvest (kg/ha) and was expressed in %.

We measured fresh and dry biomass, including total biomass, stem weight, and leaf weight, from 10 plants with three replications for each treatment during different vegetation phases. Biomass samples were dried at 70 °C to a constant weight, and the dry weight of plant material samples was determined with an accuracy of 0.1 mg using the AB54-S analytical balance (Mettler Toledo, Giessen, Germany). Determination of leaf area was conducted using the portable laser leaf area meter CL-203 (CID Bio-Science, Inc., Camas, WA, USA). The leaf area index (LAI) was also evaluated on 10 plants. The height of 20 pea plants was measured every ten days after emergence. Key parameters such as LPAH, ANPP, ANSP, and WSp were measured in 10 plants per treatment. The yield structure was determined at full maturity.

2.5. Data Processing

The two-year multi-factor experimental data for two locations on biomass and yield were submitted to a combined 3-way analysis of variance (ANOVA) (three fixed factors: fertilizer, sowing date, and seeding rate) for each location to determine the significance of management factors and their interactions using RStudio (version 2024.04.01, Package "agricolae" v1.3–7). As repeated experiment errors over the years were homogeneous, and the interaction was absent, two years of data were combined for ANOVA [39]. Before each ANOVA, a Shapiro–Wilk test for normality and equality of variance was conducted for each dependent variable. We estimated the differences among the treatment means using Fisher's least significant difference (LSD) test. Average values and standard errors (SE) were calculated. We also calculated Pearson correlation coefficients and tested their significance to detect a correlation among eleven biometric indicators (see Section 2.4). Heat map diagrams were created using the "metan" package.

3. Results

3.1. Weather Conditions During Vegetation of Pea Crop

Environmental conditions during crop cultivation affect the formation of one of the leading biological indicators, such as yield. In Kazakhstan's dry steppe and steppe zones, pea plants often experience drought in the early vegetation period and after flowering. Rainfall before flowering allows pea plants to form a vegetative mass, significantly determining yield.

In 2021, peas sown on 15 May experienced mainly very dry conditions (HTC < 0.3) except during the flower bud and full maturity phases, which were moderately dry (HTC 0.61–0.63). Average temperatures ranged from 16.5 °C during the flower bud phase to 23.2 °C at the beginning bloom. Most rainfall occurred during the flower bud (22.9 mm) and full maturity phases (18 mm), with less than 2.0 mm during other phases. For peas sown on 20 May, conditions were also very dry (HTC < 0.3), with temperatures peaking at 22.9 °C during the beginning bloom and 22.1 °C at full maturity. Rainfall was highest during the flower bud (21.9 mm) and beginning bloom (10.5 mm) phases.

The weather conditions in 2022 significantly differed from 2021, with precipitation increasing by 45% from 45 mm (Table 3). For the crop sown on 15 May, conditions were relatively favorable during the first node and flat pod phases (moderately dry). However, the beginning bloom and harvest phases experienced dry conditions. Very dry weather was noted during emergence, flower bud, and full maturity. Rainfall was fairly consistent across phases (11.9–16.5 mm), but emergence and full maturity received less than 2.3 mm. For the crop sown on 20 May, temperature variability increased, with low temperatures during the first node and harvest (~15.5 °C), while higher temperatures of 21.3 °C during flower bud and 21.6 °C during flat pod. Most phases experienced very dry to dry conditions, except for the first pod phase, which was moderately humid, and the beginning bloom phase, which was slightly humid.

The weather conditions were relatively favorable in the site in the steppe zone. In 2021, in the second field with three sowing dates, crop development occurred under dry conditions for the early and middle sowing dates, while the late-sown crop experienced moderately dry conditions (Table 4). Conditions for the 10 May sown crop were mostly very dry to dry. Temperature varied significantly, ranging from 17.1 °C (flower bud phase) to 27.7 °C (flat pod phase). Rainfall was low and uneven, with most phases receiving less than 3.7 mm and a maximum of 67.5 mm at full maturity. The crop sown on 15 May experienced a temperature variability of 6.8 °C, with a minimum temperature of 17.6 °C during the flowering bud stage and a maximum of 24.4 °C during the flat pod phase. Rainfall during most growth phases was below 1.6 mm, except the full maturity stage (70 mm). For the crop sown on 20 May, temperature variability was 10.3 °C, with lows of 17.4 °C during the flower bud and highs of 27.7 °C during the beginning bloom. Rainfall was uneven, under 3.2 mm during most phases, except full maturity (70 mm).

Table 3. Meteorological conditions by sowing dates and growth phases for the pea variety "Aksaiskii Usatii 55" in 2021 and 2022 in the dry steppe zone.

Growth Stages	Stage Date	Stage Duration, Days	Mean Temperature, °C	Total Rainfall, mm	HTC (Class)	Stage Date	Stage Duration, Days	Mean Temperature, °C	Total Rainfall, mm	HTC (Class)
Sowing date			**15 May 2021**					**15 May 2022**		
Emergence	25 May	11	18.8	1.2	0.10 (I)	22 May	8	17.9	2.3	0.16 (I)
First node	2 June	8	22.1	0.5	0.03 (I)	1 June	10	17.6	14.1	0.80 (III)
Flower bud	24 June	22	16.5	22.9	0.63 (III)	25 June	24	20.8	13.0	0.26 (I)
Beginning bloom	5 July	11	23.2	2.0	0.08 (I)	7 July	12	19.0	8.0	0.35 (II)
Flat pod	10 July	5	21.9	0.8	0.07 (I)	18 July	11	20.1	16.5	0.74 (III)
Full maturity	25 July	15	19.6	18.0	0.61 (III)	30 July	12	21.8	1.2	0.05 (I)
Harvest	5 August	11	21.3	0.0	0.00 (I)	13 August	14	18.9	11.9	0.45 (II)
Sowing–harvesting		83	19.8	45.4	0.28 (I)		91	19.7	67.0	0.37 (II)
Sowing date			**20 May 2021**					**20 May 2022**		
Emergence	29 May	10	20.0	0.0	0.0 (I)	26 May	7	18.3	2.0	0.16 (I)
First node	8 June	10	19.6	3.5	0.18 (I)	5 June	10	15.6	19.1	1.22 (VI)
Flower bud	1 July	23	17.6	21.9	0.54 (II)	2 July	27	21.3	10.0	0.17 (I)
Beginning bloom	13 July	12	22.9	10.5	0.38 (II)	13 July	11	18.8	21.5	1.04 (V)
Flat pod	19 July	6	17.0	5.3	0.52 (II)	25 July	12	21.6	1.4	0.05 (I)
Full maturity	4 August	16	22.1	3.0	0.08 (I)	8 August	14	20.5	11.0	0.38 (II)
Harvest	15 August	11	18.0	4.0	0.20 (I)	22 August	14	15.4	2.0	0.09 (I)
Sowing–harvesting		88	19.6	48.2	0.28 (I)		95	19.2	67.0	0.37 (II)

Note: Hydro-thermal Coefficient (HTC) values less than 0.3—very dry (I), 0.31–0.60—dry (II), 0.61–0.80—moderately dry (III), 0.81–1.00—slightly dry (IV), 1.01–1.20—slightly humid (V), 1.21–1.40—moderately humid (VI), 1.41–1.60—humid (VII), >1.61—very humid (VIII).

Table 4. Meteorological conditions by sowing dates and growth phases for the pea variety "Aksaiskii Usatii 55" in 2021 and 2022 in the steppe zone.

Growth Stages	Stage Date	Stage Duration, Days	Mean Temperature, °C	Total Rainfall, mm	HTC (Class)	Stage Date	Stage Duration, Days	Mean Temperature, °C	Total Rainfall, mm	HTC (Class)
Sowing date			**10 May 2021**					**10 May 2022**		
Emergence	18 May	9	18.6	3.7	0.22 (I)	18 May	9	16.9	2.0	0.30 (I)
First node	5 June	18	19.3	11.8	0.35 (II)	1 June	14	18.3	3.9	0.15 (I)
Flower bud	23 June	18	17.1	13.2	0.43 (II)	15 June	14	18.0	23.2	0.96 (IV)
Beginning bloom	28 June	5	19.1	0.0	0.00 (I)	24 June	9	21.2	20.4	1.07 (V)
Flat pod	3 July	5	27.7	0.4	0.03 (I)	10 July	16	17.6	33.2	1.18 (V)
Full maturity	29 July	26	19.7	67.5	1.32 (VI)	2 August	23	22.2	63.4	1.24 (VI)
Harvest	3 August	5	22.8	2.7	0.24 (I)	8 August	6	20.4	0.0	0.00 (I)
Sowing–harvesting		86	19.6	99.3	0.59 (II)		91	19.5	146.1	0.87 (IV)
Sowing date			**15 May 2021**					**15 May 2022**		
Emergence	23 May	9	20.4	1.6	0.09 (I)	23 May	9	15.7	4.8	0.34 (II)
First node	11 June	19	18.4	11.2	0.31 (II)	4 June	12	19.0	1.3	0.06 (I)
Flower bud	26 June	15	17.6	13.2	0.50 (II)	19 June	15	19.5	23.0	0.79 (III)
Beginning bloom	29 June	3	22.9	0.0	0.00 (I)	26 June	7	20.8	27.2	1.87 (VIII)
Flat pod	8 July	9	24.4	0.4	0.02 (I)	14 July	18	18.6	28.1	0.84 (IV)
Full maturity	3 August	26	20.1	70.2	1.34 (VI)	4 August	21	21.6	61.7	1.36 (VI)
Harvest	7 August	4	21.3	0.4	0.05 (I)	12 August	8	21.2	19.3	1.14 (V)
Sowing–harvesting		85	19.9	97.0	0.58 (II)		90	19.6	165.4	0.94 (IV)

Table 4. *Cont.*

Growth Stages	Stage Date	Stage Duration, Days	Mean Temperature, °C	Total Rainfall, mm	HTC (Class)	Stage Date	Stage Duration, Days	Mean Temperature, °C	Total Rainfall, mm	HTC (Class)
Sowing date			**20 May 2021**					**20 May 2022**		
Emergence	28 May	9	21.5	1.4	0.07 (I)	28 May	9	18.5	2.2	0.13 (I)
First node	20 June	23	17.6	19.8	0.50 (II)	6 June	9	17.1	1.3	0.09 (I)
Flower bud	28 June	8	17.4	3.2	0.23 (I)	22 June	16	20.1	43.4	1.35 (VI)
Beginning bloom	3 July	5	27.7	0.4	0.03 (I)	3 July	11	17.6	9.1	0.47 (II)
Flat pod	11 July	8	21.8	0.0	0.00 (I)	18 July	15	21.2	34.2	1.08 (V)
Full maturity	5 August	25	19.8	70.2	1.42 (VII)	8 August	21	21.2	55.3	1.18 (V)
Harvest	9 August	4	20.0	16.4	2.05 (VIII)	14 August	6	20.2	19.3	1.59 (VII)
Sowing–harvesting		82	20.0	103.9	0.64 (III)		87	19.0	175.4	1.02 (V)

Note: Hydro-thermal Coefficient (HTC) values less than 0.3—very dry (I), 0.31–0.60—dry (II), 0.61–0.80—moderately dry (III), 0.81–1.00—slightly dry (IV), 1.01–1.20—slightly humid (V), 1.21–1.40—moderately humid (VI), 1.41–1.60—humid (VII), >1.61—very humid (VIII).

The 2022 growing season was more favorable, with total precipitation up to 175 mm, compared to 103.9 mm in 2021 (Table 4). However, crops sown on the earlier dates of 10 May and 15 May experienced slightly dry conditions, while those sown later had slightly humid conditions. The crop conditions were very dry and dry for all three sowing dates during the emergence and first pod phases. Late-sowing crops (15 May and 20 May) received more rainfall, 165 and 175 mm, respectively. Average daily temperatures from sowing to harvesting were consistent, ranging between 19.0 and 19.6 °C.

3.2. Management Effect on Biomass Accumulation

A three-way ANOVA for the biomass of the "Aksaiskii Usatii 55" variety of pea was conducted separately for two agroclimatic zones to identify the relative share of the three factors, including fertilizer application, sowing date, and seeding rate and their various interactions (Table 5). The ANOVA analysis revealed that fertilizer application significantly impacted biomass accumulation at a 1% significance level in dry steppe and steppe conditions. The effect of fertilizer on biomass increased biomass from 4326 to 5066 kg/ha (~17%) in the dry steppe and from 6353 to 7565 kg/ha (~19%) in the steppe zone.

Table 5. The results of 3-way analysis of variance (ANOVA) for aboveground biomass at harvest of the pea variety "Aksaiskii Usatii 55" in dry steppe and steppe conditions (2021–2022).

Treatments	Total Aboveground Biomass (kg/ha)									
	Dry Steppe					Steppe				
			Df	Mean Sq	F-Ratio			Df	Mean Sq	F-Ratio
F (kg/ha)	LSD_{01} = 367		1	13,797,852	39.36 **	LSD_{01} = 678		1	39,631,218	21.09 **
F1	4326	b				6353	b			
F2	5066	a				7565	a			
Sowing date (SD)	LSD_{05} = 325		1	8,385,728	18.28 *	LSD_{05} = 724		2	9,627,973	4.44 *
10 May	-					6494	b			
15 May	4474	b				6866	ab			
20 May	4918	a				7516	a			

Table 5. *Cont.*

Treatments	Total Aboveground Biomass (kg/ha)									
	Dry Steppe					Steppe				
			Df	Mean Sq	F-Ratio			Df	Mean Sq	F-Ratio
Seeding rate (SR)	LSD_{05} = 456		2	315,195	0.71	LSD_{05} = 537		2	2,455,238	1.89
0.8 M seeds/ha	4714	a				-				
1.0 M seeds/ha	4663	a				6839	a			
1.2 M seeds/ha	4710	a				7258	a			
1.4 M seeds/ha						6779	a			
ANOVA										
F	**					**				
SD	*					*				
F:SD	ns					ns				
SR	ns					ns				
F:SR	ns					ns				
SD:SR	ns					ns				
F:SD:SR	ns					ns				

Note: F—fertilizer, LSD_{05}—the least significant difference (LSD) at a 5% significance level, LSD_{01}—LSD at a 1% significance level, *—significant at a *p*-value of 5%, **—significant at a *p*-value of 1%, ns—not significant, Df—degree of freedom, a, b—values followed by the same letter do not differ according to Fisher test at $p < 0.05$.

In both agroclimatic zones, the sowing date significantly impacted biomass accumulation (p = 5%). In the dry steppe, the sowing date of 20 May resulted in 4918 kg/ha of biomass, a 10% increase compared to the 15 May sowing date of 4474 kg/ha.

In the steppe zone, the sowing date of 20 May resulted in 7516 kg/ha biomass, which is a 9.5% increase compared to the 15 May sowing date of 6866 kg/ha and a 15.7% increase compared to the 10 May sowing date of 6494 kg/ha biomass. Differences between 15 May and 20 May and 10 May and 15 May were insignificant, based on the LSD value of 724 kg/ha.

The results showed that the impact of the seeding rate on biomass accumulation was insignificant. All two- and three-way interactions between factors were also insignificant for biomass in both agroclimatic zones.

Comparing significant factors' contributions to biomass variability, it was found that fertilizer application's contribution was higher than the sowing dates based on the F-ratio values of 39.36 vs. 18.28 in the dry steppe zone and 21.09 vs. 4.44 in the steppe zone.

3.3. Relation Between Biometric Indicators

The correlation coefficients between various biometric indicators of the pea crop in the dry steppe experiment are illustrated in Figure 2. WS1000 showed a positive and significant correlation with LAI (r = 0.81). Additionally, WSm had a strong positive and significant correlation with WStm (r = 0.90) and WSp (r = 0.74). BY was strongly positively correlated with WSm (r = 0.95), WStm (r = 0.91), and WSp (r = 0.71). ANPP negatively but strongly correlated with PN (r = −0.50). ANSP strongly negatively correlated with ANPP (r = −0.67). WSp showed a strong negative correlation with PN (r = −0.55). WStm strongly positively correlated WSp (r = 0.64). The correlations were moderate or weak for the remaining pairs of biometric indicators for both years. Non-significant relations are not displayed in Figure 2.

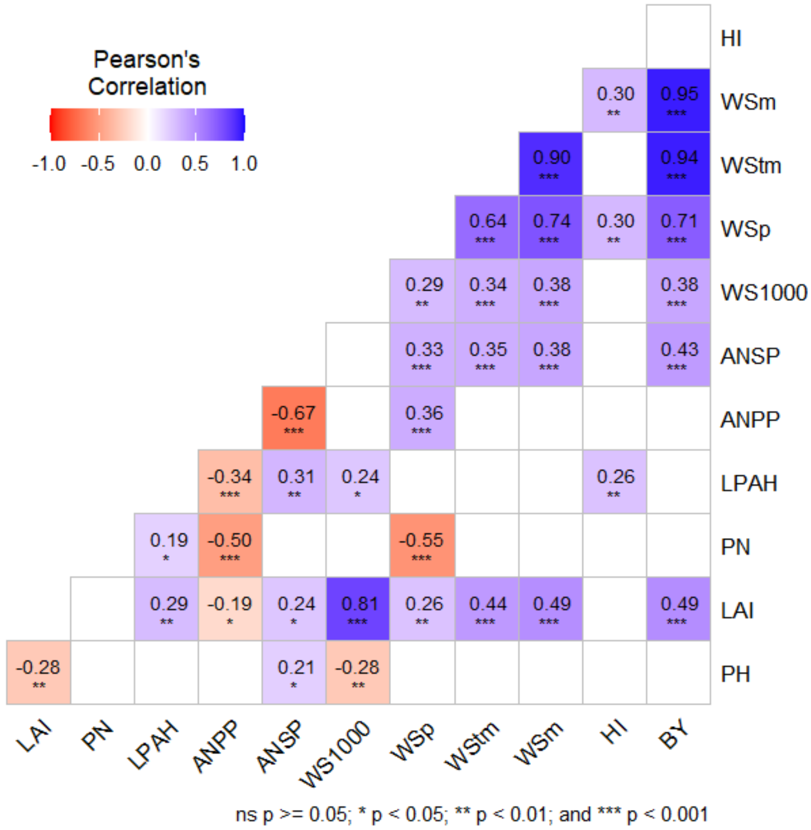

Figure 2. Pearson's correlation coefficients among eleven biometric indicators of pea crops, their significance, and a related heatmap for dry steppe conditions in 2021–2022 (N = 108). N—number of data per indicator, PH—plant height, LAI—leaf area index, PN—number of plants before harvesting per 1 m^2, LPAH—lower pod attachment height, ANPP—average number of pods per plant, ANSP—average number of seeds per pod, WS1000—the weight of 1000 seeds, WSp—the weight of seeds per plant, WStm—the weight of straw per 1 m^2, WSm—weight of seeds per 1 m^2, HI—harvest index, and BY—yield.

Figure 3 illustrates correlation coefficients between various biometric indicators of the pea crop for the experiment in the steppe zone. Statistically non-significant relations are not displayed in the figure. BY was strongly positively correlated with WSm (r = 1.0), WSp (r = 0.80), HI (r = 0.56), and WS100 (r = 0.53). WSm showed a strong positive correlation with WSp (r = 0.80) and WS100 (r = 0.53). WSp strongly positively correlated with WS100 (r = 0.51). ANSP strongly negatively correlated with ANPP (r = −0.54). LPAH showed strong positive correlation with PH (r = 0.59). The correlations were moderate or weak for the remaining pairs of biometric indicators for both years.

The relationship between pea crop biomass and yield observed in 2021 and 2022 is illustrated using scatter diagrams (Figure 4) for the experiments conducted in the dry steppe and steppe conditions. In both years and environments, linear regression and correlation analysis indicated a positive correlation between total dry biomass and yield. In the dry steppe zone, the correlation coefficients between total dry biomass and grain yield were R^2 = 0.91 in 2021 (Figure 4a) and R^2 = 0.97 in 2022 (Figure 4c). Similarly, in the steppe zone, the correlation was high in 2021 with R^2 = 0.76 (Figure 4b), but lower in 2022 with R^2 = 0.44 (Figure 4d).

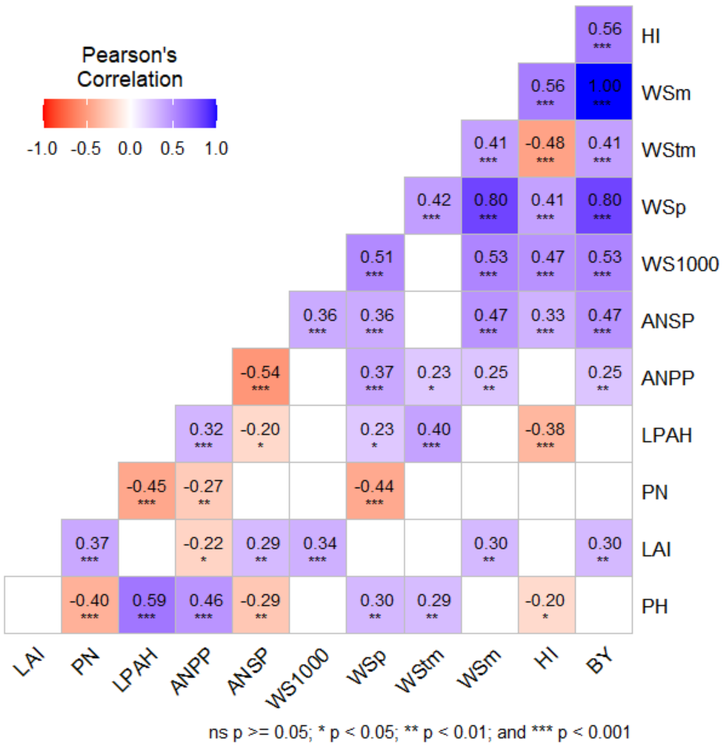

Figure 3. Pearson's correlation coefficients among eleven biometric indicators of pea crops, their significance, and a related heatmap for steppe conditions in 2021–2022 (N = 108). N—number of data per indicator, PH—plant height, LAI—leaf area index, PN—number of plants before harvesting per 1 m^2, LPAH—lower pod attachment height, ANPP—average number of pods per plant, ANSP—average number of seeds per pod, WS1000—the weight of 1000 seeds, WSp—the weight of seeds per plant, WStm—the weight of straw per 1 m^2, WSm—weight of seeds per 1 m^2, HI—harvest index, and BY—yield.

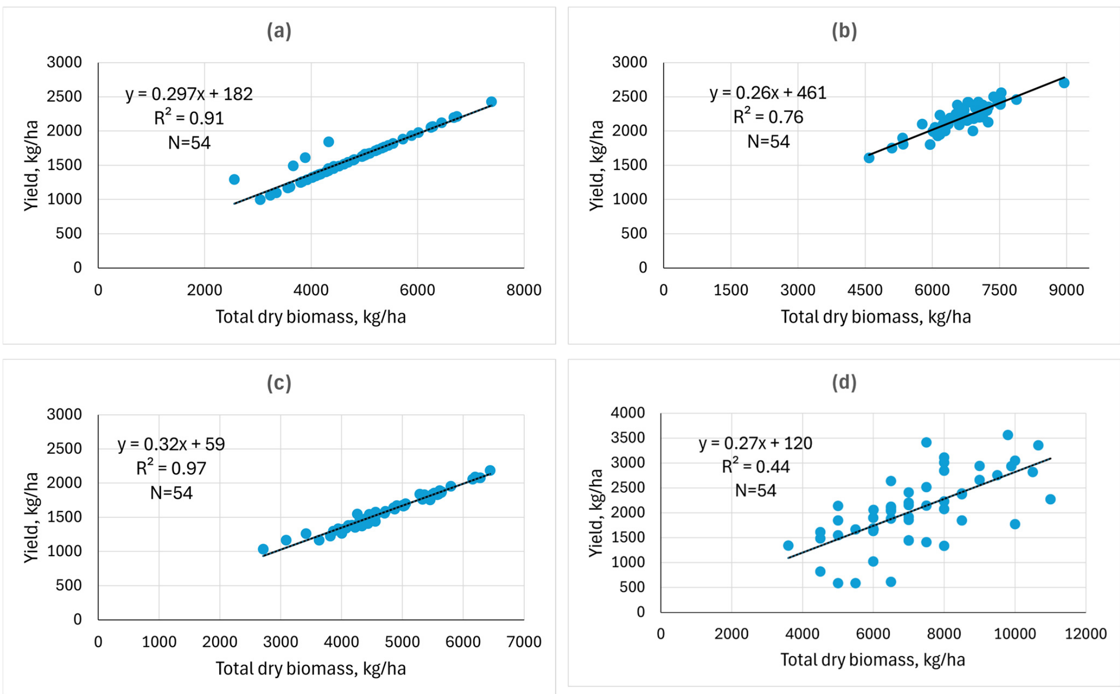

Figure 4. Relationship between total dry biomass and yield in the dry steppe zone in 2021 (**a**) and 2022 (**c**) and in the steppe zone in 2021 (**b**) and 2022 (**d**).

3.4. Agronomic Practices and Yield

A three-way ANOVA for the yield of the pea variety "Aksaiskii Usatii 55" was conducted separately for two agroclimatic zones to identify the relative share of the three factors, including fertilizer application, sowing date, and seeding rate, and their two- and three-way interactions (Table 6). Based on the ANOVA analysis results, fertilizer application significantly impacted yield in dry steppe and steppe conditions at 1% and 5% significance levels, respectively. Fertilizer application in the dry steppe conditions increased yield from 1566 to 1816 kg/ha (~16%) and from 1946 to 2295 kg/ha (~17.9%) in the steppe zone.

Table 6. The results of 3-way analysis of variance (ANOVA) for yield of the pea variety "Aksaiskii Usatii 55" in dry steppe and steppe conditions (2021–2022).

Treatments	Yield (kg/ha)									
	Dry Steppe					Steppe				
			Df	Mean Sq	F-Ratio			Df	Mean Sq	F-Ratio
F (kg/ha)	LSD_{01} = 119		1	1,517,274	32.53 **	LSD_{01} = 336		1	3,270,852	7.09 **
F1	1566	b				1946	b			
F2	1816	a				2295	a			
Sowing date (SD)	LSD_{05} = 101		1	871,244	13.06 *	LSD_{05} = 297		2	2,770,302	7.60 *
10 May	-					1812	b			
15 May	1619	b				2202	a			
20 May	1761	a				2349	a			
Seeding rate (SR)	LSD_{05} = 172		2	3583	0.06	LSD_{05} = 172		2	258,187	1.93
0.8 M seeds/ha	1739	a				-				
1.0 M seeds/ha	1660	a				2091	a			
1.2 M seeds/ha	1672	a				2216	a			
1.4 M seeds/ha						2055	a			
ANOVA										
F	**					**				
SD	*					*				
F:SD	ns					ns				
SR	ns					ns				
F:SR	ns					ns				
SD:SR	ns					ns				
F:SD:SR	ns					ns				

Note: F—fertilizer, LSD_{05}—the least significant difference (LSD) at a 5% significance level, LSD_{01}—LSD at a 1% significance level, *—significant at a p-value of 5%, **—significant at a p-value of 1%, ns—not significant, Df—degree of freedom, a, b—values followed by the same letter do not differ according to Fisher test at $p < 0.05$.

The sowing date significantly impacted yield in both agroclimatic zones, with p = 1% in the dry steppe and p = 5% in the steppe zones. The sowing date of 20 May resulted in 1761 kg/ha, or a 9.2% increase compared to the sowing date of 15 May, 1619 kg/ha, in dry steppe.

In the steppe zone, the sowing date of 15 May resulted in a yield of 2202 kg/ha, 21.5% higher than the sowing date of 10 May, 1812 kg/ha. The sowing date of 20 May resulted in a yield of 2349 kg/ha, 30.0% higher than the sowing date of 10 May. The difference between 15 May and 20 May was insignificant based on the LSD value of 297 kg/ha.

Seeding rate and none of the first- and second-order interactions between these three factors were significant or were not detected for yield in dry steppe and steppe zones.

Between fertilizer application and sowing date, fertilizer application was the larger contributor to yield variance, with an F-ratio of 32.53 vs. 13.06 in the dry steppe conditions. However, they were close contributors to yield variation in the steppe conditions, 7.09 vs. 7.60.

4. Discussion

4.1. Fertilizer Effect on Biomass Accumulation and Yield

Applying fertilizers is regarded as one of the key factors in improving crop yields. Fertilizers such as nitrogen, phosphorus, and potassium critically impact plant resistance to water stress. Research findings by Morison et al. [40] and Zhang et al. [41] show that fertilizers improve root activity, leading to enhanced absorption of water and nutrients, which is essential in dry zones.

Studies of the relationship between grain yield and biomass often show the need to consider the outcome of biomass, not just grain yield [42,43]. Our study found that in the conditions of dry steppe and steppe in Kazakhstan, the application of nitrogen–phosphorous fertilizers at a rate of 179 kg/ha contributed to an increase in biomass ranging from 4326 to 5066 kg/ha in the dry steppe and from 6353 kg/ha to 7565 kg/ha in the steppe, and an increase in yield ranging from 1566 to 1816 kg/ha in the dry steppe, and from 1946 to 2295 kg/ha in the steppe. These results demonstrate that the correct dose of nitrogen fertilizers increases biomass and improves growth indicators under stress conditions. Hatfield and Prueger [44] reported similar results.

In contrast, in a study by Khramoy and Rakhimova [45], nitrogen fertilizer rates at 30 and 60 kg/ha turned out to be ineffective, contributing to an increase in the protein content of biomass but not an increase in total biomass and yield. Nitrogen fertilizer at a rate of 90 kg/ha increased the protein content in the biomass and seeds, but it did not positively affect yield increase.

Nitrogen and phosphorus fertilizer application significantly impacted biomass accumulation and yield for all sowing dates and seeding rates in our study. The statistical analysis of three factors on the final total aboveground biomass for the two years and two sites showed that the average increase for the dry steppe zone compared to the non-fertilized treatments was 17% due to fertilizer application. For the steppe zone, the increase was 19.0% (Table 5). Similarly, the average increase in yield for the dry steppe zone compared to the non-fertilized treatments was 15%, and in the steppe zone, 17% (Table 6). During this study, multiple features in pea crop production formation were identified. The impact of nutritional conditions on biomass formation and yield after fertilizer application was evident compared to treatments without fertilizer, even when the non-fertilized treatment was combined with various sowing dates and seeding rates. Wang et al. [46] also demonstrated that the combined application of nitrogen and phosphorus fertilizers enhances photosynthetic activity, leading to increased biomass and yield. In both the dry steppe and steppe conditions under drought stress, the highest biomass value was noted in the flowering stage, 6682 kg/ha and 11,500 kg/ha, respectively.

4.2. Sowing Time Effect on Biomass and Yield

In dry steppe and steppe zones, where rainfall is limited and distribution during the growing season is often uneven, choosing the right sowing time is crucial. The right sowing time can reduce water stress in plants by better utilizing rainfall, which is aligned with key growth phases. Studies confirm that optimizing sowing time reduces the risk of drought stress [47]. Under such conditions, plants can develop deep root systems, improving access to water in the deeper soil layers. This is necessary to form a significant amount of biomass and yield.

In the study locations, peas accumulated a large amount of biomass and obtained a high yield for the later sowing dates (20 May) compared to the dry steppe's earlier sowing date (15 May). Peas sown on 20 May resulted in 4918 kg/ha of biomass, a 10% increase, and 1761 kg/ha of yield, a 9.2% increase, compared to the crop sown on 15 May. The environmental conditions during the beginning bloom phase, particularly temperature and rainfall, significantly contributed to higher HTC values. Similarly, in the steppe zone, during late sowings (15 May and 20 May) compared to 10 May. The crop sown on 20 May resulted in 7516 kg/ha biomass, a 15.7% increase, and a yield of 2349 kg/ha, 30.0% higher than the 10 May sown crop. Optimal temperature and rainfall during the flower bud phase were critical to such an impact.

These findings align with the study by Tedeeva and Okazova [25], where the best sowing dates for regular field pea varieties are from 15–17 May and up to 20 May, and for the late maturity varieties from 15–17 May and up to 21–23 May in the steppe zone. Other studies have also shown that late sowing dates facilitate more effective utilization of late spring rainfall, thereby increasing final biomass and yield. For instance, Ghodsi et al. [22] demonstrated that late sowing of peas can boost yield by 10–15% in regions with spring rainfall. However, in other cases [17,48], delayed planting of peas due to warmer temperatures and, therefore, a shorter growing season negatively influenced yield, yield components, and time to maturity or yield across environments was not decreased due to later planting [33].

In contrast, Yakushev et al. [26] have shown that a high and stable yield of peas is possible only at early sowing dates. A delay in sowing timing by 7–12 days can reduce the yield by 15–20% or more in dry years. An earlier sowing date is also preferred by farmers since in years with sufficient rainfall and a decrease in air temperature in the summer, the growing season is extended, and the crop can be harvested from the end of September to the beginning of October [25]. Such differences can be linked to varietal characteristics and their different sensitivities to growing conditions and agronomic practices, which ultimately affect biomass and yield formation, as the Poggio et al. [24] study supports. Depending upon the growing conditions and agronomic practices, the range of the yield variability can be high.

4.3. Seeding Rate, Biometric Indicators, and Yield

Based on our study's results, the effect of the seeding rate on the accumulation of pea biomass at all confidence levels was insignificant. Additionally, in both agroclimatic zones, the treatments that included different seeding rates did not significantly affect yield. The increased seeding rates under low moisture conditions may reduce water use efficiency by negatively impacting root system density, particularly in our study, where the higher seeding rate was applied within the row. Prusinski et al. [32] indicate that the seeding rate does not significantly impact pea yield formation. Similarly, Kashiwagi et al. [49] found comparable results for chickpeas in semi-arid tropical regions.

However, several studies have shown that peas' growth, development, and yield, including plant height and branching and the number of pods, depend on the seeding rate [28,29]. An increase in the seeding rate of pea seeds leads to an increase in the number of plants per m^2 and yield, but it reduces the number of seeds in the pod [30].

In our study, yield was affected by several biometric indicators. Changes in agronomic practices and temperature and humidity conditions have led to changes in yield formation factors. From the experiments in the dry steppe and steppe conditions, our results have shown that the increase in yield for peas largely depends on biometric indicators such as the weight of seeds per 1 m^2 and the weight of seeds per plant. This was followed by the weight of straw per 1 m^2, which showed a high correlation (r = 0.94) in the dry steppe while moderate in the steppe (r = 0.41). In the dry steppe, the weight of 1000 seeds moderately correlated with yield in contrast to a strong correlation with yield in the steppe. In both environments, LAI moderately correlated with yields. Other studies [50,51] had similar results.

The relationship between individual indicators and the influence of environmental factors conditions the phenotypic correlation [52]. A high correlation was observed between the weight of 1000 seeds and LAI (r = 0.81), the weight of seeds per 1 m^2, and the weight of straw per 1 m^2 (r = 0.90) in the dry steppe. A high correlation was also observed between the weight of seeds per 1 m^2 and the seed weight per plant (r = 0.80) in the steppe. A similar study by Sai Kachout et al. [53] produced comparable results. The relationship between various traits of peas has been studied before, but results vary significantly based on varietal differences and environmental conditions [54].

There was a significant, strong positive correlation between plant dry biomass and yield in both years in the dry steppe. Under the steppe conditions in 2021, the relation was strong, while in 2022, it was moderate. This means that as the total dry biomass of a pea plant increases, it has more resources to allocate towards seed production. In the dry steppe, the allocation of dry biomass to seed yield was greater in 2022 than in 2021; in the steppe, both years were quite similar. This variation can be attributed to factors such as growing conditions and harvest timing.

The low yield of peas in the dry steppe is due to the pea crop's high sensitivity to moisture deficiency and, accordingly, slow initial growth during an extreme moisture deficiency. The steppe zone was characterized by more favorable conditions for the growth and development of the pea crop compared to the dry steppe zone. However, moisture deficiency was also noted during the initial plant establishment period.

Future studies will employ a crop modeling approach to investigate the complex management and environment interactions. The goal is to quantify and understand how these factors contribute to water and nutritional stresses and their subsequent impact on biomass and yield in pea crops grown in dry steppe and steppe zones.

5. Conclusions

Important management decisions such as fertilizer application, sowing date, and seeding rate influence emergence, yield, yield components, and other physiological characteristics. Two years of data on the relationship between agronomic practices and biomass formation and yield showed that fertilizer application was the dominant explanatory factor across two agroclimatic zones, contributing significantly to biomass and yield variability, followed by the sowing date. The study results showed that the nitrogen–phosphorus fertilizer application increased biomass and yield in the dry steppe by 17% and 16%, respectively, and by 19% and 17.9% in the steppe zone. The late planting date of 20 May positively affected biomass and yield in both sites and increased biomass and yield by 10% and 9.2%, respectively, in the dry steppe and by 15.7% and 21.5–30% in the steppe. The impact of the seeding rate and all two- and three-way interactions between factors were insignificant. Our research also showed that the yield was highly correlated with biometric indicators of plants, such as the weight of seeds per 1 m^2 and seeds weight per plant. The growth and development of peas and the formation of final biomass and yield in the dry steppe and steppe zones depend on several factors. Key among these are the weather conditions during the growing season, soil water and nutrient availability, fertilizers use, and sowing timing. Future studies will use a crop modeling approach to focus on water and nitrogen stresses and their impact on pea crop growth and development.

Author Contributions: B.A.: Conceptualization; data curation; methodology; investigation; formal analysis; project administration; writing—original draft. V.S.: Formal analysis; software; visualization; writing—original draft; writing—review and editing. G.K.: Formal analysis. N.S.: Investigation; validation. Y.G.: Investigation; validation. Y.K.: Investigation; validation. N.Z.: Investigation. P.L.: Investigation; resources. A.A.: Writing—review and editing. A.K.: Funding acquisition; supervision. G.H.: Formal analysis; writing—review and editing. All authors have read and agreed to the published version of the manuscript.

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