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Research in Agricultural Sciences

CONTENTS

Research Articles

Review

ATATÜRK ÜNİVERSİTESİ YAYINLARI
ATATURK UNIVERSITY PUBLICATIONS

Research Article *Araştırma Makalesi*

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Meteorological Parameters–Soil Temperature Relations in a Sub-Tropical Summer Grassland: Physically-Based and Data-Driven Modeling

Subtropikal Bir Yaz Çayırında Meteorolojik Parametreler-Toprak Sıcaklığı İlişkileri: Fiziksel Tabanlı ve Veriye Dayalı Modelleme

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ABSTRACT

The knowledge of soil temperature dynamics at different depths is paramount for the agricultural industry because soil temperature impacts the physical, chemical, and biological processes in soil. A relationship between meteorological parameters and temperature at different depths in silt loam soil was assessed by using a physically based HYDRUS-1D model and a linear regression model. Soil temperature at 5, 10, 20, 30, and 50 cm soil layers, minimum and maximum air temperature, air pressure, relative humidity, dew point, rainfall, sunshine duration, wind speed, and evaporation data collected at a weather station were used. The correlation sensitivity for the input combinations was investigated. The quantitative evaluation based on mean absolute percentage error and R^2 showed that the predictions of both linear regression model and HYDRUS-1D models were satisfactory. The R^2 values at 5, 10, and 20 cm depths were 0.96, 0.94, and 0.88 for linear regression model, and 0.85, 0.86, and 0.78, for HYDRUS-1D model, respectively. Similarly, the mean absolute percentage error values for linear regression model were 0.81%, 0.87%, and 1.05%, whereas 3.44%, 2.87%, and 3.73% at 5, 10, and 20 cm depths for HYDRUS-1D model, respectively. Generally, the accuracy of the models diminished with increasing the soil depth. At >30 cm soil depth, both models failed to estimate soil temperature accurately. The R^2 and mean absolute percentage error values at 50 cm depth for linear regression model were 0.55% and 1.25% and 0.51% and 4.13% for HYDRUS-1D, respectively. The linear regression model performed better than the HYDRUS-1D model. Five independent variables (mean air temperature, maximum humidity, rainfall, wind speed, and evaporation) were found to significantly affect the summer-time soil temperature. Either of the methods can be used satisfactorily to predict soil temperature at 0–20 cm soil depth.

Keywords: Evaporation, humidity, HYDRUS-1D, linear regression model, wind speed

ÖZ

Toprak sıcaklığı topraktaki fiziksel, kimyasal ve biyolojik süreçleri etkilediğinden, farklı derinliklerdeki toprak sıcaklığı dinamikleri bilgisi tarım endüstrisi için çok önemlidir. Bu çalışmada siltli tın tekstür sınıfına ait toprakların farklı derinliklerinde meteorolojik parametreler ile sıcaklık arasındaki ilişkiler, fiziksel tabanlı HYDRUS-1D modeli ve bir doğrusal regresyon modeli (LRM) kullanılarak değerlendirilmiştir. Çalışma alanında 5, 10, 20, 30 ve 50 cm derinliğindeki toprak katmanlarının sıcaklık değerleri ile meteoroloji istasyonundan alınan en düşük ve en yüksek hava sıcaklığı, basınç, çiğ oluşum noktası, yağış, güneşlenme süresi, rüzgar hızı verileri kullanılmıştır. Girdi kombinasyonları için korelasyon hassasiyeti araştırılmıştır. Çalışma sonucunda ortalama mutlak yüzde hatası (OMYH) ve R2'ye dayalı kantitatif değerlendirmelerin hem LRM hem de HYDRUS-1D modellerinden elde edilen tahminlerin tatmin edici olduğunu göstermiştir. LRM modelinde 5, 10 ve 20 cm derinlik katmanlarındaki R2 değerlerinin sırasıyla 0,96, 0,94 ve 0,88 olduğu, HYDRUS-1D modelinde ise 0,85, 0,86 ve 0,78 olduğu tespit edilmiştir. Benzer şekilde OMYH değerleri 5, 10 ve 20 cm derinlik kademelerinde LRM için %0,81, %0,87 ve %1,05 iken, HYDRUS-1D modeli için %3,44, %2,87 ve %3,73 olarak hesaplanmıştır. Genel olarak modellerin doğruluğu toprak derinliğinin

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artmasıyla azalmış ve 30cm'den daha derin katmanlarda her iki modelin de toprak sıcaklığını doğru bir şekilde tahmin edemediği belirlenmiştir. Toprak derinliğinin 50 cm olduğu katmanlarda R2 ve OMYH değerleri LRM modeli için 0,55 ve %1,25, HYDRUS-1D modeli için ise 0,51 ve %4,13 olmuştur. Çalışma sonucunda ayrıca LRM modelinin HYDRUS-1D modelinden daha iyi performans gösterdiği, beş bağımsız değişkenin (ortalama hava sıcaklığı, maksimum nem, yağış, rüzgar hızı ve buharlaşma) yaz mevsimindeki toprak sıcaklığını önemli ölçüde etkilediği, her iki yönteminde 0-20 cm'lik toprak derinliğinde toprak sıcaklığını tahmin etmek için tatmin edici bir şekilde kullanılabileceği belirlenmiştir.

Anahtar Kelimeler: Buharlaşma, nem, HYDRUS-1D, lineer regresyon modeli, rüzgar hızı

Introduction

An essential variable of the land surface scheme that controls the energy and moisture exchange in the atmospheric continuum of soil and plants is soil temperature. Soil temperature plays a critical role in ecosystems, from deserts to forests (Jebamalar et al., 2012). Soil evaporation, soil aeration, soil microbial activity, and many other soil biological, chemical, and physical processes are controlled by soil temperature. Furthermore, plant growth, seed germination, and nutrient uptake by plants also depend on soil temperature (Amin et al., 2021; Yadav et al., 2020). Therefore, knowledge of ground surface and subsurface temperature at various depths is important for agricultural practices (Yilmaz et al., 2009) and for a better understanding of climate change impacts (Kourat et al., 2021; Wu et al., 2013). Studies have shown that soil temperature depends on various meteorological variables, such as air temperature, atmospheric pressure, relative humidity, wind speed, rainfall, solar radiation, and sunshine duration (Kisi et al., 2015). To determine soil temperature, solar radiation and air temperature are the main driving forces, but soil texture, moisture content, and the type of soil covering (plant canopy, crop residue, snow, etc.) also influence soil temperature variably (Amin et al., 2021; Karnieli et al., 2010).

There are numerous laboratory and field procedures for estimating soil hydraulic and thermal characteristics. The necessity of capturing the site-specific variations in soil temperature is apparent. However, it is always a difficult and time-consuming process to continuously measure soil temperature at various soil depths. Predictions by simulation models and machine learning algorithms can be the most viable alternatives for overcoming this problem to offer data on the temperature of a soil profile. A large number of meteorological stations only observe the variables above the ground surface or install sensors within the station areas to measure soil temperature, instead of installing them in the experimental fields, which creates a chance to make the observed data unrepresentative. To avoid this problem and make this work more accessible, scientists have emphasized on mathematical models that can determine soil temperature using meteorological variables and other factors which affect soil temperature. Simple models can perform poorly, but more complex models can provide better predictions. Three major types of soil temperature prediction models are mechanistic models, statistical relationships, and coupled empirical and mechanistic models (Sandor & Fodor, 2012). These models describe the atmosphere–soil–plant system with the help of mathematical tools and simulate those using computers.

A mathematical model called HYDRUS-1D (Šimůnek et al., 2005) can be used for the simulation of soil temperature dynamics. Richards' equation for saturated–unsaturated water flow and Fickian-based convection–dispersion equations for heat and solute transport are both numerically solved by HYDRUS-1D. Shein et al. (2019) performed research using HYDRUS-1D to validate the program's efficiency for predicting soil moisture and temperature dynamics and found out that the efficiency of prediction was high at surface soil depths (0–15 cm). Kanzari et al. (2018) also performed a comparison between a thermal dispersion model and the HYDRUS-1D model for the simulation of the variation of the water content and the temperature in 30 cm topsoil, which showed that thermal dispersion performed similarly to HYDRUS-1D. Besides HYDRUS-1D simulation, the linear regression model (LRM) has also been used to analyze soil temperature dynamics at various depths. Over the recent decades, the efficiency of data-driven models for simulating complicated nonlinear input–output relationships has been reported by many researchers. Several studies have been done for estimating soil temperature from meteorological parameters through linear or nonlinear methods, for example, multivariable linear regression, artificial neural network, and artificial neural fuzzy inferential system models (Bilgili, 2010; George, 2001; Kim & Singh, 2014; Tabari et al., 2010; Wu et al., 2013). Recently, Delbari et al. (2019) compared linear regression with support vector regression (SVR) in modeling soil surface temperature over diverse climate conditions, which showed that MLR can give poor results at depths over 30 cm, while SVR performs better than MLR at a deeper layer of the soil. Hossein and Ahmed (2017) used extreme machine learning for a similar task and showed that this method and linear regression gave a satisfactory result in predicting temperature at the topsoil (0–30 cm), but the accuracy diminished in the deeper soil layers. Machine learning algorithms, such as LRM, have been utilized to predict various soil physical and hydraulic properties for different types of soil in different regions. However, this type of study using either a machine learning algorithm or physically based simulation is scarce for the region of Bangladesh. It is not wise to use a model that was calibrated or developed based on information from other regions because soil properties vary widely with land topography, organic matter content, crop type, and meteorological parameters.

To find the best and most affordable model, studying multiple methods and comparing their performance are desirable. Also, an efficient study of the soil environment requires multi-depth soil temperature data, and such data are measured only at agro-meteorological stations. A limited number of agro-meteorological stations exist in Bangladesh. To our knowledge, there is no study on the comparison of the HYDRUS model with a machine learning model in predicting soil temperature. For that reason, it is imperative to find out a specific model that can predict the soil temperature of a particular region of Bangladesh that will not only provide accuracy but also reduce the time and cost to avail these data manually. This study illustrates how the temperature of the soil varies with depth with respect to various meteorological parameters and how the changes in meteorological factors affect the soil temperature. In this research, HYDRIS-1D and LRM were used to predict the soil temperature based on various meteorological data. The performances of these two methods were also compared. Therefore, the study has the following two objectives:

(i) To predict soil temperature at different soil depths by using HYDRUS-1D and LRM.
(ii) To quantify the performances of HYDRUS-1D and LRM in predicting the soil temperature values.

Methods

Study Location

The daily meteorological variables used in this study were collected from a weather station of Bangladesh Meteorological Department located at Bangladesh Agricultural University Campus, Mymensingh (24.7196° N, 90.4267° E and 18 m above mean sea level). The study area is under the agro-ecological zone named Old Brahmaputra Floodplain. The land of the study site was covered with local perennial grass of 5–8 cm cut. The proportions of sand, silt, and clay were 42%, 49%, and 10%, respectively, with an organic matter content of 1.1% in the silt loam soil of the location (Amin et al., 2022). The average temperature of June in this area varies from 26.7°C to 32.2°C with a mean relative humidity of 78.13% and an average rainfall of 37 cm. The reference evapotranspiration rate in this region considerably varies in different seasons; 2.9 mm/day in winter, 5.3 mm/day in dry summer, and 4.1 mm/day in wet season (Ali et al., 2005). The depth to water level in the shallow aquifer in this location fluctuates from 3.1 to 6.2 m in different seasons (Amin et al., 2023).

Data Collection and Processing

The measured meteorological and soil physical variables were daily soil temperature at a depth of 5, 10, 20, 30, and 50 cm, air temperature, atmospheric pressure, wind speed, relative humidity, rainfall, evaporation, water temperature, and sunshine duration. Monitoring soil temperatures at various depths was performed using multiple sensors in the field. In this study, data for the month of June 2019 were used (Figure 1).

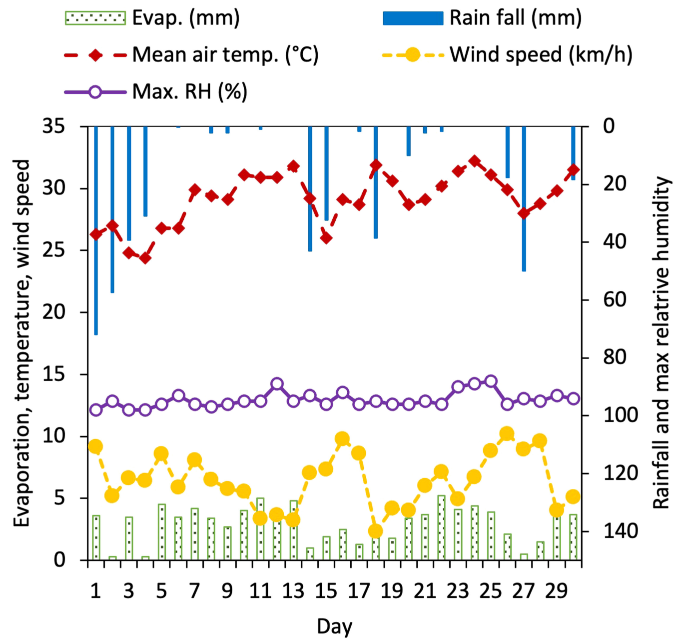

Figure 1.
Daily Variations of Meteorological Parameters in the Month of June 2019.

Prediction by Linear Regression Model

Method Description

Regression analysis enables one to comprehend how the independent variables are changed while the other independent variables are kept constant, and how this alters the typical value of the dependent variable. In this analysis, the conditional expectation of the dependent variable given the independent variables is calculated. The regression function, or estimation objective, is a function of the independent variables in every situation. The linear connection between a scalar dependent variable (*Y*) and one or more independent variables (*X*) is known as linear regression. In the case where there is only one explanatory variable, simple linear regression is employed. The procedure is known as multiple linear regression when there are more than one explanatory variable. The general formula for regression is (Menon et al., 2017):

$$Y = aX + c \tag{1}$$

where *Y* is the measurement of the dependent variable, that is, temperature, *X* is the independent variables, and *c* and *a* are constant. If there are *m* independent variables and every variable is *n* dimensional, then *X* can be written as:

$$X_{nxm} = \begin{bmatrix} X_{11} & X_{12} & \cdots & X_{1m} \\ X_{21} & X_{22} & \cdots & X_{2m} \\ \vdots & \vdots & \vdots & \vdots \\ X_{n1} & X_{n2} & \cdots & X_{nm} \end{bmatrix} = \begin{bmatrix} X_{(1)} & X_{(2)} & \cdots & X_{(m)} \end{bmatrix} \tag{2}$$

where X_i are the *n*-dimensional regression coefficients in the model for the ith variable. The predicted temperature values are obtained by implementing linear regression based on the independent factors. In this study, the least square approach of linear regression has been used.

Least Square Method

In regression analysis, the method of least squares is a common technique for approximating the solution of overdetermined systems by minimizing the sum of the squares of the residuals resulting from each individual equation. The total of squared residuals is reduced in the least-squares sense by the best fit. A function connecting the value of the dependent variable (*Y*) to the values of an independent variable is found using the conventional formulation. The prediction is given by the following equation (Menon et al., 2017):

$$\check{Y} = aX + c \tag{3}$$

In this equation, the intercept (*c*) and the slope (*a*) of the regression line are free variables. The estimate of these parameters, according to the least square approach, is defined as the value that minimizes the sum of squares between the measurements and the model predictions (thus, the name least squares). This amounts to minimizing the expression (Menon et al., 2017):

$$\epsilon = \sum_i \left(Y_i - \check{y}_i\right)^2 = \sum_i \left[Y_i - \left(aX_i + c\right)\right]^2 \tag{4}$$

where ϵ stands for error, which is the quantity to be minimized. Taking the derivative of ϵ with respect to a and c and setting them to zero, we can find the value of a and c. The least square can be extended to more than one independent variable (using matrix algebra) and to nonlinear functions.

Formulation of Linear Regression Model for Soil Temperature Prediction

One of the most critical steps in developing a satisfactory forecasting model is the selection of the input variables. Because these variables determine the structure of the forecasting model and affect the model's weighted coefficient and results, the first step in this analysis is the selection of independent variables. It is known that soil temperature is related to various meteorological variables. Therefore, the daily soil temperature (Y) can be characterized as the function of the air pressure (X_1), maximum air temperature (X_2), minimum air temperature (X_3), average air temperature (X_4), dew point (X_5), maximum humidity (X_6), minimum humidity (X_7), average humidity (X_8), rainfall (X_9), wind speed (X_{10}), sunshine duration (X_{11}), evaporation (X_{12}), and water temperature (X_{13}). The relationship between soil temperature and input variables can be expressed as follows:

$$Y = f\left(X_1, X_2, \ldots X_{13}\right) = a_1 X_1 + a_2 X_2 + \ldots + a_{13} X_{13} + c \qquad (5)$$

Here, independent variables must be only included in the model. Because the regression model must be established in a way that the best estimation should be performed using a few independent variables with the maximum possible degree of independence. Cross-correlations between input and output variables were calculated in order to determine the best input structure.

Soil Temperature Prediction by HYDRUS-1D

Model Description

In this study, HYDRUS-1D was implemented to predict the soil temperature at various depths. The HYDRUS-1D model solves the coupled equations governing liquid water, water vapor, and heat transport in the soil, together with the surface water and energy balance for the soil. The code assumes that temperature and pressure gradients work together to drive the movement of liquid and vaporized water in the subsurface. Conduction, convection of sensible heat by liquid water movement, diffusion of latent heat by water vapor, and diffusion of sensible heat by water vapor are all methods for transferring soil heat. Various types of meteorological information can be supplied to solve the surface energy balance at the upper boundary dynamically (Kleissl et al., 2007). Thus, water contents and temperatures of the soil profile can be calculated and coupled to meteorological parameters. In a case study, Saito et al. (2006) showed that soil water dynamics are strongly associated with the soil temperature regime.

Governing Equations

The HYDRUS-1D code for soil heat and water flux has been described in detail by Šimůnek et al. (2005). Convection–dispersion equation is used in HYDRUS for simulating one-dimensional heat transfer modeling. Neglecting the effect of water vapor diffusion on transport, this equation can be expressed as:

$$\frac{\partial C_p(\theta)T}{\partial t} = \frac{\partial}{\partial x}\left[\lambda(\theta)\frac{dT}{dx}\right] - C_w \frac{\partial qT}{\partial x} - C_w ST \qquad (6)$$

where $\lambda(\theta)$ is the coefficient of the apparent thermal conductivity of the soil, T is temperature, t is time, S is sink term, θ is the volumetric water content, q is the Darcian fluid flux density, and $C_p(\theta)$ and C_w are the volumetric heat capacities of the porous medium and the liquid phase, respectively. C_p (θ) is calculated using the following equation (de Vries, 1963):

$$C_p(\theta) = C_{nn} + C_{oo} + C_w + C_{av} \qquad (7)$$

where θ_n, θ_o, and θ_v are volumetric fraction of solid phase, organic matter, and gas phase, respectively, whereas C_n, C_o, C_a are volumetric heat capacity of solid phase, organic matter, and gas phase, respectively.

The apparent thermal conductivity is defined as (de Marsily, 1986):

$$\lambda(\theta) = \lambda_o(\theta) + \beta_t C_w |q| \qquad (8)$$

where β_t is the thermal dispersivity, $\lambda_o(\theta)$ is the thermal conductivity of the soil defined as (Chung & Horton, 1987):

$$\lambda_o(\theta) = b_1 + b_2\theta + b_3\theta^{(0.5)} \qquad (9)$$

where b_1, b_2, and b_2 are empirical parameters.

Model Parameterization

Soil hydraulic parameters, which were found by van Genuchten–Mualem single porosity model (van Genuchten, 1980) using the known soil texture and bulk density, are shown in Table 1. In this study, the default value for silt-loam soil textures was calculated considering no hysteresis. The value of the heat transport parameters used in this study is given in Table 2.

Q_r is residual soil water content, Q_s is saturated soil water content, K_s is saturated hydraulic conductivity, and l, α, and n are empirical parameters. In this study, the default values for silt loam soil were chosen.

Default values were used for C_n, C_o, and C_w. For water flow parameters calculation, the upper boundary condition was selected as the atmospheric boundary condition with surface runoff, the lower boundary condition as free drainage, and the initial condition as water contents. For heat transport parameters calculation, temperature amplitude was taken as 5°C, and Chung and Horton's method was used for thermal conductivity calculation. The upper and lower boundary conditions for heat transport were selected as the soil temperature boundary conditions.

Prediction Performance Assessment

To evaluate the performance of the linear regression and HYDRUS-1D model, the mean absolute percentage error (MAPE) and the coefficient of determination (R^2) were used to see the convergence between the target values and the output values. Here, MAPE is defined as follows (Melesse & Hanley, 2005):

$$MAPE = \frac{1}{n}\sum_{i=1}^{n} \text{abs}\left(\frac{o_i - p_i}{o_i}\right) \text{x}100 \qquad (10)$$

Table 1.
Soil Hydraulic Parameters Used in the Study

Q_r (cm³/cm3)	Q_s (cm³/cm³)	α (1/cm)	n	k_s (cm/day)	l
0.067	0.45	0.02	1.41	10.8	0.5

Table 2.
Soil Heat Transport Parameters

Solid	OM	Disp.	b_1(Wm^{-1}K^{-1})	b_2(Wm^{-1}K^{-1})	b_3(Wm^{-1}K^{-1})	C_n(Jm^{-3}K^{-1})	C_o(Jm^{-3}K^{-1})	C_w(Jm^{-3}K^{-1})
0.55	0.015	5	1.47×10^{19}	1.55×10^{19}	3.16×10^{19}	1.43×10^{14}	1.87×10^{14}	3.12×10^{14}

Disp., dispersion; OM, organic matter.

where o_i is the measured value, p_i is the predicted value, and n is the number of samples.

In addition, the coefficient of determination between the target value and the output value is defined as follows (Bilgili, 2010):

$$R^2 = 1 - \frac{\sum (y_i - \check{y}_i)^2}{\sum (y_i - \bar{y})^2} \tag{11}$$

where y_i is the measured value, and $\check{y}_i$ is the predicted value.

Results

Measured Soil Temperature

The temporal variation of the soil temperature at different depths is shown in Figure 2. Soil temperature at different times of the month varied with the depth of the soil. It was apparent that the soil temperature near the surface was higher than the temperature in deeper soil. Also, the temporal variation in temperature at different depths followed a similar pattern, but the range of fluctuations was diminished with depth. The range of fluctuations at 30 and 50 cm depths was much lower. This occurred due to the high thermal inertia of the soil and the time lag between the temperature fluctuations at the surface and deep in the soil. Therefore, the temperature in the deeper soil was lower than that of the upper soil layers (Kalogirou & Florides, 2004). However, the temperature at the 50 cm layer was higher than that at the 30 cm layer. The 50 cm layer remained relatively warm probably because of the heat conduction from the deeper soil below.

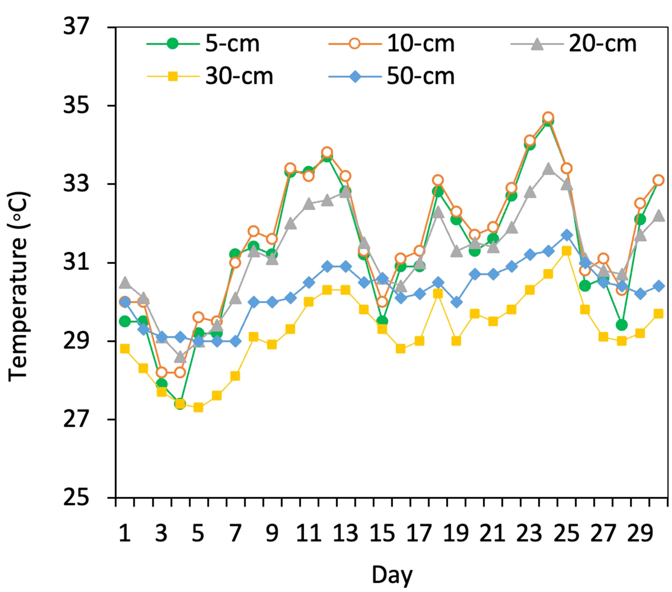

Figure 2.
Variation of the Average Soil Temperature at Different Depths Over the Month of June 2019.

Correlation Between Meteorological Parameters

There was a high rate of correlation between the soil temperature, which is the dependent variable, and the various meteorological variables. The obtained correlation coefficients are shown in Figure 3. Soil temperature has a strong positive correlation with maximum atmospheric air temperature, such as at 5 cm depth the correlation factor was .94 explaining that soil temperature will change proportionally with air temperature, whereas a strong negative correlation with humidity, such as at 5 cm depth the correlation factor was –.63 indicating that the relation of soil temperature is inversely proportional to average humidity, and weak negative correlation with rainfall, the correlation factor was –.47 at 5 cm depth. In addition, there is a weak correlation between soil temperature and air pressure and wind speed. For example, at 5 cm soil depth, the correlation factor for air pressure was .26 and for wind speed was .44.

Linear Regression Model Parameters

In the LRM, the most significant point is to select the predictor variables that provide the best prediction equation for modeling the dependent variable. All independent variables were added to enter the regression model formulated in section 2.3.3 (Formulation of linear regression model for soil temperature prediction), and the following model was obtained for the month of June for the 5 cm soil depth:

$$\begin{aligned} Y_5 = {} & 0.17 + 0.04X_1 + 1.87X_2 + 1.24X_3 - 2.36X_4 \\ & + 0 * X_5 - 0.20X_6 - 0.15X_7 + 0.01X_8 + 0.04X_9 \\ & - 0.03X_{10} - 0.02X_{11} + 0.12X_{12} + 0.20X_{13} \end{aligned} \tag{12}$$

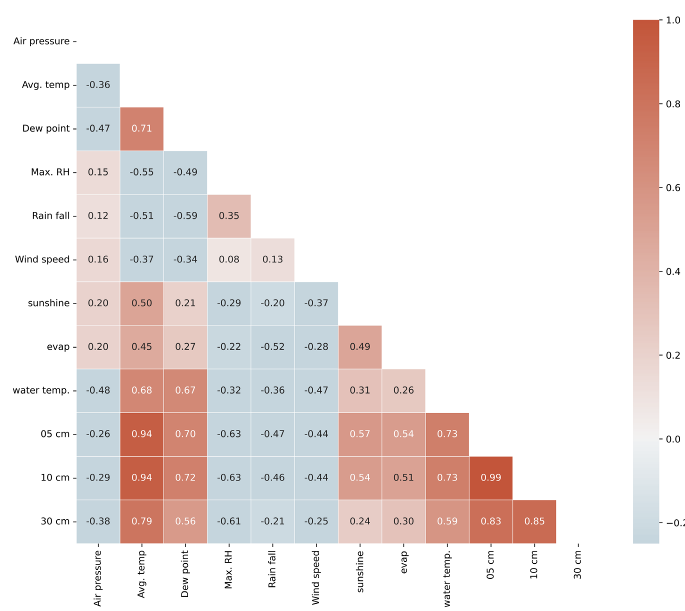

Figure 3.
Correlation Matrix Between Different Meteorological Parameters and Soil Temperature.

where the positive coefficients indicate the proportional relationship of these variables with soil temperature and the negative coefficients refer to an inversely proportional relationship with soil temperature. However, as described earlier and shown in Figure 3, the variables have multiple collinearities. Here, collinearity means some independent variables have a dependency on other independent variables, for example, average temperature and dew point have a high dependency on each other. This collinearity will cause the model to predict inaccurately. This collinearity among variables can also be proved by the variance inflation factor (VIF) (Craney & Surles, 2002). The VIF calculated after the first step of linear regression using all the variables is shown in Table 3. In statistics, the VIF is the ratio of the variance of estimating some parameters in a model that includes multiple other terms by the variance of a model constructed using only one term. In a simple least squares regression analysis, it measures the degree of multicollinearity. If VIF is high, then the variable in the model has high multicollinearity. One can infer that the regression coefficients are inaccurately assessed due to multicollinearity if the VIF is greater than 10 (Miles, 2014).

Table 4 depicts the *p*-values of the independent variables. The *p*-value suggests which variable is statistically significant to predict the soil temperature. Most of the variables have large *p*-value due to high collinearity among the variables.

It is clear from Table 3 that some variables have very high multicollinearity. Therefore, the stepwise regression technique was applied. The VIF values and significant levels (*p*-values) were used to evaluate the estimator performance of the regression model. Thus, the best independent variables were selected for the LRM, and the following model is obtained for the 5 cm soil depth:

$$Y_5 = 0.2 + 0.71X_4 - 0.2X_6 + 0.08X_9 - 0.1X_{10} + 0.14X_{12} \quad (13)$$

For the month of June, five independent variables were used to predict the soil temperature, which are average air temperature, maximum humidity, rainfall, wind speed, and evaporation. Similarly, four other independent equations were found from the LRM for the 10, 20, 30, and 50 cm of soil depth, which are shown as follows, respectively:

$$Y_{10} = 28.38 + 4.82X_4 - 1.22X_6 + 0.44X_9 - 0.72X_{10} + 0.68X_{12} \quad (14)$$

$$Y_{20} = 29.34 + 3.69X_4 - 0.96X_6 + 0.94X_9 - 0.39X_{10} + 0.46X_{12} \quad (15)$$

$$Y_{30} = 27.79 + 2.83X_4 - 1.02X_6 + 1.04X_9 + 0.12X_{10} + 0.18X_{12} \quad (16)$$

$$Y_{50} = 29.31 + 1.79X_4 - 0.8X_6 + 0.54X_9 + 0.46X_{10} + 0.04X_{12} \quad (17)$$

The final VIFs and *p*-values are shown in Table 5. All the VIFs of the final variables are below 5, which infer that the final variables have less collinearity among them. The *p*-values of all the variables are less than .05, which indicates that all the variables are statistically significant in predicting soil temperature.

To evaluate the performance of the LRM, the MAPE and the coefficient of determination (R^2) were used to see the convergence between the target values and the output values. The values of MAPE and R^2 at different soil depths for LRM are given in Table 6.

It is clear that LRM can give very satisfactory results in predicting the temperature at a depth of 5–20 cm. Not only the MAPE values are small, but the R^2 values are also desirable. For soil temperature below 20 cm depth, MAPE were still small, but R^2 values decreased considerably. From the linear regression equation and Figure 3, it is found that the soil temperature at different depths was highly correlated with mean air temperature, evaporation, and relative humidity. However, if the depth of soil increases, the correlation of soil temperature with these meteorological parameters declines.

HYDRUS-1D Predictions

Values of R^2 and MAPE of the HYDRUS-1D predictions of the soil temperature at different depths are shown in Table 7 and it is obvious from the table that the HYDRUS-1D satisfactorily simulated the soil temperature at the shallow depth of the soil (0–20 cm) and less so at the deep soil (30–50 cm). The predictions of HYDRUS-1D matched well with the measured soil temperature values at the depths of 0–20 cm, whereas it overestimated the soil temperature below 20 cm depth (Figures 4 and 5).

Discussion

Previous study shows that soil heat capacity and soil moisture content have a larger impact on soil temperature than meteorological parameter in deeper soil (Bilgili, 2010). In this study, soil

Table 3.
Variance Inflation Factor (VIF) Between Different Meteorological Parameters for All Soil Depths

Mean temperature	Maximum Temperature	Minimum Temperature	Dew Point	Minimum RH	Maximum RH	Average RH	Water temperature	Evaporation	Wind Speed	Air Pressure	Sunshine	Rainfall
47.770	18.270	8773	185	58	54	15	13	10	08	7	5	4

Table 4.
p-Value for Different Meteorological Parameters in Predicting Soil Temperature for All Soil Depths

Mean temperature	Maximum Temperature	Minimum Temperature	Dew Point	Minimum RH	Maximum RH	Average RH	Water Temperature	Evaporation	Wind Speed	Air Pressure	Sunshine	Rainfall
.581	.503	.499	.984	.424	.011	.950	.015	.077	.605	.478	.785	.624

Table 5.
Final Variance Inflation Factor (VIF) and p-Value for Different Parameters for All Soil Depths

Variable	Mean Temperature	Maximum RH	Rainfall	Wind Speed	Evaporation
VIF	4.73	4.95	2.02	3.75	4.55
p	.0	.003	.012	.05	.016

Table 6.
MAPE and R^2 Values at Different Soil Depths for the Linear Regression Model

Depth (cm)	R^2 Value	MAPE (%)
5	0.96	0.81
10	0.94	0.87
20	0.88	1.05
30	0.73	1.30
50	0.55	1.25

MAPE, mean absolute percentage error.

Table 7.
MAPE and R^2 Values for HYDRUS-1D Simulation at Different Soil Depths

Depth (cm)	R^2 Value	MAPE (%)
5	0.85	3.44
10	0.86	2.87
20	0.75	3.73
30	0.58	8.33
50	0.51	4.13

MAPE, mean absolute percentage error.

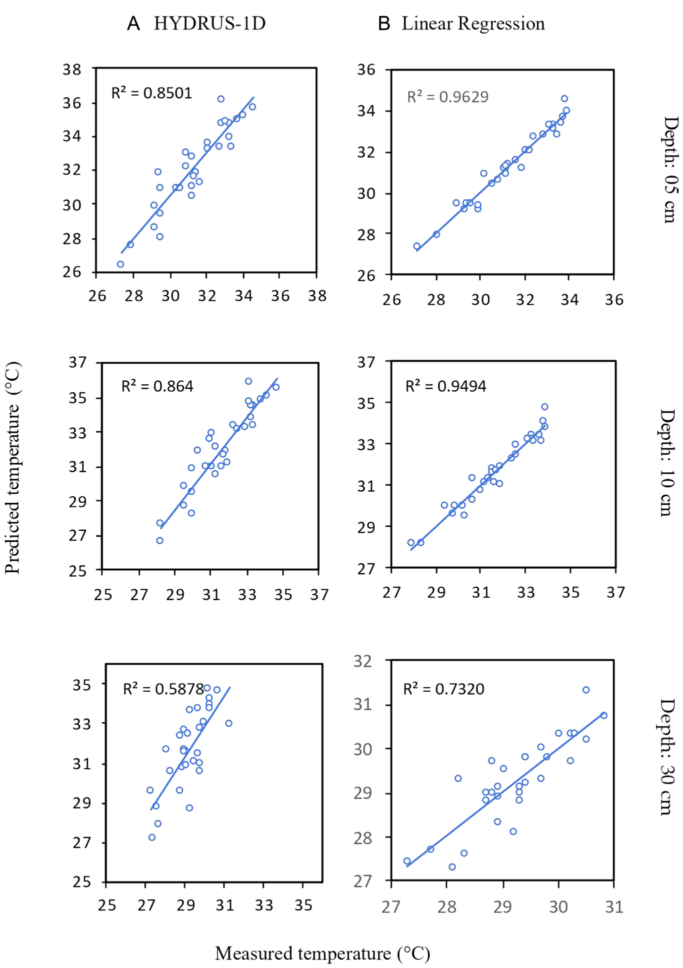

Figure 4.
Comparison of the Measured and Predicted Soil Temperature Values at Different Depths by HYDRUS-1D Simulation and Linear Regression Model.

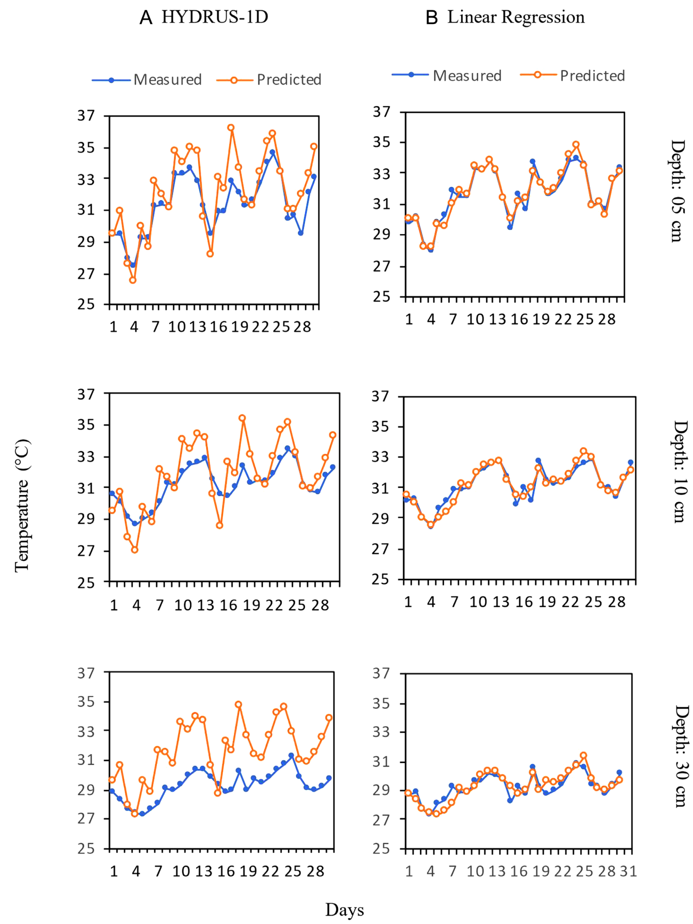

Figure 5.
Measured and Predicted Soil Temperature Values at Different Depths for the Month of June by HYDRUS-1D Simulation and Linear Regression Model.

heat capacity and soil moisture content were not considered in LRM. That is why the predicted values for the deeper soils were not accurate. Although the predicted values for soil depths lower than 20 cm do not vary considerably from the measured value, they do not follow the trend. Therefore, it can be inferred that only the meteorological parameters can predict the soil temperature up to the depth of 20 cm more accurately. Citakoglu (2017) compared the adaptive neural-fuzzy inference system (ANFIS), artificial neural network (ANN), and LRM to predict soil temperatures in Turkey and showed that ANFIS worked better than the other two methods. However, ANFIS and ANN need a lot of data to train the model, whereas LRM can use small data to predict the temperature. Tabari et al. (2010) used relative humidity, air temperature, precipitation, and solar radiation data in ANN and LRM to estimate soil temperatures at different soil depths and found ANN as more suitable than LRM.

However, Tabari et al. (2010) did not consider multicollinearity among independent variables. Sandor and Fodor (2012) compared HYDRUS-1D, CERES, and modified CERES models in predicting soil temperature at different depths in Hungary and showed that the HYDRUS-1D model performed better than the other two models. They also showed that HYDRUS-1D provide acceptable results in deeper soil (40 and 60 cm). However, they calibrated the HYDRUS-1D model using 1 year data before validation and measured soil hydraulic parameters experimentally using different apparatus, whereas in this study, the default values were used for soil hydraulic parameters. Thus, it can be assumed that, to get accurate predictions, the model needs to be calibrated with additional data from different soil layers. The soil's physical properties including soil organic matter content, soil texture, and moisture content can vary in different layers. Sandor and Fodor (2012) stated that the thermal properties of soil of particular regions (e.g., thermal conductivity) are required to predict soil temperature accurately. Since soil temperature is influenced by vegetative growth and soil water balance, the HYDRUS-1D model will give more accurate results if these inputs are integrated in the model.

Comparisons between the measured and predicted values for different models are shown in Figure 4. Also, the fluctuations of the measured and predicted values for different models at different depths over the month are shown in Figure 5. The LRM provided better results than the HYDRUS-1D simulation. Not only the LRM had lower values of MAPE, but it also had higher R^2 values. It means that the LRM predicted the temperature more accurately and captured the trend more precisely than HYDRUS-1D. However, the performance of both models changed with the depth of the soil. The LRM predicted the output based on meteorological parameters given as input to the model. Therefore, it only finds the relationship between the given input and output, and it does not depend on the empirical parameters, such as the thermal properties of soil that need to be measured externally. On the other hand, the HYDRUS-1D model attempts to solve the convection-dispersion equation that requires estimating the thermal conductivity and volumetric heat capacity of the soil (Sandor & Fodor, 2012). The HYDRUS-1D also requires vegetative growth data for better prediction.

Conclusion and Recommaendations

Both HYDRUS-1D and LRMs predicted soil temperature satisfactorily, but their performance varied with the soil depth. The LRM outperformed the HYDRUS-1D model. However, the predicted results of HYDRUS-1D are more mathematically solid and explainable, while the LRM uses a data-driven approach. To get more accuracy from HYDRUS-1D, more accurate calibration with more detailed input data, for example, leaf area index, soil moisture dynamics, etc., would be needed. It appears that five independent variables were found to significantly affect the soil temperature for the month of June, which were mean air temperature, maximum humidity, rainfall, wind speed, and evaporation. Further studies should be conducted to investigate the capability of an LRM in predicting the temperature of more structured soils with higher clay and organic matter contents. The performance of the HYDRUS model can be improved by incorporating more measured values and long-term data. Also, the developed model performance can be validated using more data and for different regions. Additional efforts would be necessary to improve prediction accuracy in the deeper layer of the soil.

Data Availability Statements: All data generated or analyzed during this study are included in this article. The data and materials are available upon request from the corresponding author.

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Augmenting Spring Wheat Productivity Through Seed Priming Under Late-Sown Condition in Bangladesh

Bangladeş'te Geç Ekim Koşullarında Yazlık Buğday Verimliliğinin Tohum Ön İşlemesi Yoluyla Artırılması

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ABSTRACT

The sowing of wheat can be delayed in Bangladesh because of the late harvesting of previous crops. Under late-sown conditions, heat stress results in poor development of wheat, which may be avoided by seed priming techniques. The purpose of this study was to assess the effectiveness of several seed priming methods for boosting wheat growth and yield when sown late. In this regard, from December 2019 to March 2020, a field investigation was carried out at the Agronomy Field Laboratory of Bangladesh Agricultural University. The experiment comprised three factors, Factor A: wheat variety namely, BARI Gom-27 and BARI Gom-33; Factor B: sowing dates such as 01 December 2019, 15 December 2019, and 30 December 2019; Factor C: Method of seed priming namely, control (no priming), priming with 20,000 ppm calcium chloride and priming with 20,000 ppm potassium chloride. With three replications, the experiment was set up using a split–split plot design. Research revealed that seed priming was generally effective in promoting plant growth, spikes number m^{-2}, grains $spike^{-1}$, thousand-grain weight, and grain yield. Both potassium chloride and calcium chloride performed significantly similar. As BARI Gom-33 is more resistant to heat stress, it outperformed BARI Gom-27 in terms of spike length and grains $spike^{-1}$. However, BARI Gom-27 and BARI Gom-33 performed quite similarly and wheat yield decreased gradually with the delay of sowing due to temperature stress. A clear advantage of seed priming was found in increasing grain yield at all sowing dates. Therefore, it is recommended to sow wheat by 15 November following seed priming and in case of delay sowing seed priming is a must to mitigate the temperature stress to some extent.

Keywords: Growth, heat stress, seed invigoration, sowing time, wheat, yield

ÖZ

Bangladeş'te önceki ürünlerin geç hasat edilmesi nedeniyle buğday ekimi geciktirilebilmektedir. Geç ekim koşullarında, sıcaklık stresi buğdayın zayıf gelişmesine neden olur ve bu durum tohum ön işleme teknikleri kullanılarak önlenebilmektedir. Bu çalışmanın amacı, geç ekim yapıldığında tohum ön işleme yöntemlerinin buğday büyümesini ve verimini artırmada etkinliğini değerlendirmektir. Bu amaçla, araştırmamız Aralık 2019'dan Mart 2020'ye kadar, Bangladeş Tarım Üniversitesi Zirai Araştırma arazilerinde gerçekleştirilmiştir. Araştırma, Faktör A - BARI Gom-27 ve BARI Gom-33 olmak üzere iki farklı buğday çeşidi; Faktör B - 01 Aralık 2019, 15 Aralık 2019 ve 30 Aralık 2019 olmak üzere üç farklı ekim tarihi; ve Faktör C - kontrol grubu (ön işlem yapılmamış tohumlar), 20000 ppm CaCl2 ve 20000 ppm KCl ile ön işlem yapılmış tohumlar olmak üzere üç faktörden oluşmuştur. Deneme bölünen bölünmüş parseller deneme desenine göre üç tekerrürlü olarak kurulmuştur. Araştırma, tohum öncesi işlemenin bitki büyümesini, metrekaredeki başak sayısını, başaktaki tane sayısını, bin tane ağırlığı ve tane verimini artırmada genel olarak etkili olduğunu göstermiştir. Hem KCl hem de CaCl2 ön işleme uygulamaları, önemli ölçüde benzer bir performans sergilemiştir. BARI Gom-33 çeşidi, sıcaklık stresi ile mücadele konusunda daha dirençli olduğu için, başak uzunluğu ve başaktaki tane sayısı açısından BARI Gom-27'den daha iyi sonuçlar göstermiştir. Ancak, BARI Gom-27 ve BARI Gom-33 çeşitlerinde ekim geciktikçe benzer sonuçlar göstererek sıcaklık stresi nedeniyle buğday verimi azalmıştır. Tüm ekim tarihlerinde tane verimini artırmada tohum öncesi işlemin önemi açık bir şekilde görülmüştür. Bu nedenle, tohum ön işlemesi yapıldıktan sonra buğdayın 15 Kasım'a kadar ekilmesi önerilir ve ekimin gecikmesi durumunda, sıcaklık stresini bir dereceye kadar azaltmak için tohum ön işlemesi şarttır.

Anahtar Kelimeler: Büyüme, sıcaklık stresi, tohum güçlendirme, ekim zamanı, buğday, verim

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Introduction

One of the most popular cereal grains consumed worldwide is wheat (*Triticum aestivum* L.). Wheat is the second most significant cereal crop in Bangladesh after rice (Jahan et al., 2021), and consumption of grain is rising steadily as a result of its affordable cost of production, favorable market price, and high nutritional content. Due to the country's shifting dietary preferences, wheat has now a prominent place in agricultural policies in Bangladesh and has become one of the most important grain crops. Bangladesh now produces 1.09 million tons of wheat covering a 0.34 m ha area, yielding an average of 3.3 t ha^{-1} (BBS, 2021). The average amount of wheat produced in Bangladesh is relatively low when compared to several other countries that grow wheat. Also, due to several biotic and abiotic causes, the yield of Bangladeshi wheat in farmers' fields is much lower than rice and maize (2.0 t ha^{-1}) when compared to research fields (Ahmed et al., 2019; Kamrozzaman et al., 2016; Shabi et al., 2018). The date of sowing and variety choice are of the highest importance when considering the various factors influencing the nation's poor yield of wheat.

The right sowing date can help with the specific environmental conditions that each crop variety needs to thrive to its full potential. In Bangladesh, the best period to sow wheat is from mid-November through the first week of December. However, late harvesting of kharif crops, notably T. aman rice, causes wheat sowing to be delayed. Additionally, there may not be enough irrigation water available, and occasionally there may be too much moisture and water logging due to excessive rainfall, which can also delay wheat sowing. When wheat is sown early, it encounters higher temperature resulting in inadequate root development and poor growth of plants (Kamrozzaman et al., 2016). Delay planting affects germination, growth, grain development, and eventually suppresses yield (Tahir et al., 2009). Timely planting extends the tillering phase and produces a sufficient number of tillers, spikes, grains $spike^{-1}$, and grain weight, which ultimately improves grain and straw output (Qasim et al., 2008). With each week of delayed sowing, Braun et al. (2010) found that grain output dropped, with a loss of 200–250 kg grain ha^{-1}. Wheat yields in Bangladesh are poor mostly due to environmental constraints brought on by late planting and a short winter (Islam et al., 1993).

High temperatures is the most major environmental stressor, although others such as poor soil moisture, low light intensity, and others can have an adverse effect on wheat development and yield (Modarresi et al., 2010; Trnka et al., 2004). There are two types of heat stress that wheat normally encounters: continual and terminal. The phrase "continual heat stress" refers to the heat stress that persists from sowing to maturity stages and "terminal heat stress" refers to heat stress that begins during reproductive development phases, notably from heading to maturity stages (Reynolds et al., 2001). As per an investigation by Karim et al. (1999), in Bangladesh, the wheat yield might drop by roughly 68% with a 4°C increase in temperature. According to Wiegard & Cellular (1981), for each 1.0°C increase in the mean daily air temperature, the grain filling period for wheat was delayed by 3 days. However, according to the projected future climate, unless the right cultivars and crop management strategies are used, rising temperatures would result in a considerable decrease in wheat output (Ortiz et al., 2008). The detrimental impact of high temperatures on wheat output can be mitigated by using special agronomic management strategies.

Wheat's high-temperature stress can be lessened by using a variety of physiological techniques. Seed priming is one of these methods, which is a safe and affordable strategy to improve wheat development (Farooq et al., 2006a). "Seed priming" seeks to control the germination process by regulating the temperature and moisture level of the seeds. It is a useful physiological pre-germination technique that enhances seed performance and promotes coordinated germination of seed quickly (Matsushima & Sakagami, 2013) by imposing stress conditions on the seed before germination, which provides improved resistance to forthcoming stresses (Anwar et al., 2021b; Yadav et al., 2011). Plants that have been grown from primed seed, develop more quickly and completely, with early blooming, maturity, and larger yields as well as decreased likelihood of crop failure. Various sorts of priming methods are hydro-priming with water, osmo-priming with organic osmotic solution, halo-priming by inorganic salt solutions, thermo-priming by low or high temperatures depending on species, bio-priming with biological compounds, and solid matrix priming with solid matrices (Ashraf & Foolad, 2005). Greater germination percentage, synchronized germination, and speedier seedling emergence are advantages of seed priming, and these qualities are directly related to crop development and yield (Anwar et al., 2012; Farooq et al., 2007; Mim et al., 2021).

Although applying seed priming techniques in controlled environments has been shown to promote germination and seedling growth (Anwar et al., 2020; Basra et al., 2005; Farooq et al., 2009b) and also some achievements (Du & Tuong, 2002) in boosting the performance of crops have been confirmed, but there has not been much detailed study done to evaluate the impact of various seed priming procedures to boost wheat development and yield in late-sown conditions. Given the foregoing, the goal of the current experiment was to determine how well various seed priming strategies increased wheat growth and yield when it was seeded late in the season.

Methods

A field trial was carried out at the Agronomy Field Laboratory of Bangladesh Agricultural University from December 2019 to March 2020 to determine the effectiveness of various seed priming procedures to boost the growth and yield of wheat under late-sown conditions. Geographically, the region was situated at 24°75′ N latitude and 90°50′ E longitude, with an altitude of 18 m above sea level. This region is a part of the Old Brahmaputra Floodplain (AEZ 9), which has non-calcareous dark gray floodplain soil under the Sonatola series. The land was medium-high and well drained with a silty-loam texture. The soil of the experimental field was more or less neutral in reaction (pH: 6.65), organic matter content (1.21%), total nitrogen (0.12%), available phosphorous (26.07 ppm), exchangeable potassium (0.15 me %), and the general fertility level of the soil was moderate. The experimental site belongs to a subtropical monsoon climate with a humid environment. Table 1 provides information on the pattern of rainfall, sunlight hours, temperature swings, and relative humidity over the research period, and Figure 1 depicts the weekly averages for maximum, minimum, and mean temperatures.

The experiment comprised three different sowing dates viz. 01 December 2019 (D_1), 15 December 2019 (D_2), and 30 December 2019 (D_3); two seed priming agents with control treatment viz. no priming (P_0), priming with 20,000 ppm $CaCl_2$ (P_{Ca}), priming with

Table 1.
Weather Data From November 2019 to March 2020 at the Experimental Site During the Growing Season of Wheat

Month and Year	Air Temperature (°C) Maximum	Minimum	Average	Rainfall (mm)	Relative Humidity (%)	Sunshine (Hours)
December 2019	25.4	13.5	19.8	17.7	80.2	201.3
January 2020	24.02	12.15	19.22	0.00	84.35	227.2
February 2020	26.8	15.54	21.28	1.17	83.00	164.8
March 2020	30.65	17.70	23.76	1.90	73.19	208.2

Source: Weather Yard, Department of Irrigation and Water Management, Bangladesh Agricultural University, Mymensingh.

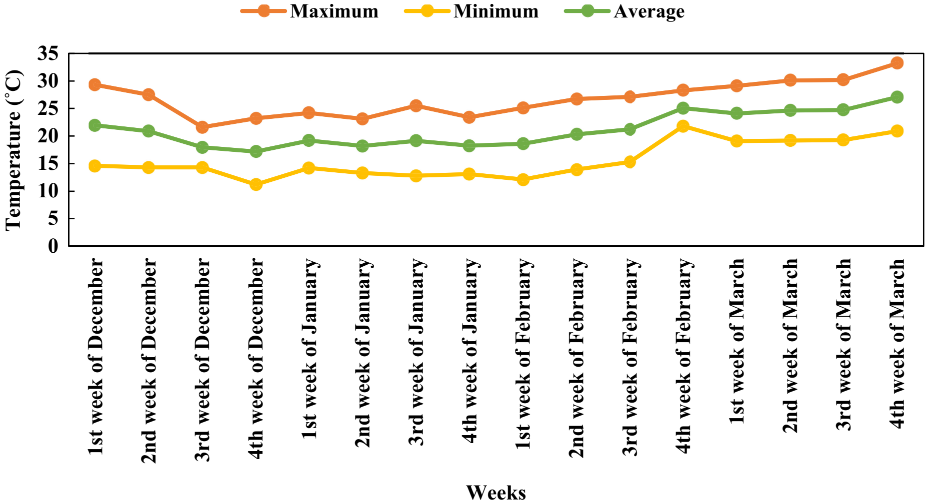

Figure 1.
Weekly Average Maximum, Minimum, and Mean Temperature From December 2019 to March 2020.

20,000 ppm KCl (P_K); and two wheat varieties viz. BARI Gom-27 (V_1) and BARI Gom-33 (V_2). The experiment employed laboratory-grade two priming agents made at MERCK, India: potassium chloride (KCl) and calcium chloride ($CaCl_2$). A split–split plot design with three replications was used to set up the experiment. Sowing dates were assigned to the main plots, seed priming techniques to the subplots, and variety was allocated to the sub-subplots. There were 54 plots overall, each measuring 10 m^2 (2.5 m × 4.0 m).

The land was prepared in the third week of November 2019. A power tiller was used to repeatedly plow the ground. The land was cleared of weeds and the remnants of the previous crop. Following leveling, the experimental plots were set up in accordance with the chosen treatments and layout. At the time of the final land preparation, one-third of recommended urea dose and the full amount of Tripple Super Phosphate (TSP), Muriate of Potash (MoP), gypsum, and boric acid were applied at 180, 50, 120, and 7.5 kg ha^{-1}, respectively. On days 20 and 55 following sowing, the remaining two-thirds of urea were top-dressed in two equal portions. Both wheat varieties' seeds were steeped for 6 hours at room temperature (25 ± 2°C) in various priming agent solutions that had been previously made using distilled water. The seed weight to solution volume ratio was 1:5 (w:v). The seeds were then taken out of the priming solution and thoroughly washed with distilled water to eliminate any remaining chemical residues. Forced air was then used to dry the seeds to their original moisture level. Dry seeds were placed in polythene bags and kept in a refrigerator at 5°C until needed. After sprouting, the seeds were sown in the plot at 110 g seeds per plot, spaced 20 cm apart. Three distinct date–1 December, 15 December, and 30 December 2019–were chosen for the sowing of the seeds. The optimum period to sow was thought to be on 1 December; 15 December and 30 December were deemed late and extremely late, respectively. So, at various stages, seedlings are subject to heat stress. After sowing, the seeds were kept safe from birds. Three irrigations were given, the first irrigation was given at 20 days after sowing (DAS) at the crown root initiation stage, the second one at the heading stage (60 DAS), and the third one at the grain filling stage (80 DAS). To ensure the crop's proper development, intercultural activities like weeding were carried out.

The cultivars were harvested individually and according to a plot after they were fully mature on 15 March, 21 March, and 29 March 2020, respectively, 1st, 2nd, and 3rd sowing dates. At harvest, data on the height of the plant; number of spikes m^{-2}; spike length, number of spikelets $spike^{-1}$; grains $spike^{-1}$; grains $spikelet^{-1}$; 1000-grain weight; grain, straw, and biological yield; and harvest index were documented. The yields of grain and straw were calculated plot-wise on a basis of 14% moisture and represented as t ha^{-1}.

The data were collected, tabulated, and statistically analyzed. Using the computer program MSTAT, an analysis of variance was performed with a 5% level of probability. Duncan's Multiple Range Test was used to determine the average differences between the treatments.

Results

Main Effect

Sowing date

With the exception of spike length and grains spikelet^{-1}, the sowing date had a substantial impact on the growth, yield-contributing characteristics, and yield of wheat. The delay in planting led to a reduction in wheat plant height. The highest plant height (95.38 cm) was found when sowing was done on 01 December. At very late sowing (30 December), the plant (88.80 cm) was shortened by 7 cm compared to the optimum sowing date (1 December). Number of spikes m^{-2} also followed a similar trend where the highest value (146.38) was obtained with early sowing (1 December). Apart from the sowing on 30 December (139.80), the remaining two dates produced statistically equivalent numbers of spikes m^{-2}. The performance of the 30 December sowing was the worst in terms of spikelets spike^{-1} (12.77). A clear advantage of sowing date in increasing spikelets spike^{-1} was evident on 01 December (15.85) and 15 December (14.92) sowing, but not thereafter. In terms of grains spike^{-1} of wheat, 1 December sowing showed maximum grains spike^{-1} (47.66), whereas 30 December sowing exhibited minimum grains spike^{-1} (38.50). From Table 2, it is clear that up to 15 December sowing the number of grains spike^{-1} of wheat was considerable. With the delay in sowing, wheat's thousand-grain weight dropped. The sowing that took place on 1 December produced the maximum weight of 1000 grains (43.52 g), while the sowing that took place on 30 December produced the lowest weight of 1000 grains (31.04 g). With the postponement of sowing, wheat grain yield was also reduced. Wheat sowing on 1 December resulted in the maximum grain yield (2.99 t ha^{-1}). Wheat grain yield (1.67 t ha^{-1}) was lowered by 44% as a result of the very late sowing (30 December). Also, early sowing led to the maximum straw yield (3.54 t ha^{-1}) and when sown very late, the straw yield was recorded as being the lowest. The highest harvest index (45.79%) of wheat was found when sowing was done on 01 December. With the delay of sowing, harvest index was gradually decreased (Table 2).

Seed priming

Seed priming had a significant influence on all yield parameters and yield except spike length, spikelets spike^{-1}, and grains spikelet^{-1}. When compared to non-primed seeds, it was shown that priming the seeds enhanced wheat plant stature. Seed priming performed significantly better than the control (90.03 cm), but there were no significant differences between calcium (94.17 cm) and potassium (94.81) priming. From Table 3, it is clear that on average due to seed priming plant height was increased by 5 cm. As a result of seed priming, there were more wheat spikes m^{-2} than there were under control. With KCl priming, the greatest number of spikes m^{-2} (145.81) was produced which was

Table 2.
Effect of Sowing Date on Plant Characters, Yield Parameters, and Yield of Wheat

Sowing Date	Plant Height (cm)	Spikes m^{-2} (no.)	Spike Length (cm)	Spikelets Spike^{-1} (no.)	Grains Spike^{-1} (no.)	Grains Spikelet^{-1} (no.)	1000-Grain Weight (g)	Grain Yield (t ha^{-1})	Straw Yield (t ha^{-1})	Harvest index (%)
01 December	95.38a	146.38a	12.08	15.85a	47.66a	3.02	43.52a	2.99a	3.54a	45.79a
15 December	94.82a	145.82a	12.20	14.92a	44.88a	3.03	41.07b	2.69b	3.32a	44.73a
30 December	88.80b	139.80b	12.03	12.77b	38.50b	3.04	31.04c	1.67c	2.71b	38.11ab
S$\bar{x}$	27.41	27.41	0.14	2.66	22.11	0.27	2.66	0.07	0.10	22.35
Level of significance	**	**	NS	**	**	NS	**	**	**	**
CV (%)	5.6	3.6	3.1	11.2	10.8	17.2	4.2	10.9	10.2	11.0

Note: NS = Not significant.
Means with the same letters or without letters within the same column do not differ significantly.
**Significant at 1% level of probability.

Table 3.
Effect of Seed Priming on Plant Characters, Yield Parameters, and Yield of Wheat

Seed Priming	Plant Height (cm)	Spikes m^{-2} (no.)	Spike Length (cm)	Spikelets Spike^{-1} (no.)	Grains Spike^{-1} (no.)	Grains Spikelet^{-1} (no.)	1000-Grain Weight(g)	Grain Yield (t ha^{-1})	Straw Yield (t ha^{-1})	Harvest Index (%)
No priming	90.03b	141.03b	12.21	13.87	41.50b	3.02	37.11b	2.21b	3.02b	41.70b
$CaCl_2$ priming	94.17a	145.17a	12.05	14.85	44.66a	3.01	38.96a	2.55a	3.28a	43.17a
KCl priming	94.81a	145.81a	12.05	14.8	44.88a	3.06	39.57a	2.59a	3.27a	43.76a
S$\bar{x}$	15.58	25.70	0.36	2.07	7.99	0.08	1.30	0.02	0.09	3.38
Level of significance	*	*	NS	NS	*	NS	**	**	*	*
CV (%)	4.2	2.7	5.0	9.9	6.5	9.5	3.0	6.4	9.9	4.3

Note: NS = Not significant.
Means with the same letters or without letters within the same column do not differ significantly.
**Significant at 1% level of probability.
*Significant at 5 % level of probability.

Table 4.
Effect of Variety on Plant Characters, Yield Parameters, and Yield of Wheat

Variety	Plant Height (cm)	Spikes m^{-2} (no.)	Spike Length (cm)	Spikelets $Spike^{-1}$ (no.)	Grains $Spike^{-1}$ (no.)	Grains $Spikelet^{-1}$ (no.)	1000-Grain Weight (g)	Grain Yield (t ha^{-1})	Straw Yield (t ha^{-1})	Harvest Index (%)
BARI Gom-27	92.22	143.22	10.32b	14.17	42.70b	3.03	37.79	2.35	3.13b	42.45
BARI Gom-33	93.78	143.22	13.89a	14.86	44.66a	3.03	39.30	2.55	3.25a	43.30
$S\bar{x}$	25.70	25.70	0.36	1.28	0.07	0.08	20.10	0.17	0.01	21.65
Level of significance	NS	NS	**	NS	**	NS	NS	NS	**	NS
CV (%)	5.5	3.5	5.0	7.8	0.6	9.8	11.6	16.9	0.9	10.9

Note: NS = Not significant.
Means with the same letters or without letters within the same column do not differ significantly.
**Significant at 1% level of probability.

statistically similar to $CaCl_2$ priming (145.17) and the lowest was registered with no priming (141.03). When compared to the control, seed priming greatly outperformed it in terms of number of grains spike^{-1} (41.50), but there was no significant difference between calcium (44.66) and potassium (44.88) priming and on average due to seed priming wheat grains spike^{-1} was increased by 7%. As compared to the control, priming boosted 1000-grain weight by roughly 5.5%. Seed priming demonstrated higher effectiveness in this regard. The maximal 1000-grain weight (39.57 g) obtained by KCl seed priming was comparable to $CaCl_2$ priming (38.96 g). Using KCl priming, the best grain yield was attained (2.59 t ha^{-1}) which was statistically equivalent to $CaCl_2$ priming (2.55 t ha^{-1}). Seed priming outperformed the control by a large margin and boosted yield. When compared to non-primed seeds, it was shown that priming the seeds enhanced the yield of wheat straw. The performance of seed priming was much better than the control, but there was no noticeable difference between calcium (3.28 t ha^{-1}) and potassium (3.27 t ha^{-1}) priming. The harvest index for seeds primed with KCL was greatest (43.76%), followed by seeds primed with $CaCl_2$ (43.17). Due to seed priming, the harvest index rose by 2% on average (Table 3).

Variety

In wheat varieties, a significant varietal effect was seen in the spike length, grains spike^{-1}, and straw yield. Between the two varieties, the performance of BARI Gom-33 was better in terms of length of spike (13.89 cm), number of grains spike^{-1} (44.66), and straw yield (3.25 t ha^{-1}) of wheat. BARI Gom-27, on the other hand, generated 10.31 cm long spikes, 42.70 grains spike^{-1}, and 3.13 straw t ha^{-1}. (Table 4).

Interaction Effect

Variety and seed priming

With the exception of spikelets spike^{-1}, grains spikelet^{-1}, and harvest index, interaction between variety and seed priming had a substantial impact on all yield parameters and yield of wheat. Apart from the interaction between BARI Gom-27 and control, which exhibited reduced plant height (89.48 cm) of wheat, other interactions of variety and seed priming resulted in statistically identical plant height. BARI Gom-33 with KCL priming had the tallest plant (95.65 cm). When the seeds of BARI Gom-33 were primed with KCL, the maximum number of spikes m^{-2} (146.65) was generated which was statistically equivalent to other interactions except BARI Gom-27 with control which resulted in lower spikes m^{-2} (140.48). The BARI Gom-33 with control treatment had the longest spike (14.09 cm), which was statistically equal to the BARI Gom-33 with $CaCl_2$ priming (13.83 cm) and BARI Gom-33 with KCl priming (13.75 cm), but the BARI Gom-27 with $CaCl_2$ priming had the smallest spike (10.27 cm). Similar to this, BARI Gom-33 with KCL priming generated the most grains spike^{-1} (46.44), whereas BARI Gom-27 with control treatment produced the least (40.77). BARI Gom-33 with KCL priming also generated the maximum 1000-grain weight (40.66 g), whereas BARI Gom-27 with control treatment produced the minimum (36.70 g). Grain yield was found highest (2.72 t ha^{-1}) in BARI Gom-33 with KCL and all other interactions produced significantly similar grain yield of wheat except BARI Gom-27 with control treatment (2.14 t ha^{-1}) and BARI Gom-33 with control treatment (2.28 t ha^{-1}) (Figure 2). In the case of interaction between variety and seed priming except for BARI Gom-27 with control (2.93 t ha^{-1}), all other interactions produced a significantly similar straw yield and the highest was noticed in BARI Gom-33 with KCL priming (3.34 t ha^{-1}) (Table 5).

Variety and sowing date

Two varieties performed well irrespective of the sowing date in the situation of variety and sowing date interaction. Irrespective of varieties, the performance of the 30 December sowing was the worst. Tallest plant (96.38 cm), maximum number of spikes m^{-2} (147.38), spikelets spike^{-1} (16.47), grains spike^{-1} (49.00), 1000-grain weight (44.42 g), grain yield (2.46 t ha^{-1}), straw yield (3.60 t ha^{-1}), and harvest index (46.32 %) were documented in BARI Gom-33 when sown on 1 December (Figure 3, Table 6). All of these parameters were gradually decreased with the delay of sowing for both varieties. Though the spike length of BARI Gom-27 followed this trend spike length of BARI Gom-33 did not, where the highest spike length (14.04 cm) was obtained with BARI Gom-33 when sown on 15 December. Most of the parameters were found lowest in BARI Gom-27 sown on 30 December, but the lowest spike length was found in BARI Gom-33 sown on 30 December (Table 6).

Seed priming and sowing date

Length of spike and grains spikelets^{-1} were not significantly varied when seed priming and sowing date interacted with each other. The tallest plant (97.26 cm) and highest number of spikes m^{-2} (148.26) were noticed in $CaCl_2$ priming and 15 December sowing. A clear advantage of priming in increasing plant height and spikes m^{-2} was evident up to 15 December sowing, but not thereafter. The highest number of spikelets spike^{-1} (16.40), grains spike^{-1} (49.33), highest 1000-grain weight (44.95 g), and grain yield (3.16 t ha^{-1}) was observed in KCl priming and 1 December sowing (Figure 4, Table 7). Table 7 indicates that up to the 15 December sowing, the benefit of priming in improving these

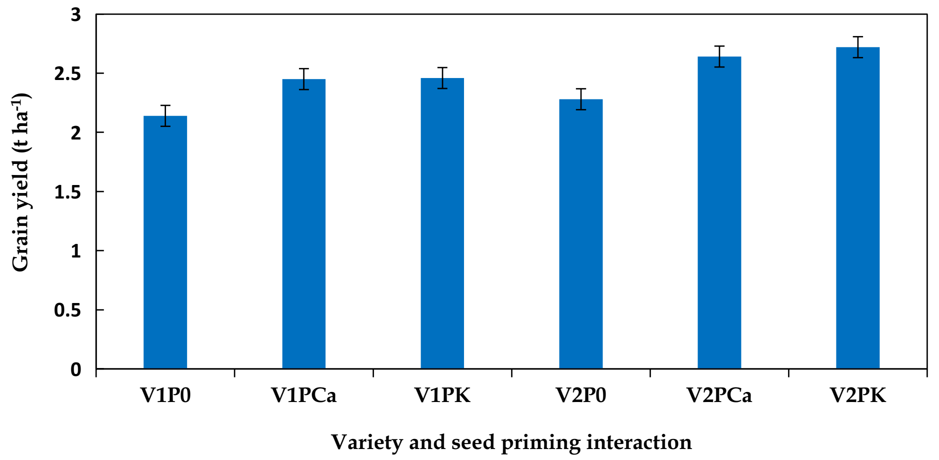

Figure 2.
Grain Yield of Wheat as Influenced by the Interaction Between Variety and Seed Priming. Bar Represents Standard Error of Means. Here, V_1 = BARI Gom-27, V_2 = BARI Gom-33; P_0 = No priming, P_{Ca} = $CaCl_2$ priming, P_k = KCl priming.

Table 5.
Interaction Effect of Variety and Seed Priming on Plant Characters, Yield Parameters, and Yield of Wheat

Variety × Seed Priming		Plant Height (cm)	Spikes m^{-2} (no.)	Spike Length (cm)	Spikelets $Spike^{-1}$ (no.)	Grains $Spike^{-1}$ (no.)	Grains $Spikelet^{-1}$ (no.)	1000-Grain Weight (g)	Straw Yield (t ha^{-1})	Harvest Index (%)
	No priming	89.48b	140.48b	10.34b	13.51	40.77b	3.05	36.70d	2.93b	41.82
BARI Gom-27	$CaCl_2$ priming	93.23ab	144.23ab	10.27b	14.61	44.00ab	3.02	38.18b–d	3.25ab	42.49
	KCl priming	93.96ab	144.96ab	10.36b	14.38	43.33ab	3.03	38.48bc	3.21ab	43.05
	No priming	90.57ab	141.57ab	14.09a	14.23	42.22ab	2.99	37.52cd	3.12ab	41.58
BARI Gom-33	$CaCl_2$ priming	95.12a	146.12a	13.83a	15.08	45.33ab	3.01	39.73ab	3.31a	43.86
	KCl priming	95.65a	146.65a	13.75a	15.27	46.44a	3.09	40.66a	3.34a	44.47
$S\bar{x}$		27.41	27.41	0.14	2.66	22.11	0.27	2.66	0.10	22.35
Level of significance		**	**	**	NS	**	NS	**	*	NS
CV (%)		4.2	2.7	5.0	9.9	6.5	9.5	3.0	9.9	4.3

Note: NS = Not significant.
Means with the same letters or without letters within the same column do not differ significantly.
**Significant at 1% level of probability.
*Significant at 5% level of probability.

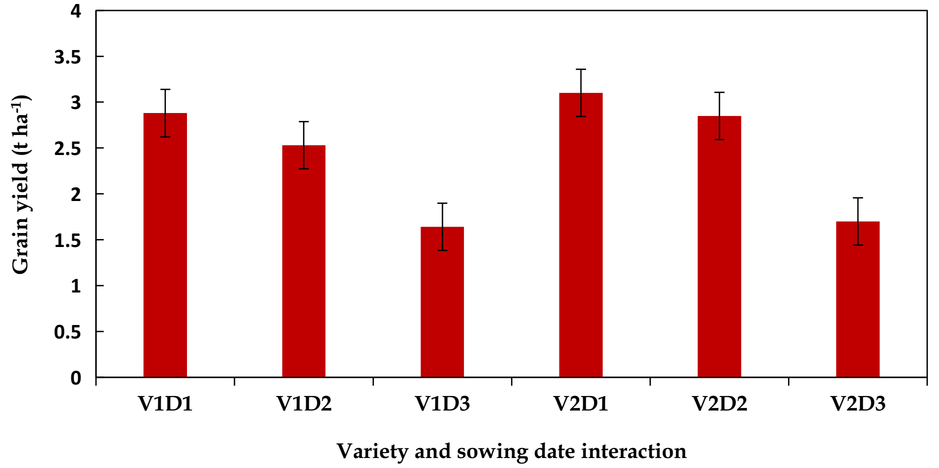

Figure 3.
Grain Yield of Wheat as Influenced by the Interaction Between Variety and Sowing Date. Bar Represents Standard Error of Means. Here, V_1 = BARI Gom-27, V_2 = BARI Gom-33, D_1 =01 December, D_2 =15 December, D_3 =30 December 2019.

Table 6.
Interaction Effect of Variety and Sowing Date on Plant Characters, Yield Parameters, and Yield of Wheat

Variety × Sowing Date		Plant Height (cm)	Spikes m^{-2} (no.)	Spike Length (cm)	Spikelets $Spike^{-1}$ (no.)	Grains $Spike^{-1}$ (no.)	Grains $Spikelet^{-1}$ (no.)	1000-Grain Weight (g)	Straw Yield (t ha^{-1})	Harvest Index (%)
	01 December	94.38ab	145.38ab	10.38b	15.22ab	46.33ab	3.05	42.63b	3.48ab	45.27a
BARI Gom-27	15 December	93.98ab	144.98ab	10.37b	14.42bc	43.66b	3.06	39.94c	3.21b	44.15a
	30 December	88.31c	139.31c	10.22b	12.86cd	38.11c	2.98	30.80d	2.70c	37.94b
	01 December	96.38a	147.38a	13.78a	16.47a	49.00a	2.99	44.42a	3.60a	46.32a
BARI Gom-33	15 December	95.66a	146.66a	14.04a	15.43ab	46.11ab	3.01	42.21b	3.44ab	45.31a
	30 December	89.30bc	140.30bc	13.84a	12.68d	38.88c	3.09	31.28d	2.73c	38.29b
$S\bar{x}$		27.41	27.41	0.14	2.66	22.11	0.27	2.66	0.10	22.35
Level of significance		**	**	**	**	**	NS	**	**	**
CV (%)		5.6	3.6	3.1	11.2	10.8	17.2	4.2	10.2	11.0

Note: NS = Not significant.
Means with the same letters or without letters within the same column do not differ significantly.
**Significant at 1% level of probability.

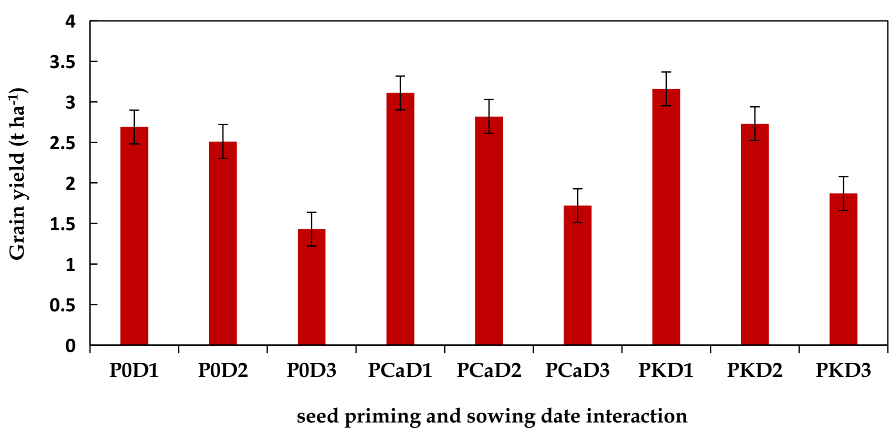

Figure 4.
Grain Yield of Wheat as Influenced by the Interaction Between Seed Priming and Sowing Date. Bar Represents Standard Error of Means. Here, P_{Ca} = $CaCl_2$ priming, P_{k} = KCl priming; D_1 = 01 December, D_2 = 15 December, D_3 = 30 December 2019, P_0 = No priming.

Table 7.
Interaction Effect of Seed Priming and Sowing Date on Plant Characters, Yield Parameters, and Yield of Wheat

Seed Priming × Sowing Date		Plant Height (cm)	Spikes m^{-2} (no.)	Spike Length (cm)	Spikelets $Spike^{-1}$ (no.)	Grains $Spike^{-1}$ (no.)	Grains $Spikelet^{-1}$ (no.)	1000-Grain Weight (g)	Straw Yield (t ha^{-1})	Harvest Index (%)
	01 December	93.38a–c	144.38a–c	12.14	14.90ab	45.00bc	3.03	41.51b	3.30ab	45.15ab
No priming	15 December	90.90b–d	141.90b–d	12.20	14.55a–c	44.00cd	3.07	40.30b	3.28ab	43.38b
	30 December	85.81d	136.81d	12.30	12.16d	35.50f	2.96	29.51d	2.50c	36.58d
	01 December	95.38a–c	146.38a–c	11.99	16.25a	48.66ab	3.01	44.11a	3.68a	45.76ab
$CaCl_2$ priming	15 December	97.26a	148.26a	12.12	15.51a	46.00a–c	2.96	41.43b	3.30ab	46.12a
	30 December	89.88cd	140.88cd	12.04	12.78cd	39.33e	3.07	31.33c	2.86bc	37.64d
	01 December	97.40a	148.40a	12.11	16.40a	49.33a	3.01	44.95a	3.65a	46.48a
KCl priming	15 December	96.31ab	147.31ab	12.29	14.71a–c	44.66bc	3.08	41.50b	3.40a	44.68ab
	30 December	90.71b–d	141.71b–d	11.76	13.38b–c	40.66de	3.09	32.28c	2.78c	40.12c
$S\bar{x}$		15.58	0.36	0.36	2.07	7.99	0.08	1.30	0.09	3.38
Level of significance		**	**	NS	**	**	NS	**	**	**
CV (%)		5.6	3.6	3.1	11.2	10.8	17.2	4.2	10.2	11.0

Note: NS = Not significant.
Means with the same letters or without letters within the same column do not differ significantly.
**Significant at 1% level of probability.

parameters was obvious. Interaction between $CaCl_2$ priming and 1 December sowing produced the highest straw yield (3.68 t ha^{-1}) and the maximum harvest index (46.12%) was recorded in $CaCl_2$ priming and 15 December sowing. All the parameters were found lowest in no priming and very late (30 December) sowing (Table 7).

Variety, seed priming, and sowing date

When variety, seed priming, and sowing date all interacted with each other they substantially impacted yield parameters and yield of wheat except grains $spikelet^{-1}$. Tallest plant (98.53 cm), number of spikes m^{-2} (149.53), spikelets $spike^{-1}$ (17.13), grains $spike^{-1}$ (51.33), 1000-grain weight (46.06 g), grain yield (3.28 t ha^{-1}), and harvest index (47.20 %) were recorded in BARI Gom-33, KCl priming and 1 December sowing (Figure 5, Table 8). The longest spike (14.36 cm) was registered with BARI Gom-33, no priming, and 30 December sowing, whereas the highest straw yield was documented in BARI Gom-33, $CaCl_2$ priming, and 1 December sowing. Most of the parameters were found lowest in BARI Gom-27, no priming, and 30 December sowing whereas the lowest spikelets $spike^{-1}$ and weight of 1000 grains were documented in BARI Gom-33, no priming, and 30 December sowing (Table 8).

Discussion

Throughout the life cycle, plants often experience a period of abiotic stress in their natural settings, which can affect their normal development and growth. Previous studies (Arun et al., 2022; Patanè et al., 2009; Wahid et al., 2008) have shown that priming seed is a previous exposure to a certain stress which provides plants better resistance to future stress. Therefore, it was proposed that seed treatment prior to sowing would aid in quicker and higher seed germination, improved survival, enhanced growth, and greater vigor in wheat seedlings. Compared to unprimed seeds, plants grown from primed seeds frequently develop more quickly (Anwar et al., 2021a).

The sowing dates in this study had a substantial impact on plant height. When the sowing date was delayed, plants' height dramatically fell. The shortened growth period in late sowings caused the plants' height to decline. It may be possible that early-sown crops benefited from improved climatic circumstances, particularly in terms of temperature and solar radiation, which led to the tallest plants. These results are consistent with Akram et al. (2007), who claimed that sowing dates significantly influenced plant height and also, they documented taller plants in early-sown rice than in late-sown rice. But in contrast to plants without priming, seed priming dramatically raised the height of wheat cultivars produced under the same conditions. In some crop species, seed priming significantly improved stand, establishment, and early vigor (Harris et al., 1999), which lead to accelerated growth and greater plant height. According to Farooq et al., (2011), primed seeds often produce more dry matter and grow plants with higher plant heights and root weights than untreated seeds. Additionally, Ali et al. (2013) provided evidence that several seed priming techniques increased the plant height of wheat. A further finding made by Anwar et al. (2012) was that the seed priming technique had a positive effect on the plant height of direct-seeded aerobic rice. The current study reveals the same results as earlier ones.

It was shown that high temperatures caused a significant drop in spikes m^{-2} and spikelets spike in late-sown wheat, which may have also decreased grains $spike^{-1}$, weight of 1000 grains, and grain yield. If seeds are sown too early, low temperature may impact germination, and if seeds are sown too late, high temperature may diminish crop output. Thus, it is essential to sow seeds at the proper time. If wheat is sown later, low temperatures that are common during late sowing will negatively affect the germination process of seed, emergence of seedling and seedling vigor that led to fewer spikes m^{-2} and ultimately reduces yield and harvest index. Impaired pollination and seed set (Farooq et al., 2011), a drop in the number of ear heads, and a reduction in the quantity of grains $spike^{-1}$ (Nawaz et al., 2013) may be related to the obvious deleterious consequences of high temperatures. The findings of the study reveal that seed priming increased the number of spikes m^{-2} and spikelets $spike^{-1}$. As demonstrated by several studies (Patanè et al., 2009; Wahid et al., 2008), seed priming gives plants a higher resistance to stress, As a result, it was anticipated that seed treatment before sowing may assist

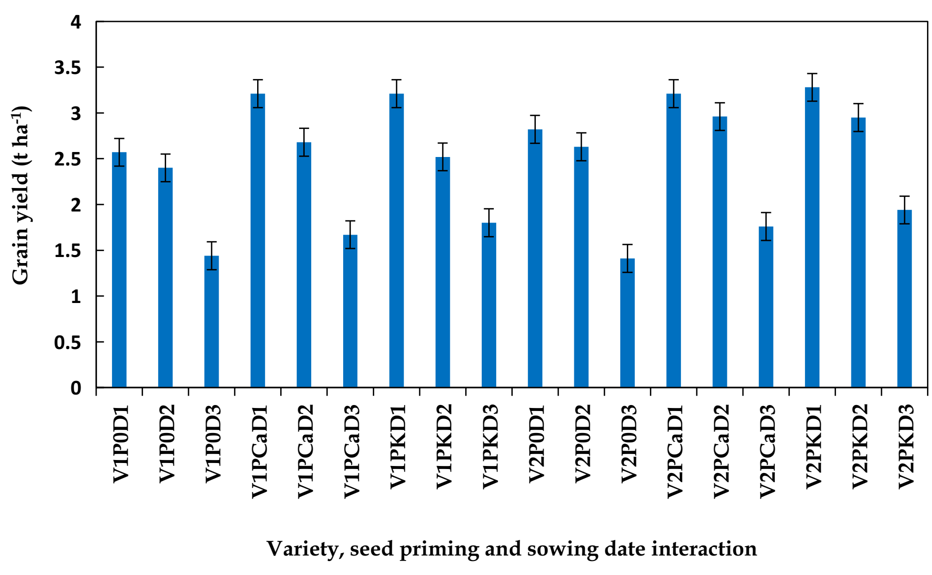

Figure 5.

Grain Yield of Wheat as Influenced by the Interaction Among Variety, Seed Priming, and Sowing Date. Bar Represents Standard Error of Means. Here, V_1 *= BARI Gom-27,* V_2 *= BARI Gom-33,* D_1 *=01 December,* D_2 *= 15 December,* D_3 *= 30 December 2019,* P_0 *= No priming,* P_{Ca} *=* $CaCl_2$ *priming,* P_k *= KCl priming.*

Table 8.
Interaction Effect of Variety, Seed Priming, and Sowing Date on Plant Characters, Yield Parameters, and Yield of Wheat

Variety × Seed Priming × Sowing Date			Plant Height (cm)	Spikes m^{-2} (no.)	Spike Length (cm)	Spikelets $Spike^{-1}$ (no.)	Grains $Spike^{-1}$ (no.)	Grains $Spikelet^{-1}$ (no.)	1000-Grain Weight (g)	Straw Yield (t ha^{-1})	Harvest Index (%)
		01 December	92.26a–c	143.26a–c	10.44c	15.06a–d	43.66a–e	3.08	41.00bc	3.20a–d	44.78a–c
	No priming	15 December	90.46a–c	141.46a–c	10.34c	14.03a–d	43.33a–e	3.12	39.10c	3.13a–e	43.44a–c
		30 December	85.73c	136.73c	10.24c	12.30cd	35.33e	2.95	30.00de	2.46f	37.25bc
		01 December	94.63a–c	145.63a–c	10.18c	15.80ab	48.00a–c	3.06	43.06ab	3.63a	45.28ab
BARI Gom-27	$CaCl_2$ priming	15 December	96.20ab	147.20ab	10.17c	15.13a–d	44.66a–d	2.95	40.83bc	3.23a–d	45.30ab
		30 December	88.86a–c	139.86a–c	10.51c	12.90b–d	39.33c–e	3.04	30.66de	2.90b–f	36.90bc
		01 December	96.26ab	147.26ab	10.51c	15.66ab	47.33a–c	3.02	43.83ab	3.63a	45.75ab
	KCl priming	15 December	95.30a–c	146.30a–c	10.61c	14.10a–d	43.00a–e	3.12	39.90c	3.26a–d	43.71a–c
		30 December	91.10a–c	141.33a–c	9.96c	13.40b–d	39.66c–e	2.95	31.73de	2.73d–f	39.68a–c
		01 December	94.50a–c	145.50a–c	13.84ab	15.60ab	46.33a–c	2.99	42.03bc	3.40a–c	45.52ab
	No priming	15 December	91.33a–c	142.33a–c	14.07ab	15.06a–d	44.66a–d	3.02	41.50bc	3.43a–c	43.32a–c
		30 December	85.90bc	136.90bc	14.36a	12.03d	35.66de	2.96	29.03e	2.53ef	35.91c
		01 December	96.13ab	147.20ab	13.80ab	16.70a	49.33ab	2.96	45.16a	3.73a	46.24ab
BARI Gom-33	$CaCl_2$ priming	15 December	98.33a	149.33a	14.07ab	15.90ab	47.33a–c	2.97	42.03bc	3.36a–d	46.94a
		30 December	90.90a–c	142.10a–c	13.62b	12.66b–d	39.33c–e	3.09	32.00de	2.83c–f	39.68a–c
		01 December	98.53a	149.53a	13.71ab	17.13a	51.33a	3.01	46.06a	3.66a	47.20a
	KCl priming	15 December	97.33a	149.33a	13.97ab	15.33a–c	46.33a–c	3.03	43.10ab	3.53ab	45.66ab
		30 December	97.33a–c	142.10a–c	13.55b	13.36b–d	41.66b–e	3.22	32.83d	2.83c–f	40.55a–c
$S\bar{x}$			27.41	27.41	0.14	2.66	22.11	0.27	2.66	0.10	22.35
Level of significance			**	**	**	**	**	NS	**	**	**
CV (%)			5.6	3.6	3.1	11.2	10.8	17.2	4.2	10.2	11.0

Note: NS = Not significant.
Means with the same letters or without letters within the same column do not differ significantly.
**Significant at 1% level of probability.

wheat seedlings combat various abiotic challenges under late-sown conditions (Mim et al., 2021).

In this study, seed priming increased the number of grains spike^{-1} and 1000-grain weight, which ultimately boosted yield. Under high-temperature stress, seed priming can boost the grain and straw yield of wheat. According to Farooq et al. (2008), in late-sown wheat, seed priming improved seed emergence, stand establishment, grain and straw yields, and the harvest index. Seed priming significantly enhanced grain output (17%) as compared to non-primed wheat seed Ramamurthy et al. (2015). Ali et al. (2013) also noted that various seed priming methods improved the number of viable tillers, the weight of one thousand grains, grain yield, and the biological yield of wheat. Higher grain output from primed seed may be the result of well-established, vigorous seedlings that acquire resources more quickly (Anwar et al., 2012; Harris et al., 1999; Mahajan et al. 2011). Additionally, Farooq et al. (2009a) claimed that the quick and controlled synthesis of emergent metabolites in primed seeds resulted in more robust and healthy seedlings that improved growth and increased yield. Anwar et al. (2012) stated that primed stands may produce more grain due to greater numbers of panicle-bearing tillers resulting from less seedling mortality. The stronger seedlings from primed seeds produced more grain because they were able to gather resources quicker and more successfully than seedlings from unprimed seeds (Farooq et al., 2009a).

In this study, the influence of wheat variety on spike length, grain spike^{-1}, and straw production was significant. Two varieties (BARI Gom-27 and BARI Gom-33) responded differently to different sowing dates and it was noticed that early-sown wheat performed well than late sown and this nature was observed in both varieties. Though BARI Gom-33 performed marginally better than BARI Gom-27, overall, the results show that both types performed almost equally well and the grain yield of these kinds steadily declines with the delaying of sowing. For all sowing dates, BARI Gom-27 and BARI Gom-33's grain yield increased, which is a definite benefit of seed priming. The purpose of seed priming was to speed up germination and shield the seed from environmental stress throughout the crucial stage of seedling growth in order to ensure consistent establishment and higher yields (Arun et al., 2021).

The priming agents employed in this experiment, KCl and $CaCl_2$, performed nearly similarly. However, there were other instances when KCl priming outperformed $CaCl_2$ priming only marginally. Farooq et al. (2006b) found that increasing rice yield under dry direct sowing conditions looked to be possible with KCl and $CaCl_2$ priming. According to Toklu et al. (2015), in contrast to the control, PEG, KCl, and hydro-priming treatments increased wheat grain output. Suryakant et al. (2000) reported that the priming treatment with IAA, KCl, water, and $ZnSO_4$ followed by sowing of sprouted produced the highest grain, straw, and biological yields of wheat, whereas the dry seed sowing method produced the lowest yields. Anwar et al. (2012) also determined that the best way to promote seed germination and seedling vigor was to prime seeds with KCl or $CaCl_2$. According to Anwar et al. (2021a), winter rice can be benefitted from priming with KCl or $CaCl_2$ (20,000 ppm) to increase seed germination, seedling growth, and seedling survival when exposed to cold stress.

Conclusions and Recommendation

Finally, current research supports that both of the varieties performed fairly similar and grain yield decreases gradually with the delay of sowing due to temperature stress. At all planting dates, boosting grain yield was demonstrated to be a definite benefit of seed priming. Therefore, it is recommended to sow wheat by 15 November following seed priming and in case of delay sowing seed priming is a must to mitigate the temperature stress to some extent. With the intention of opening up new possibilities for improving seed priming to reduce heat stress in late-sown wheat, particularly at the reproductive stage, KCl and $CaCl_2$ emerged as the best priming agents. Consequently, it can be asserted that seed priming is a viable technique for at least somewhat lowering the effect of temperature stress in the event of a delay. But more investigations should be done throughout the world to strengthen this recommendation.

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How Does the Change in Feed Prices Affect Meat Prices? A Case Study of Turkey

Yem Fiyatlarındaki Değişim Et Fiyatlarını Nasıl Etkiler? Türkiye Örneği

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ABSTRACT

This study aims to understand the relationship between meat and meat product prices and feed prices. For this purpose, causality and long-run relationship between variables are examined using the Granger causality test and autoregressive distributed lag model approaches. The data of the study is formed from the Meat Consumer Price Index and Feed Price Index shared by the Turkish Statistical Institute. The data set is composed of 70 observations covering the period from January 2016 to October 2021. The results of the Granger causality test show that the Feed Price Index is the Granger cause of the Meat Consumer Price Index. According to the long-run estimation results of the autoregressive distributed lag model, a 1% increase in the Feed Price Index increases the Meat Consumer Price Index by 0.97%. It is estimated that the deviations from the long-run equilibrium will be adjusted in approximately 4 months. Considering the results of the study showing that the prices of meat and meat products are significantly affected by feed prices, it can be concluded that the subsidies to the feed crops and feed industry has the potential to impact meat prices positively.

Keywords: ARDL model, Consumer Price Index, feed prices, Granger causality test, meat prices

ÖZ

Bu çalışma, et ve et ürünleri fiyatları ile yem fiyatları arasındaki ilişkiyi anlamayı amaçlamaktadır. Bu amaçla değişkenler arasındaki nedensellik ve uzun dönem ilişkileri Granger nedensellik testi ve ARDL modeli yaklaşımları kullanılarak incelenmiştir. Çalışmanın verileri, Türkiye İstatistik Kurumu tarafından paylaşılan Et Tüketici Fiyat Endeksi (MCPI) ve Yem Fiyat Endeksi'nden (FPI) oluşturulmuştur. Veri seti, Ocak 2016 ile Ekim 2021 arasındaki dönemi kapsayan 70 gözlemden oluşmaktadır. Granger nedensellik testi sonuçları, FPI'nin MCPI'nin Granger nedeni olduğunu göstermektedir. Otoregresif Dağıtılmış Gecikme (ARDL) modelinin uzun dönemli tahmin sonuçlarına göre, FPI'deki %1'lik bir artış MCPI'yi %0,97 artırmaktadır. Yaklaşık 4 ayda kısa dönemdeki sapmaların düzeleceği ve sistemin uzun dönem dengesine yakınsayacağı tahmin edilmektedir. Et ve et ürünleri fiyatlarının yem fiyatlarından önemli ölçüde etkilendiğini gösteren çalışmanın sonuçları dikkate alındığında, yem bitkileri ve yem sanayine yönelik teşviklerin et fiyatlarını olumlu yönde etkileme potansiyeline sahip olduğu ifade edilebilir.

Anahtar Kelimeler: ARDL modeli, Tüketici Fiyat Endeksi, yem fiyatları, Granger nedensellik testi, et fiyatları

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Introduction

Animal feed has a high importance in terms of animal husbandry as it constitutes a significant part of the variable costs in production activities (Albez, 2018; Tandoğan & Çiçek, 2016). Turkey, whose meat consumption is increasing every year due to the increasing population and changing consumption habits, is not at the desired level in feed production, which is the main input of production activity. According to Organisation for Economic Co-operation and Development (OECD) (OECD, 2021), meat consumption in Turkey was 1566.5 thousand tons in the 2000s, reaching 2859.6 in the 2010s with an increase of 82.55% compared to the previous period. Although there are substantial increases in feed crop production and compound feed production in the same period, it can be stated that there are many problems that need to be overcome considering the fact that 45%–50% of the mixed feeds produced depend on imported feed raw materials; unlike the developed countries, the use of compound feed in livestock is 60% on a dry matter basis in the livestock sector and the current roughage production in Turkey cannot meet the total need in this regard (Özkan & Şahin Demirbağ, 2016; TÜRKİYEM-BİR, 2019).

As the need for feed cannot be met in the market, the increases in feed prices cause an increase in meat prices which affects the consumer negatively, while this situation triggers meat imports and affects the producer negatively. Although the increments in feed prices significantly increase the expenses of the producers, the fact that the producer sales prices do not increase significantly prevents the producers from making investments to improve the product quality and production capacity. In this respect, it can be stated that the increase in feed prices has the potential to pose a threat to food security in meat. Due to the critical impact that feeds can have on meat prices, meat consumption, and the livestock sector, it is possible to come across many studies examining the relationship between meat consumption and/or meat prices and feed production/feed prices.

For instance, Arıkan et al. (2019) examined the relationship between broiler meat prices and broiler feed prices in Turkey. They found that there was a cointegration relationship between variables. Mat et al. (2020) analyzed the causality relationship between the red meat consumer price in Turkey and the factors that affect it. They ascertained that the prices of fattening feed are the Granger cause of red meat consumer prices and carcass red meat prices. Yalçınkaya and Aktaş (2019) investigated the effect of the abolition of Value-Added Tax (VAT) on animal feed prices and meat prices, which has been implemented since 2016, through the Granger causality test and Johansen cointegration analysis. They reported that the VAT exemption applied to animal feed did not statistically affect meat prices. In a study examining whether there is a cointegration relationship between beef consumption in Turkey and beef price, chicken meat price, and per capita income (Erdoğdu & Çiçek, 2017), it is stated that increases in beef prices, in the long run, will affect consumption negatively following with the economic theory. It has been concluded that the increases in chicken meat prices will affect consumption positively. Özer (2013) examined the factors affecting beef carcass meat prices in Turkey with the autoregressive distributed lag (ARDL) approach. The results show that cattle feed prices have a positive and statistically significant effect in the short and long run. Musunuru (2017), investigating the relationships between grain prices, meat prices, and exchange rates in the USA, used the Johansen cointegration test, the Granger causality test, and Vector autoregression (VAR) analysis. While the results of the Johansen cointegration test revealed no long-run relationship between the variables, the results of the Granger causality test showed a feedback relationship between corn prices and lean hog prices, and live cattle prices were the Granger cause of corn prices. Arıkan et al. (2022) analyzed the factors affecting broiler chicken prices using the boosting regression method. They found that their prices are affected by raw material prices of feed as well as economic conditions in Turkey. A general evaluation of the literature suggests that, as expected, numerous empirical findings support the significant impact of feed prices on meat prices. Therefore, studies that address the possible effects of feed prices on meat prices from different perspectives and provide a better understanding are particularly important.

This study aims to understand the relationship between meat prices and feed prices. For this purpose, the causality relationship and long-run relationship between the Meat Consumer Price Index (MCPI) and the Feed Price Index (FPI) are examined with the Granger causality test and the ARDL model. The primary motivation for using indexes instead of direct product prices in the study is to perform a comprehensive analysis by understanding the effects of developments in feed prices on meat and meat products rather than revealing the relationship between feed prices only with carcass meat or some meat products. The MCPI shared by the Turkish Statistical Institute (TURKSTAT) (2022), based on 2015 (2015 = 100), increased by 230.50% in October 2021. This price increment makes it more difficult to access animal products, which are already not accessible enough for all segments of society (Akın et al., 2020). It is thought that the results of the study can be used by decision-makers to develop policies to prevent price increases by explaining the relationship between feed prices and meat prices. In addition, the results of the study can be used to make long-run investment planning for the livestock sector and the sectors that provide input to the livestock sector.

Methods

The main materials of the study are the MCPI which is among the sub-headings of the Consumer Price Index (CPI), and the FPI, which is one of the sub-headings of the Agricultural Input Price Index (AIPI) shared by TURKSTAT. The data set consists of monthly data and covers the period from January 2016 to October 2021. When the TURKSTAT database is scanned, it is seen that 2003 (2003 = 100) is accepted as the base year for the CPI and the index starts from January 2003, while the AIPI starts from January 2016 based on the year 2015 (2015 = 100). In order to standardize the CPI and AIPI data, the CPI data are recalculated based on 2015 (2015 = 100). For the variables used in the study, first, logarithmic transformation was applied, and then seasonal adjustment was made with the moving average (additive) technique.

The MCPI constitutes 5.19% of the item weight in the general CPI and includes the items in Table 1. The FPI, on the other hand, has the subheadings of roughage and concentrated feed.

Descriptive statistics for MCPI and FPI are given in Table 2. The MCPI and FPI data for the January 2016 and October 2021 periods are given in Figure 1.

To estimate the effect of FPI on MCPI, the equation presented below is formed.

$$lnMCPI = \beta_0 + \beta_1 lnFPI + \varepsilon_t \quad (1)$$

It is expected that FPI will have a positive and statistically significant impact on MCPI, taking into account the fact that feed expenditures are among the main expense items in livestock and the results obtained from previous studies.

The study uses the ARDL model to examine the long-run relationship between MCPI and animal feed prices. Thanks to the ARDL model proposed by Peseran et al. (2001), if the variables are I(0) or I(1), the long-run relationship between the variables can

Table 1.
Weights for Items of MCPI

Item Name*	Weight in CPI (%)	Weight in Food and Non-alcoholic Beverages CPI (%)	Weight in MCPI (%)
Veal	2.15	8.50	41.48
Lamb	0.91	3.61	17.64
Poultry	1.40	5.54	27.04
Offal	0.06	0.23	1.11
Garlic-flavored sausage (Sucuk)	0.43	1.70	8.28
Sausage	0.05	0.19	0.91
Salami	0.08	0.33	1.60
Prepared meat dishes	0.10	0.40	1.95
Total	5.19	20.49	100.00

Source: TURKSTAT, 2022; Original Calculations.
CPI = Consumer Price Index; MCPI = Meat Consumer Price Index.
*The items specified for the MCPI and the weights of these items may change over time. For example, the first data shared for Prepared Meat Dishes in the TURKSTAT database is based on 2019M01.

Table 2.
Descriptive Statistics

Variables	Mean	Standard Deviation	Maximum	Minimum
MCPI	151.0500	36.18147	231.9200	105.4000
FPI	144.8291	36.54755	230.4600	102.8800

Source: TURKSTAT, 2022; Original Calculations. Period: 2016MM01–2021M10.
FPI = Feed Price Index; MCPI = Meat Consumer Price Index.

be examined. Another important advantage of the ARDL model is that this technique is more robust for small sample sizes (Narayan, 2004).

There are a number of steps that must be followed before making long-run and short-run (error correction model (ECM) estimations with the ARDL model. One of the first steps is to determine the order of integration for the series to be included in the model. Although the ARDL model can provide robust results for I(0) and I(1), this is not the case for I(2) and higher order of integration. Another critical step is to decide on the appropriate lag length and conditional ECM for ARDL(p,q) model dependent variable and its regressors. Akaike Information Criteria (AIC), Schwarz criterion (SC), or Hannan–Quinn criterion are generally used when determining the appropriate lag length. For the estimation results of the selected model to be acceptable, there should be no serial correlation, heteroscedasticity, specification error, or normality problems in the relevant model, and attention should be paid to the stability of parameter estimations (Mert & Çağlar, 2019).

The representation of ARDL with a constant term and no trend variable can be formulated as follows:

$$LnMCPI_t = \beta_0 + \sum_{i=1}^{p} \beta_{1i} lnMCPI_{t-i} + \sum_{i=0}^{q} \beta_{2i} lnFPI_{t-i} + \varepsilon_t \quad (2)$$

where p represents the optimal lag order for the MCPI variable, q is the optimal lag order for the FPE variable, and β_0 represents the constant term.

Pesaran et al. (2001) proposed five different conditional ECMs for cointegration analysis with the ARDL approach. Case 1 is recommended for special cases such as both the dependent and independent variables fluctuate around the zero mean, whereas case 2 is a more reliable option when some variables have a nonzero

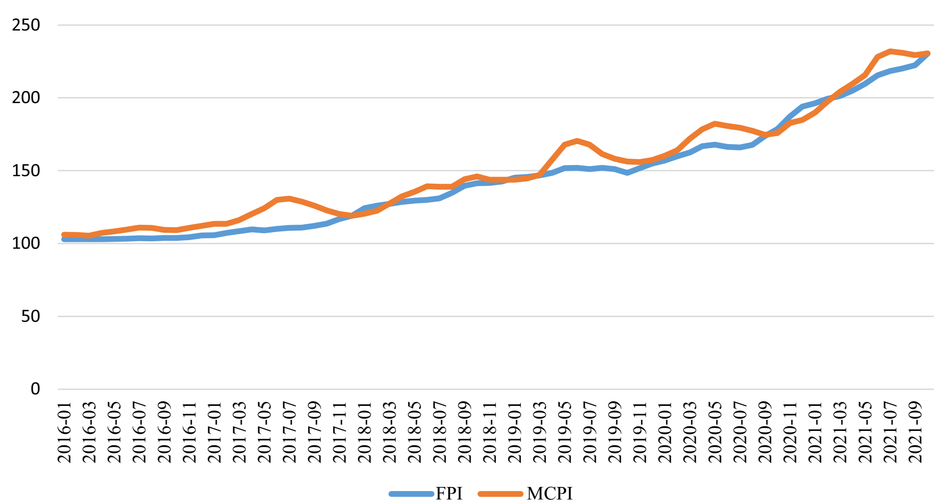

Figure 1.
Meat Consumer Price Index and Feed Price Index for January 2016–October 2021 Periods (2015 = 100).

mean (Kripfganz & Schneider, 2018). Cases 4 and 5 contain a trend, and no significant results were obtained for the trend variable in the preliminary examination made for the model developed. For this reason, case 3, which has common use in the literature (Kripfganz & Schneider, 2018; Mert & Çağlar, 2019), is preferred. The model can be formulated with the variables used in the study as follows;

$$\Delta lnMCPI = \beta_0 + \sum_{i=1}^{p} \beta_{1i} \Delta lnMCPI_{t-i} + \sum_{i=0}^{q} \beta_{2i} \Delta lnFPI_{t-i} + \beta_3 lnMCPI_{t-1} + \beta_4 lnFPI_{t-1} + \varepsilon_t \tag{3}$$

where, Δ represents the operator of the first difference. The existence of a long-run relationship between the variables is tested with the bounds test. In this test, the null hypothesis (H0 = β_3 = β_4 = 0) stating that there is no cointegration relationship is against the alternative hypothesis (H1 ≠ $\beta_3 \neq \beta_4 \neq$ 0) (Bölük & Mert, 2015). The existence of cointegration can be accepted if the calculated F-statistics values are above the upper critical bounds determined for I(0) and I(1). There are alternative critical values for I(0) and I(1) in the literature. It is recommended to perform the test by selecting the most appropriate critical values according to the sample size. Due to this study's relatively small sample size, critical values calculated by Narayan (2005) are used.

After examining the estimation results for the long run, the ECM estimation is used to understand whether the deviations from the short-run equilibrium can be compensated. The ECM, which is also defined as short-run estimation, can be formulated as follows:

$$\Delta lnMCPI_t = \delta_0 + \sum_{i=1}^{p} \delta_1 \Delta lnMCPI_{t-i} + \sum_{i=0}^{q} \delta_2 \Delta lnFPI_{t-i} + \omega ECT_{t-1} + \varepsilon_t \tag{4}$$

Here, *ECT* represents the error correction term and ω is the speed of adjustment parameter. Suppose the coefficient is negative and statistically significant. In that case, it indicates a deviation from the long-run equilibrium due to many reasons, such as an increase in energy prices or import/export restrictions, will be corrected.

After examining the long-run relationships in the study, the causality relationship between the variables is examined with the Granger causality test developed by Granger (1969). According to this approach, when estimating an X_t variable, if a better result is obtained by using all the available information than when using the information except the information that the Y_t variable has, it is stated that the Y_t variable causes the X_t variable (Granger, 1969; 1980). The Granger causality model formed for the study can be expressed with the following equation on the condition that the variables are stationary in the first-order difference:

$$\Delta lnMCPI_t = \sum_{i=1}^{p} \alpha_i \Delta lnMCPI_{t-i} + \sum_{i=1}^{p} \beta_i \Delta lnFPI_{t-i} + \varepsilon_t \tag{5}$$

$$\Delta lnFPI_t = \sum_{i=1}^{p} \alpha_i \Delta lnFPI_{t-i} + \sum_{i=1}^{p} \beta_i \Delta lnMCPI_{t-i} + \varepsilon_t \tag{6}$$

Here, *i* is the number of lags and is usually determined by information criteria such as AIC and SC. Rejection of the generated $\beta_1 = \beta_2 = ... = \beta_i = 0$ hypothesis; for Equation 5, it means that FPI is the Granger cause of MCPI, while for Equation 6, it means that MCPI is the Granger cause of FPI. When both of these situations are valid, it can be stated that there is feedback (Granger, 1969).

Results

Unit Root Tests

Stationarity analysis is essential for the methods planned to be applied for the series in this study. While the Granger causality test requires stationary variables, determining the order of

Table 3.
ADF and PP Unit Root Test Results for Series

Variables	ADF Unit Root Test Results (Constant)		PP Unit Root Test Results (Constant)	
	Test Critical Values	ADF Test Statistics	Test Critical Values	PP Test Statistics
lnMCPI	1% (−3.531592)	1.189280	1% (−3.528515)	1.497722
	5% (−2.905519)		5% (−2.904198)	
	10% (−2.590262)		10% (−2.589562)	
D(lnMCPI)	1% (−3.531592)	−5.882170*	1% (−3.530030)	−4.304283*
	5% (−2.905519)		5% (−2.904848)	
	10% (−2.590262)		10% (−2.589907)	
LNFPI	1% (−3.530030)	1.966187	1% (−3.528515)	3.423265
	5% (−2.904848)		5% (−2.904198)	
	10% (−2.589907)		10% (−2.589562)	
D(lnFPI)	1% (−3.530030)	−4.527846*	1% (−3.530030)	−4.376264*
	5% (−2.904848)		5% (−2.904848)	
	10% (−2.589907)		10% (−2.589907)	

ADF = augmented Dickey–Fuller; FPI = Feed Price Index; MCPI = Meat Consumer Price Index; PP = Phillips–Perron.
ADF and PP test statistics values; *if $p < .01$.

integration for the variables is necessary for the ARDL model. For this reason, unit root tests are performed. Augmented Dickey–Fuller and Phillips–Perron unit root tests, which are widely preferred as unit root tests, are chosen (Table 3).

When the unit root test results in Table 3 are examined, it is seen that both series are stationary at first difference. For this reason, the first-order difference series is used for the Granger causality test. Since both variables are stationary in I(0) or I(1), it can be stated that there is no obstacle for the ARDL model in terms of stationarity.

Autoregressive Distributed Lag Model

After the stationarity test, the ARDL model is estimated. The maximum lag length is determined as 12, and AIC is used to select the most appropriate lag length. Estimation results and diagnostic tests are shown in Table 4.

When the estimation results in Table 4 are examined, the appropriate lag length for the MCPI is 2 and the appropriate lag length for the FPI is 6. While the adjusted R^2 value of the model is calculated as 0.99, the *F*-statistic value is statistically significant at the 1% significance level. When the diagnostic tests are reviewed, it is determined that the model does not have heteroscedasticity, model specification, normality, and serial correlation problems.

In order to test the stability of parameters, the CUSUM and CUSUM of squares graphs in Figure 2 are examined.

Since the plots remain within the critical bounds for both CUSUM and CUSUM of squares, it can be stated that the parameter estimations meet the stability condition.

After obtaining the estimation results and performing the diagnostic tests, the bounds test is performed to test whether there is a cointegration relationship between the series. Bounds test results and the long-run estimation results are given in Table 5.

In Table 5, the *F*-statistic value is calculated as 11.15, which is above the upper critical values at all significance levels. Therefore,

Table 4.
ARDL(2,6) Model Estimation Output and Diagnostic Tests

Variable	Coefficient	Standard Error	*t*-Statistic
lnMCPI (-1)	1.163130	.110208	10.55393*
lnMCPI (-2)	−0.419519	.104940	−3.997704*
lnFPI	0.430594	.144179	2.986532*
LNFPI(-1)	−0.351851	.267661	−1.314543
LNFPI(-2)	−0.004547	.292940	−0.015522
LNFPI(-3)	0.087795	.294681	0.297934
LNFPI(-4)	0.121176	.293157	0.413349
LNFPI(-5)	−0.497551	.280256	−1.775343**
LNFPI(-6)	0.463039	.161307	2.870537*
C	0.061915	.042359	1.461671
Adj R^2	.99	*F*-Statistic	2514.422 (p = .00)
Residual Diagnostics			
Heteroscedasticity Test: Breusch-Pagan-Godfrey		F = 1.09	p = .38
Ramsey RESET Test (Number of fitted terms = 1)		F = 0.99	p = .32
Normality Test (Jarque-Bera)		JB = 1.01	p = .60
Breusch-Godfrey Serial Correlation LM Test		*F*-stat = 0.86	p = .59

ARDL = autoregressive distributed lag; FPI = Feed Price Index; MCPI = Meat Consumer Price Index.
t-Statistics values; *if $p < .01$, **if $.01 < p < .10$.

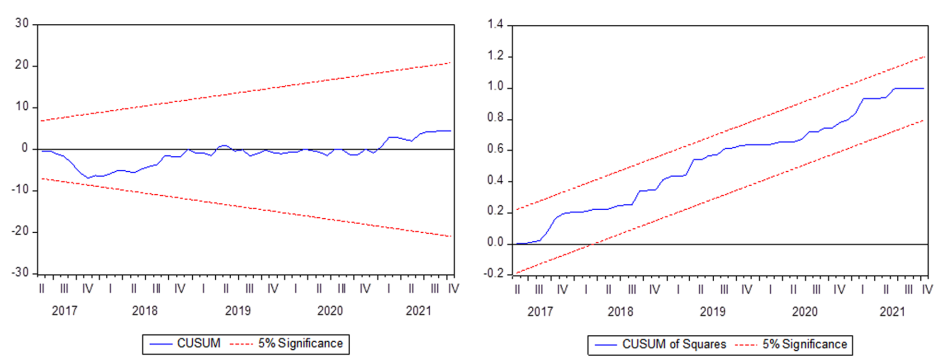

Figure 2.
CUSUM and CUSUM of Squares Graphs for Autoregressive Distributed Lag(2,6) Model.

Table 5.
F-Bounds Test and Estimation Results for Long-Run

***F*-Bounds Test**			
***F*-Statistic Value**	**Significance Level**	**I(0)[#]**	**I(1)[#]**
11.14656	10%	4.175	4.93
	5%	5.13	5.98
	1%	7.32	8.435
Estimation Results for Long-Run			
Variable	Coefficient	Standard Error	*t*-Statistic
LNFPI	0.969832	.032492	29.84801*

FPI = Feed Price Index.
t-Statistics values; *if $p < .01$.
[#]Critical values (for $n = 65$) generated by Narayan (2005) are used.

the H0 (no cointegration) hypothesis is rejected and it is concluded that there is a cointegration relationship between the series.

After examining the bounds test results, long-run estimations are evaluated. The estimation results presented in Table 5 reveal that the results obtained for the FPI are statistically significant at the 1% significance level. According to the results, in the long run, a 1% increase in the FPI increases the MCPI by 0.97%.

The estimation results of the ECM showing the short-run relationships between the variables are given in Table 6. Since the *p*-value obtained for the CointEq(-1) variable is not incompatible with the t-Bounds distribution, the t-Bounds test is performed.

When the results shared in Table 6 are examined, it is seen that the error correction coefficient is negative and statistically significant at the 1% significance level according to the ECM. In line

Table 6.
Short-Run Estimation Results (Error Correction Model) and t-Bounds Test

Variable	**Coefficient**	**Standard Error**	***t*-Statistic**
C	.061915	.012329	5.021724*
D(lnMCPI(-1))	.419519	.103926	4.036726*
D(lnFPI)	.430594	.137152	3.139534*
D(lnFPI(-1))	–.169912	.179060	–0.948915
D(lnFPI(-2))	–.174459	.173008	–1.008389
D(lnFPI(-3))	–.086664	.169561	–0.511109
D(lnFPI(-4))	.034512	.168543	0.204768
D(lnFPI(-5))	–.463039	.153806	–3.010539*
CointEq(-1)#	–.256389	.053806	–4.765077*
t-Bounds Test			
Test statistic value	Significance level	I(0)	I(1)
–4.765077	10%	–2.57	–2.91
	5%	–2.86	–3.22
	2.5%	–3.13	–3.5
	1%	–3.43	–3.82

FPI = Feed Price Index; MCPI = Meat Consumer Price Index.
t-Test statistics values; *if $p < .01$.
[#]*p*-Value incompatible with t-Bounds distribution.

Table 7.
Results of the Granger Causality Test

Null Hypothesis	***F*-Statistics**	**Probability**
D(lnFPI) does not Granger Cause D(lnMCPI)	3.66737	.0599
D(lnMCPI) does not Granger Cause D(lnFPI)	0.06914	.7934

FPI = Feed Price Index; MCPI = Meat Consumer Price Index.

with the results, it can be stated that the deviations from the long-run equilibrium will be adjusted in approximately 4 months (1/0.256389 = 3.90).

Granger Causality Test

The Granger causality test results for the models presented in Equations 5 and 6 are in Table 7. Considering the SC criterion, the test is performed at the first lag for both variables.

The results showed that the FPI is the Granger cause of the MCPI at the 10% significance level, whereas the MCPI is not the Granger cause of the FPI. While the results support the hypothesis that feed prices affect meat prices, they reveal no feedback process between the variables.

Discussion

This study investigates the relationship between FPI and MCPI using econometric methods. The ARDL model estimated for this purpose shows that the FPI has a statistically significant effect on the MCPI in the long run. When the literature is examined, it is seen that there is a cointegration relationship between feed prices and meat prices in previous studies conducted for Turkey, similar to this study. Arıkan et al. (2019) reached a cointegration relationship between broiler feed prices and broiler meat prices, while Çoban et al. (2019) found a cointegration relationship between corn prices and wholesale beef prices. Although cointegration relations have been determined for various feed materials and meats, no study has been found that investigates the effect of feed prices on meat and meat product prices for Turkey from a general perspective.

The long-run elasticity of FPI is very close to the unit elasticity, but it is inelastic (0.97). In a recent study examining the long-run effect of the AIPI on the FCPI (Food and Non-alcoholic Beverages Price Index, the agricultural input price elasticity was calculated in the range of 1.30–1.36 (Işık & Özbuğday, 2021). The dissimilarity of these results may be related to the differences between the datasets used for the studies. Further studies examining the effect of agricultural input prices on food consumer prices will contribute to a better understanding of the relationships between the variables.

While the Granger causality test shows that the FPI is the Granger cause of the MCPI, it is determined that the MCPI is not the Granger cause of the FPI, that is, there is no feedback relationship between the variables. The results obtained are consistent with the previous study for Turkey since the direction of causality is from feed price to meat price (Mat et al., 2020). When the studies conducted in the USA on this subject are examined, it has been found that meat prices are the Granger cause of grain prices used as feed, and there is a feedback relationship between these types of variables (Musunuru, 2017; Pozo & Schroeder, 2012). The one-way Granger causality relationship obtained in the Turkish example can be associated with the high rate of input imports in the feed market in Turkey. It is quite possible that the FPI will be affected by the world price of the imported goods rather than the supply–demand mechanism in the country because of imports for feedstuffs. However, the differences observed between the two markets can also be explained by the fact that the data used in other studies (Musunuru, 2017; Pozo & Schroeder, 2012) are futures prices, and the data used in this study are MCPI prepared based on consumer prices. Therefore, more studies are needed to understand the effect of meat prices on feed prices in Turkey.

Conclusion and Recommendations

When the results are evaluated in general terms, it can be stated that feed prices have a significant effect on meat prices. Therefore, policies that prevent increases in feed prices are very important in preventing increases in meat consumer prices. Considering the studies predicting red meat consumption and poultry meat consumption would increase significantly in the coming years (OECD, 2021; Özen, 2019), the feed crop production and feed industry should be supported effectively. In this context, policies should be implemented to ensure stability in diesel and fertilizer prices, which constitute a significant part of the input costs in feed crop production. In addition, reducing the import of red meat and butchery animals is beneficial, which is another problem that negatively affects the producer. However, considering that the demand for meat will increase and it will take time to solve the structural problems in the livestock sector, it makes sense to reduce imports within time so that consumers are not adversely affected by this situation.

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Growing Forage Pea (*Pisum arvense* L.) for Hay: Different Sowing Dates and Plant Densities in Central Anatolia

Kaba Yem Amaçlı Yem Bezelyesi (*Pisum arvense* L.) Yetiştiriciliği: İç Anadolu'da Farklı Ekim Zamanları ve Bitki Sıklıkları

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ABSTRACT

The study was carried out to determine the effects of different sowing times (October and November) and plant densities (80, 100, and 120 seeds m^{-2}) on hay yield and quality of some forage pea cultivars (Özkaynak and Taşkent) in 2018 and 2019 years of Eskisehir ecological conditions. The experiment was established in Randomized Complete Block Design with three replications. Hay yield, crude protein, neutral detergent fiber, acid detergent fiber, and acid detergent lignin contents were investigated. Hay yield, acid detergent fiber, and acid detergent lignin contents were higher in 2018 (5139.2 kg ha^{-1}, 31.76%, and 8.02%, respectively) but crude protein (13.89–14.44%) and neutral detergent fiber (37.52–37.77%) contents did not change significantly between the years. Cultivars and plant densities did not cause any significant variation on the examined characteristics but late autumn sowing caused a 1.51% increase in crude protein content, which was significant. Neither late autumn sowing nor different plant densities caused any negative effects on hay yield and quality of forage peas. Therefore, forage peas could be sown in both October and November using any of the Özkaynak or Taşkent cultivars at 80 seeds m^{-2} plant density in Central Anatolia conditions.

Keywords: Forage pea, hay quality, hay yield, plant density, sowing date

ÖZ

Bu çalışma, bazı yem bezelyesi çeşitlerinde (Özkaynak ve Taşkent) farklı ekim zamanları (Ekim, Kasım) ve bitki sıklıklarının (80, 100, 120 tohum m^{-2}) kuru ot verimi ve kalitesine etkilerini belirlemek amacıyla 2018 ve 2019 yıllarında Eskişehir ekolojik koşullarında yürütülmüştür. Deneme Tesadüf Blokları Deneme Desenine göre üç tekrarlamalı olarak kurulmuştur. Çalışmada kuru ot verimi, ham protein (HP), nötr deterjan lif (NDF), asit deterjan lif (ADF) ve asit deterjan lignin (ADL) oranları incelenmiştir. Kuru ot verimi, ADF ve ADL oranları (sırasıyla 5139,2 kg ha^{-1}, %31,76 ve %8,02) 2018'de daha yüksek olurken, HP (%13,89–%14,44) ve NDF (%37,52–%37,77) oranları yıllar arasında önemli bir değişiklik göstermemiştir. Çeşitler ve ekim sıklığı arasında incelenen özellikler yönünden önemli bir farklılığın olmadığı, ancak geç sonbahar ekiminin HP içeriğinde %1,51'lik bir artışa neden olduğu belirlenmiştir. Güzlük ekim ve farklı bitki sıklıklarının yem bezelyesinin kuru ot verimi ve kalitesi üzerinde herhangi bir olumsuz etkisi olmamıştır. Bu nedenle, İç Anadolu koşullarında Özkaynak veya Taşkent yem bezelyesi çeşitlerinin Ekim-Kasım aylarında ve 80 tohum m^{-2} kullanılarak ekilmesi önerilmektedir.

Anahtar Kelimeler: Yem bezelyesi, yem kalitesi, kaba yem verimi, bitki sıklığı, ekim zamanı

Introduction

Forage pea (*Pisum sativum* ssp. *arvense* L.) is an important cool-season leguminous forage species grown for grain or hay production in temperate climate zone. In addition to the main cropping in cool areas, the plant could be grown as an intermediate crop (Kaplan & Gökkuş, 2018) or second crop (Ileri et al., 2018) in temperate climate zone like Central Anatolia in Turkey. Intermediate cropping gives an advantage for producers without decreasing the sowing area of warm-season crops such as corn, soybean, etc. On the other hand, forage plants do not compete with cash crops during the main growing season or, especially perennials, do not suit crop design (Ağırbaş et al., 2017). Whereas, intermediate or second crop forage production provides an important advantage for producers without any decrement in cash crop sowing area in cropping design. Forage pea could be cultivated as an intermediate crop before warm-season main crops or as a second crop after cool-season cereals in the Central Anatolia region or any other region having similar ecology. Local producers are sowing silage corn followed by winter forage pea as an intermediate crop (Kalkan & Avcı, 2020).

Forage peas produce high-quality hay, which is rich in minerals and contains about 15–20% crude protein (CP) (Açıkgöz, 2001; Kocer & Albayrak, 2012) and has high digestibility which is about 70–80% (Uzun et al., 2005a). In addition to hay and grain production, forage pea is also produced for green manure, silage, and grazing (Ateş & Tekeli, 2017). On the other hand, it is both suitable for mixed cultivation with cereals and used in crop rotation (McKenzie & Spaner, 1999; Uzun et al., 2005b). It is an important legume species in crop rotation, as it can be cultivated in winter conditions of the Central Anatolia region without irrigation. However, the sowing time of winter forage peas is an issue to be considered in this region, where winters are cold. In this ecology, seeds should be sown in autumn to provide germination and ensure the plants go through winter as a seedling. In autumn planting, plants with four to five leaves and the form of rosettes entering the winter are least affected by the cold (Alan & Geren, 2012; Annicchiarico & Iannucii, 2007). Thus, plants could start growing early in the following spring and higher production could be achieved compared to spring sowing. Winter sowings could reach the harvesting stage earlier than spring sowing and do not cause delaying plantation of warm-season crops besides higher yield. Therefore, determining the appropriate sowing date of forage peas in autumn is important in the region.

As the plant density increases in forage crops, yield, and quality values increase up to a point (Açıkgöz, 2001). Besides, appropriate plant density is also important against winter damage, especially for autumn sowing (Knott & Belcher, 1998). Since the seed size in forage peas is quite variable among cultivars, it is more common to determine the number of seeds to be sown per unit area rather than by weight. Some researchers suggested that the sowing density should be between 60 and 100 per square meters for forage peas (Konuk & Tamkoç, 2018; Tan et al., 2012; Uzun et al., 2012).

In this study, the effects of different sowing times [normal autumn (October) and late autumn (November)] and plant density (80, 100, and 120 seeds m^{-2}) on hay yield and quality in two registered forage pea cultivars (Özkaynak and Taşkent), which are widely used in Central Anatolia region, were examined.

Methods

The two-year field study was carried out in Eskisehir Osmangazi University, Faculty of Agriculture Research Areas in the 2017–2018 and 2018–2019 growing seasons. In the study, the effects of two sowing times; timely (middle of October) and late sowing (middle of November), and three plant densities (80, 100, and 120 seeds m^{-2}) on hay yield and quality of two forage pea cultivars (Ozkaynak and Taskent) were investigated. The experiment was established in Randomized Complete Block Design with three replications. Combinations of factors were randomly allocated within the blocks. The sowing was carried out using 30 cm row spacing on 5 rows and each was 5 m long (7.5 m^2). While sowing, 30 kg ha^{-1} N and 70 kg ha^{-1} P_2O_5 were applied using diammonium phosphate (DAP) fertilizer. October and November sown plants reached four to six and two to four leaf stages, respectively, until winter. The experiment was arranged as an intermediate crop and conducted under rainfed conditions.

The yearly average temperatures of Eskisehir in the experimental years were 12.2 and 13.6°C, respectively, and were similar to the long-term average (12.9°C). Total precipitation was higher than the long-term average (352.4 mm) and the relative humidity

Table 1.
*Meteorological Data Belong to the Experiment Field in Study Years and Long-Term Average**

	Total Rainfall (mm)				Mean Temperature (°C)				Mean Relative Humidity (%)			
Month	**2017**	**2018**	**2019**	**LTA**	**2017**	**2018**	**2019**	**LTA**	**2017**	**2018**	**2019**	**LTA**
January	28.3	31.5	60.2	38.7	–1.7	2.2	4.3	0.3	99.3	95.5	91.0	98.2
February	8.8	40.5	50.1	32.5	2.8	6.6	3.4	4.7	92.2	90.7	79.6	92.6
March	26.9	74.8	13.4	33.4	8.5	10.1	6.3	9.3	80.4	81.5	64.5	81.6
April	60.2	16.5	26.7	35.0	10.8	15.4	9.5	13.1	73.5	60.7	69.3	67.8
May	101.0	84.8	42.2	44.8	15.4	17.6	16.5	16.5	83.4	83.0	65.1	86.1
June	49.3	72.5	45.7	30.6	20.1	20.6	20.9	20.4	85.3	80.7	67.9	83.3
July	9.5	38.3	33.5	14.0	23.7	23	21.3	23.3	73.8	71.4	62.3	75.8
August	29.9	25.0	2.4	7.8	22.4	23.5	22.3	22.9	60.2	62.2	61.0	74.1
September	6.8	4.3	5.0	14.4	20.9	19.1	18.1	20.0	58.3	62.9	62.1	68.1
October	52.7	41.0	18.3	27.0	11.9	14	14.2	12.9	78.3	75.5	70.1	79.6
November	33.4	29.6	33.9	29.2	6.7	8.4	7.9	7.5	86.9	79.2	76.2	80.3
December	34.0	63.6	74.1	45.1	4.5	2.7	2.9	3.6	92.5	96.0	89.9	93.6
Mean	440.8	522.4	405.5	352.4	12.2	13.6	12.3	12.9	80.3	78.3	71.6	81.8

Note: *T.C. Ministry of Agriculture and Forestry General Directorate of Meteorology
LTA = Long-term average.

value was lower than the long-term average (81.8%). During the growing period of plants (October–June), rainfall was higher in the first year (Table 1). The temperature was lower in February, March, April, and May of the second year.

The soil of the study area has a clay-loam texture class and is in the class of slightly alkaline (7.68), moderately calcareous (14.61%), nonsaline, low in phosphorus (61.6 kg ha^{-1}) and organic matter (1.62%), and sufficient in potassium (1688 kg ha^{-1}). The field has good drainage and there is no groundwater problem.

Sowings were done by hand on October 20 and November 16 in the first year and October 26 and November 16 in the second year for timely and late sowing dates. Weed control was done by hand hoeing in the early spring of both years. Harvest was carried out using a hand sickle and considering the full blooming stage of forage pea (Uzun et al., 2005a). In every plot, a randomly selected 1 m^2 area was harvested and oven-dried at 60°C until it reached a constant weight to determine hay yield. Dried samples were grounded in the experimental mill to pass through a 2 mm sieve and the CP ratio was determined by the Kjeldahl method. Neutral detergent fiber (NDF), acid detergent fiber (ADF), and acid detergent lignin (ADL) contents were determined according to the principles specified by Van Soest et al. (1991).

Data were subjected to ANOVA based on a general linear model for repeated measurement using SAS 9.3 statistical software (SAS Institute, 2011) and means were separated using Tukey Multiple Comparison Test.

Results

Hay yield, CP, NDF, ADF, and ADL contents were investigated in the study conducted to determine the sowing time and plant density using two forage pea cultivars in Eskisehir conditions. The mean values and variance analysis of examined characteristics were summarized in Table 2.

While the effect of years on hay yield was significant ($p < .01$), cultivars and sowing time did not cause a significant effect (Table 2). An average hay yield was 4434.3 kg ha^{-1} and it was higher in the second year (5139.2 kg ha^{-1}) than in the first year (3729.5 kg ha^{-1}). All interactions related to hay yield were insignificant.

The average CP content was 14.16% and it did not change significantly depending on years and cultivars but the effect of sowing time was significant ($p < .01$). Late-sown plants had higher CP content (14.92%) compared to timely sown plants (13.41%). In the first year, neither sowing density nor sowing time did not significantly affect CP content, whereas CP content was significantly higher in late sowings, and it was more pronounced at the plots sown using 100 seeds m^{-2} in the second year. On the other hand, the hay harvested from the plots that were sown using 80 and 100 seeds m^{-2} densities had statistically higher CP content in timely sowings. Similar fluctuations were also observed among the factors' effects related to CP content; hence triple interaction was significant (Figure 1).

An average NDF content was 37.64% and it did not change significantly among the treatments, hence, neither treatments' effect nor their interactions were statistically significant (Table 2).

In the experiment, overall ADF content was 27.98% and the years' effect was significant ($p < .01$) but the effects of sowing density and sowing time were not significant (Table 2). The first-year samples had lower ADF content (24.21%) than that of the second year (31.77%). There was no significant interaction effect on ADF content in the experiment.

Table 2.
Averages and Variance Analysis Results of Some Pea Cultivars Planted at Different Dates and Density

Treatments	Hay Yield (kg ha^{-1})	Crude Protein (%)	NDF (%)	ADF (%)	ADL (%)
Year (Y)					
2018	3729.5 B	13.89	37.52	24.21 B	4.20 B
2019	5139.2 A	14.44	37.77	31.76 A	8.02 A
Cultivar (C)					
Ozkaynak	4337.3	13.74	36.65	27.53	6.32
Taskent	4531.4	14.59	38.64	28.44	5.90
Sowing time (S)					
October	4548.7	13.41 B	38.09	28.49	6.20
November	4320.1	14.92 A	37.21	27.47	6.01
Plant density (P)					
80 seeds/m^{-2}	4667.1	13.96	36.79	27.49	6.36
100 seeds/m^{-2}	4825.1	14.49	37.27	27.57	5.78
120 seeds/m^{-2}	3810.9	14.05	38.89	28.89	6.18
Mean	4434.3	14.16	37.64	27.98	6.11
Y	**	ns	ns	**	**
C	ns	ns	ns	ns	ns
S	ns	**	ns	ns	ns
P	ns	ns	ns	ns	ns
Y × C	ns	ns	ns	ns	ns
Y × S	ns	**	ns	ns	ns
Y × P	ns	ns	ns	ns	ns
C × S	ns	ns	ns	ns	ns
C × P	ns	ns	ns	ns	ns
S × P	ns	ns	ns	ns	*
Y × C × S	ns	ns	ns	ns	ns
Y × C × P	ns	ns	ns	ns	ns
Y × S × P	ns	*	ns	ns	ns
C × S × P	ns	ns	ns	ns	ns
Y × C × S × P	ns	ns	ns	ns	ns

Note: Averages marked with different letters differ at 1% significance level
*F-test significant at $p \leq .05$.
**F-test significant at $p \leq .01$.
ADF = acid detergent fiber; ADL = acid detergent lignin; NDF = neutral detergent fiber; ns = not significant.

In the experimental samples, ADL content showed significant differences ($p < .01$) over the years, while the other factors did not have a significant effect. The average ADL content was 6.11% and it was determined as 4.20% and 8.02% in the first and second years, respectively. While the highest ADL content was obtained from 80 seeds m^{-2} plant density in timely sowing, it was the highest at 120 seeds/m^{-2} plant density in late sowing. These differences caused significant sowing time × plant density interaction (Figure 2).

Discussion

Hay yield was higher in the second year compared to the first year. In the second year, precipitation and temperature were

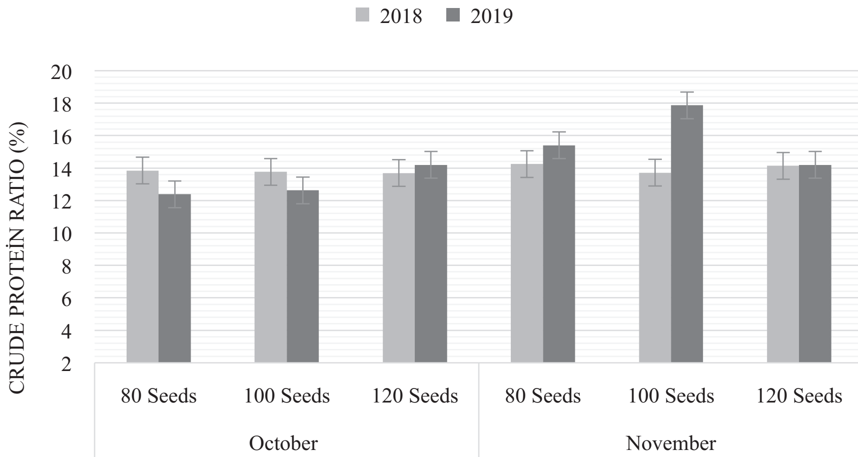

Figure 1.
Interaction Effect of Year × Sowing Time × Plant Density on Crude Protein Content in Forage Pea Sown at Different Sowing Times and Plant Densities in Autumn.

lower in the period from early spring to the end of May. The main reason for the increase in the second year may be the low temperature, which may increase hay yield by lengthened growing season because forage pea is a typical cool-season legume and the optimum temperature for good growth performance of pea is between 13 and 18°C (Rubatzky & Yamaguchi, 1997). Özkaynak and Taşkent cultivars were well adapted to the region (Dereli, 2015), so there was no difference between them in terms of hay yield. Both cultivars showed the same performance in winter sowing. In the experiment, timely or late-sown plants enter winter in the rosette growing stage and they showed their growth performance in the spring, hence, there were no significant differences concerning hay yield between sowing times. Indeed, the suggestion of Mukherjee et al. (2013) on this topic support also this interpretation. Tan et al. (2014) reported that the number of seeds planted per unit area determines the hay production and Uzun & Açıkgöz (1998) declared that hay yield increases with increasing plant density up to optimum plant density, thereafter there is not any significant increase observed (Uzun et al., 2017). Researchers (Kadıoğlu et al., 2020; Konuk & Tamkoç, 2018; Uzun & Açıkgöz, 1998) suggested 60–100 seeds per m^{-2} depending on the ecological condition for forage pea plantation. In this experiment, there were no significant yield differences among sowing density for hay yield. In this condition, it can be stated that the sowing rate of 80 seeds m^{-2} is appropriate in the region.

The cultivars, which are well adapted to the region (Dereli, 2015), were developed by the same researcher and are morphologically similar (Halil & Uzun, 2019); therefore, it is expected that the cultivars may have some similarities concerning some properties like CP content. Indeed, both cultivars had similar CP content in this experiment. Crude protein content showed a significant difference between timely and late sowings. The late-sown plants reached spring at a shorter height than timely sowing; therefore, late-sown plants completed their development faster than timely sown ones. Consequently, they had less photosynthesis time compared to timely sown plants. For this reason, their CP contents were higher because they accumulated less carbohydrates in protoplasm and cell walls due to faster growth. Krawutschke et al. (2013), and Karayel and Bozoğlu (2015) also reported similar ideas. Sowing at different plant densities did not have a significant effect on CP content. Tan et al. (2014) also found similar results. In addition, Alatürk et al. (2021) stated that increasing plant density caused competition between plants, which also causes late maturation and increases the protein content. In this study, CP

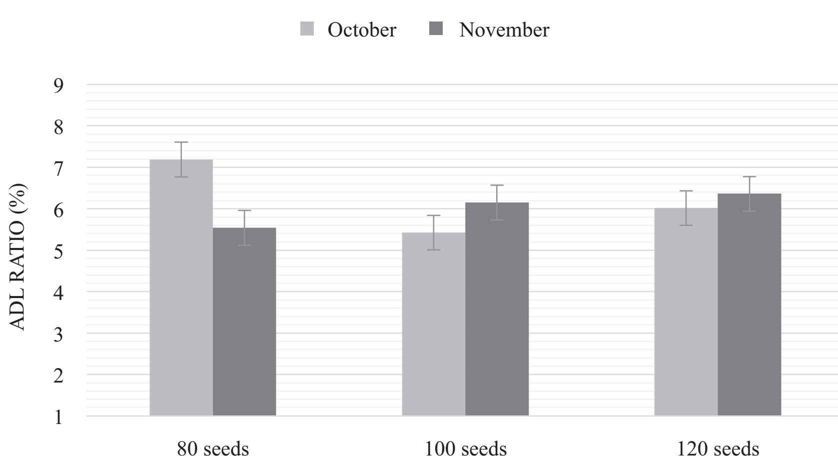

Figure 2.
Interaction Effect of Sowing Time × Plant Density on Acid Detergent Lignin (ADL) Content in Forage Peas Sown at Different Sowing Times and Plant Densities in Autumn.

ratio was not affected significantly by plant density because it did not cause serious competition. Forage CP content is a very important quality factor. The higher the CP value of forage, the higher the quality (Lithourgidis et al. 2006). Ruminants should consume forage, which has at least 7% CP content for survival rate (Meen, 2001). In this case, it can be emphasized that the CP content obtained in the study is sufficient for ruminant nutrition.

In the research, the difference between cultivars in terms of NDF content was insignificant. This situation probably originated from similarities between the cultivars for growth characteristics. Our NDF content results were similar to the results reported by other researchers (Başbağ et al., 2015; Kadıoğlu, 2011; Tan et al., 2014). Different sowing times did not have a significant effect on the NDF ratio. Neither sowing time nor sowing density, even years, did not cause any significant differences in NDF content. These factors probably did not cause any serious differences in growth characteristics, which cause changes in the NDF content of the plant. Hence, the plants that grow under these conditions had similar NDF content values. Some researchers also reported similar results for plant density (Borreani et al., 2007; Tan et al., 2014), sowing time (Pursley et al., 2020), and years (Javanmard et al., 2009). The NDF ratio is an important factor in determining forage quality. Dry matter intake increases with the decrease in the NDF content (Albayrak & Türk, 2013; Joachim & Jung, 1997). The results of NDF values obtained in the study were in superior quality class according to forage standards (NRC, 2001).

Acid detergent lignin is a main constituent of ADF, thus the effect of applications on ADL was similar to ADF content. In the study, ADF and ADL contents showed a similar changing trend with the hay yield according to years. Climatic conditions were more favorable for peas grown in the second year; hence, plants produced more dry matter and consequently stored more cell wall constituents such as cellulose and lignin, which are the main constituent of ADF. Therefore, ADF and ADL contents were higher in the second year. The other researchers (Uzun et al., 2017) also reported similar results. The cultivar, sowing time, and plant density applications did not have a significant effect on ADF content. The ADF content of Özkaynak (27.53%) and Taşkent (28.44%) cultivars are consistent with previous studies (Türk et al., 2007; Uzun et al., 2017). Sowing time did not affect ADF and ADL contents because plants sown in autumn might be accumulated similar cell wall material. Acid detergent fiber content of the hay is a good indicator of its digestibility as the ADF content increases the digestibility decrease (Açıkgöz et al., 2013). In this study, the overall ADF ratio was 27.98% and it was in the first class according to forage standards (NRC, 2001).

Conclusion and Recommendations

In the Eskisehir, animal raisers use harvest residues such as straw, sugar beet, and beet leaves for roughage deficit. Forage peas could be sown in winter as an intermediate crop and harvested in late spring before corn sowing and then, silage or grain corn could be sown. In this case, there is no restriction of main crop cultivation in the irrigated condition in the region. For this aim, forage peas could be sown in autumn from October to the middle of November using any of the cultivars of Ozkaynak or Taskent at 80 seeds m^{-2} plant density in the region. This practice contributes to alleviating good-quality hay shortages in the region.

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Effects of Different Phosphorus Sources on the Yield and Yield Components of Forage Pea

Çeşitli Fosfor Kaynaklarının Yem Bezelyesinde Kuru Ot Verimi ve Kalite Özellikleri Üzerine Etkileri

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ABSTRACT

This experiment was conducted to evaluate the effects of two different doses (B0 or B1) of phosp horus-solubilizing bacteria (*Bacillus megaterium* M-3) inoculation, two different doses (0 or 3 t ha^{-1}) of poultry manure, and three different doses (0, 50, and 100 kg P_2O_5 ha^{-1}) of commercially available phosphorus fertilizer on the dry matter yield, plant height, crude protein, neutral detergent fiber, and acid detergent fiber contents of forage pea in the irrigated condition of Erzurum between 2009 and 2010. While the effects of bacteria inoculation and poultry manure applications on dry matter yield varied over the years, an increase was observed in dry matter yield with increasing doses of phosphorus fertilizer. In addition, considering the 2-year averages, the highest dry matter yield considering the 2-year averages was obtained with the application of bacteria, poultry manure, and phosphorus fertilization together. Therefore, in order to obtain the highest dry hay yield in Erzurum and similar ecological conditions with low and/or medium phosphorus content in the soil and irrigated, *Bacillus megaterium* inoculation and 3 t ha^{-1} poultry manure together with 100 kg ha^{-1} P_2O_5 application can be recommended.

Keywords: Dry matter yield, phosphorus fertilization, phosphorus-solubilizing bacteria, poultry manure

ÖZ

Bu deneme, iki farklı dozda (B0 veya B1) fosfor çözücü bakteri (*Bacillus megaterium* M-3) aşılaması, iki farklı dozda (0 veya 3 t ha^{-1}) tavuk gübresi ve 3 farklı dozda (0, 50 ve 100 kg P_2O_5 ha^{-1}) ticari fosforlu gübre uygulamasının yem bezelyesinin kuru madde verimi, bitki boyu, ham protein, NDF ve ADF içerikleri üzerine etkilerini değerlendirmek amacıyla 2009–2010 yılları arasında Erzurum'da sulu koşullarda yürütülmüştür. Bakteri aşılaması ve tavuk gübresi uygulamalarının kuru madde verimi üzerine etkileri yıllara göre değişirken, artan dozlarda fosforlu gübre uygulaması ile kuru madde veriminde artış gözlenmiştir. Ayrıca iki yıllık ortalamalar dikkate alındığında en yüksek kuru madde verimi bakteri, tavuk gübresi ve fosforlu gübrelemenin birlikte uygulanması ile elde edilmiştir. Bu nedenle, toprakta düşük ve/veya orta düzeyde fosfor içeriğine sahip, sulanan Erzurum ve benzer ekolojik koşullarda en yüksek kuru madde verimini elde etmek için *Bacillus megaterium* aşılaması ile beraber 3 t ha^{-1} tavuk gübresi ve 100 kg ha^{-1} P_2O_5 uygulaması önerilebilir.

Anahtar Kelimeler: Kuru ot verimi, fosforlu gübreleme, fosfor çözücü bakteri, tavuk gübresi

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Introduction

Forage pea (*Pisum sativum* spp. *arvense* L.) is an annual cold-season legume plant with high forage yield and hay quality. Besides yielding high amounts of quality hay, this plant is of importance since it can be involved in short-term cropping systems and increase the amount of nitrogen that is present in the soil. Phosphorus plays an important role in increasing hay production and improving root and nodule development, nutrient intake, and plant growth in forage peas, as with the other forage legumes (Mitran et al., 2018). The use of inorganic, organic, and biological fertilizers are the major applications utilized in order to replenish the plant nutrients that are depleted in agricultural soils such as phosphorus (Masarirambi et al., 2012). However, the phosphate anions in chemical fertilizers form unsoluble salt complexes by interacting with Ca^{2+}, Fe^{3+}, and Al^{3+} ions in the soil and, as a consequence of this interaction, the amount of phosphorus available in the soil for plants decreases to 5–25% (Lambers & Plaxton, 2018; Schnug & Haneklaus, 2016). Moreover, the intense use of inorganic fertilizers causes soil degradation, which has a negative effect on the crop yield. This might be avoided by limiting the amount of inorganic fertilizers used (Debele, 2021). In addition, the practice of sustainable agriculture requires the use of organic fertilizers in combination with inorganic fertilizers because of increasing fertilizer prices and in order to decrease their negative impacts on the environment such as the accumulation of cadmium (Chukwu et al., 2014; Kaynar, 2014; Roba, 2018). Microorganisms that are used as biological fertilizers are known as plant growth-promoting rhizobacteria (PGPR). These microorganisms promote plant growth by increasing the amount of phosphorus that plants can use in soil. Plant growth-promoting rhizobacteria enable the dissolution of phosphorus that is actually available in the soil but has formed a complex by altering the enzyme and hormone secretion, which in turn reduces the need for chemical fertilizers (Chen & Liu, 2019; Meena et al., 2017). Thus, in studies employing biological fertilizers and organic fertilizers such as cattle manure and poultry manure, it was determined that the physical and chemical properties of the soil improved, and the yield increased in many plants (Azmi et al., 2019; Eleduma et al., 2020; Türkkan & Kibar, 2022).

The objective of this experiment was to determine the effects of applications of phosphorus-solubilizing bacteria inoculation, poultry manure, and mineral phosphorus on the dry matter yield and quality characteristics of forage peas.

Methods

The field experiment was carried out in the experimental field of the Agriculture Faculty of Agriculture of Atatürk University in Erzurum. The experiment used a randomized complete block with three replications with a factorial arrangement. Two levels of bacteria inoculation (B0 or B1), two doses of poultry manure (0 or 3 t ha^{-1}), and three doses of phosphorus (0, 50, and 100 kg P_2O_5 ha^{-1}) were applied. Each plot was 5 × 3 m in size, with a 0.5 m buffer inside each edge and a 2 m buffer outside. Six lines of plants were sown with a 30 cm distance between the rows (Tan, 2018).

Annual total precipitation was 410.2 mm, whereas it was 437.8 mm in the first year and 475.9 mm in the second year, and the values were higher than the long-term average. June in the first year and May in the second year received more precipitation (Table 1). The long-term (1929–2009) average temperature was 5.3°C, and the annual mean temperature values were higher (5.8°C for the first year and 7.9°C for the second year) than the long-term average. The highest temperature was 17.2°C in July in the first year and was 19.5°C in July in the second year.

The seeds to be sown in the experiments were inoculated with *Rhizobium leguminosarum* bacteria obtained from Ankara Soil and Fertilizer Research Institute. Phosphorous fertilizer (triple superphosphate) and poultry manure were mixed into the soil using a harrow. *Bacillus megaterium* was prepared at 10^8 CFU mL^{-1} density after the incubation and was inoculated to the seeds to be sowed in the plots. Kirazlı variety of forage peas (12 kg da^{-1}) (*Pisum sativum* ssp. *arvense* L.) were planted in preprepared seed beds at 4–6 cm depth (Tan, 2018) on the first year April 20 and on April 29 in the second year by using a hand drill. Seeds inoculated with phosphorus-solubilizing bacteria (*Bacillus megaterium* M-3) were sowed using different planting drills in order to prevent contamination. In 2 years, they were irrigated three times when the plants turned dark green due to moisture deficiency in the soil in the growing season.

Using the Bouyoucus hydrometer method (Gee & Hortage, 1986), the soil texture was found to be loamy in both years. The pH levels of soils were potentiometrically determined to be neutral (7.45 in the first year and 7.65 in the second year) by utilizing a pH meter (McLean, 1983). The lime content of the soil was found to be at the medium level (0.82% in the first year and 0.85% in the second year) using a Scheibler calcimeter volumetrically (Nelson, 1982). The organic matter content of the soil was determined in the "low-level class" (1.40% in the first year and 1.80% in the second year) by using the Smith-Weldon method (Nelson & Sommers, 1982). Using the flame photometry method (Thomas, 1982), the

Table 1.
Climatic Data of Experimental Area in 2009, 2010, and Long-Term Average at Erzurum

	Total Precipitation (mm)			Average Temperature (°C)			Average Relative Humidity (%)		
	2009	2010	LYA	2009	2010	LYA	2009	2010	LYA
J	2.30	52.20	19.80	−12.10	−4.30	−9.70	82.40	84.00	77.00
F	18.80	14.80	24.80	−3.10	−1.80	−8.60	84.70	82.30	77.00
M	51.10	82.20	31.00	−0.70	3.10	−2.80	73.80	69.10	75.00
A	42.70	54.20	58.40	4.30	5.60	5.40	64.60	71.30	66.00
M	43.20	63.60	70.00	10.00	10.40	10.50	61.00	69.60	63.00
J	76.20	50.50	41.60	14.70	15.90	14.90	65.00	60.10	58.00
J	29.20	55.50	26.20	17.20	19.50	19.30	60.70	56.00	52.00
A	22.80	9.00	15.10	17.10	20.30	19.40	50.60	44.80	49.00
S	43.70	8.80	20.00	12.40	17.00	14.30	53.10	48.10	52.00
O	51.00	72.20	47.90	8.70	9.20	7.60	62.40	70.20	65.00
N	41.40	0.00	32.90	1.80	1.80	−0.10	75.70	66.10	73.00
D	15.40	12.90	22.50	−1.10	−1.90	−6.60	84.70	76.60	78.00
Total/average	437.80	475.90	410.20	5.80	7.90	5.30	68.20	66.50	65.40

Note: LYA = long year average.

potassium content was high (118 kg ha^{-1} in the first year and 158 kg ha^{-1} in the second year). Soil's phosphorus content was found insufficient (27.5 kg ha^{-1} in the first year and 62 kg ha^{-1} in the second year) according to the molybdophosphoric acid method (Olsen & Summers, 1982).

After removing one row from each side of the plots and a 0.5 m area from the start or end of each plot, the harvesting process was carried out. The plants were harvested when they formed (Tan, 2018) by using a scythe. Before the plants were harvested, ten plants were selected from each parcel, and plant heights were measured. Harvested plants were oven-dried at 68°C to a constant weight and they were weighed in order to determine the dry matter yield (Jones, 1991).

After weighing, the oven-dried plant samples were grounded and passed through a 2 mm sieve for chemical analysis. The total nitrogen content of plants was determined using the Kjeldhal method, and the crude protein content was calculated by multiplying by 6.25 (Jones, 1991). Neutral detergent fiber (NDF) and acid detergent fiber (ADF) ratios were determined by using an ANKOM 200 fiber analyzer (ANKOM Technology, Fairport, NY) according to the procedure described by Van Soest et al. (1991).

The data were analyzed using variance analysis in JMP package software (SAS Institute, 2002). Mean values were compared using the LSD test (Yıldız & Bircan, 1994).

Results and Discussion

Plant growth-promoting rhizobacteria inoculation resulted in a significant increase in the plant height. The plant height, which was 88.33 cm on average, increased to 89.88 cm with PGPR inoculation. However, the application of poultry manure had no significant effect on the plant height (Table 2). On the other hand, applications of phosphorus fertilizer caused an increase in plant height in parallel with the phosphorus doses and reached the highest value of 90.79 cm in 100 kg ha^{-1} P_2O_5. In a similar study, it was reported that the increasing phosphorus doses yielded a higher level of increase in the plant height compared to the other yield factors (Yılmaz, 2008). There was no statistically significant difference found between plant height values by the years. Besides, PGPR inoculation yielded a higher level of increase in the

Table 2.
Effects of Phosphorus-Solubilizing Bacteria, Poultry Manure, and Phosphorus Fertilizer Applications on Plant Height (cm), Dry Matter Yield (t ha^{-1}), Crude Protein Ratio (%), ADF (%), and NDF (%) Ratio in Forage Pea

		PH	DHY	CPR	ADF	NDF
B	B_0	86.77^B	3.73^B	17.65	24.20	38.84^A
	B_1	89.88^A	3.94^A	17.88	23.89	37.49^B
	Av.	88.33	3.83	17.76	24.04	38.17
P	P_0	85.16^C	3.60^C	16.85^B	24.05	38.01
	P_{50}	89.04^B	3.81^B	17.92^A	24.09	38.42
	P_{100}	90.79^A	4.10^A	18.51^A	24.00	38.08
	Av.	88.33	3.83	17.76	24.04	38.17
PM	PM_0	88.08	3.77^B	17.61	24.14	37.64^B
	PM_1	88.58	3.90^A	17.92	23.95	38.70^A
	Av.	88.33	3.83	17.76	24.04	38.17
Years	2009	87.97	4.01^A	18.97^A	23.55^b	36.26^B
	2010	88.69	3.66^B	16.55^B	24.54^a	40.08^A
	Av.	88.33	3.83	17.76	24.04	38.17
	B	**	**	NS	NS	*
	P	**	**	**	NS	NS
	PM	NS	**	NS	NS	*
	Y	NS	**	**	*	**
	B × P	*	**	NS	NS	NS
	B × PM	**	**	*	NS	NS
	B × Y	*	**	NS	*	*
	P × Y	*	**	NS	*	*
	PM × P	*	NS	NS	*	NS
	PM × Y	NS	**	**	NS	NS
	B × P × PM	NS	NS	NS	NS	NS
	B × P × Y	*	**	NS	NS	NS
	B × PM × Y	*	**	NS	*	NS
	P × PM × Y	NS	NS	NS	NS	**

Note: *Values shown in capital letters are significant at 1% ($p < .01$), and small letters are significant at 5% ($p < .05$).
ADF = acid detergent fiber; B = bacteria; CPR = crude protein rate; DHY = dry hay yield; NDF = neutral detergent fiber; NS = none significant; P = phosphorus; PH = plant height; PM = poultry manure; Y = year.

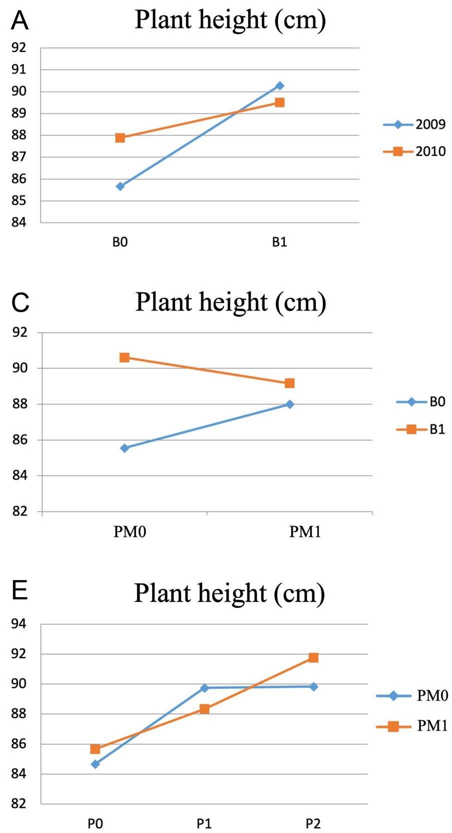

Figure 1.
A–E, Effects of Phosphorus-Solubulizing Bacteria, Poultry Manure, and Phosphorus Fertilizer Applications on Plant Height (cm) in Forage Pea. B × Y, B × P, B × PM, P ×Y, PM × P.

plant height in the first year in comparison to the second year, and as a result of different effects, B × Y interaction was found statistically significant ($p < .05$) (Figure 1A).

Plant height increased linearly depending on increased P doses under B0 conditions, whereas plant height increases ceased after P1 doses under B1 conditions. It caused the B × P interaction to be statistically significant ($p < .05$) (Figure 1B). Poultry manure application increased the plant height under the B0 condition, whereas it caused a decrease under the B1 condition. This result showed that the B × PM interaction was statistically significant ($p < .01$) (Figure 1C). This result might be because the phosphorus arising from the bacteria inoculation and the phosphorus content of poultry manure might have reached the potentially toxic level for nitrogen-fixing bacteria (Amba et al., 2011). While the plant height linearly increased in parallel with phosphorus doses in the first year, a remarkable increase was observed after the P1 dose in the second year. This different reaction caused a significant P × Y interaction ($p < .05$) (Figure 1D). The plant height increase ceased after the P1 dose without poultry manure application, whereas plant heights increased after the P1 dose together with the poultry manure application. It resulted in a significant PM × P interaction ($p < .05$) (Figure 1E). Therefore, it was determined that the use of inorganic fertilizer and poultry manure resulted in a higher increase in yield when compared to the sole use (Almaz et al., 2017).

Plant growth-promoting rhizobacteria inoculation statistically significantly increased the dry matter yield ($p < .01$). Dry matter yield was found to be 3.73 t ha^{-1} without PGPR inoculation, whereas it increased to 3.94 t ha^{-1} in PGPR inoculation plots (Table 3). The effect of poultry manure application on dry matter yield was statistically significant ($p < .01$). Dry matter yield, which was 3.77 t ha^{-1} without poultry manure application, increased to 3.90 t ha^{-1} with poultry manure application. Besides, dry matter yield statistically significantly increased with increasing phosphorus doses ($p < .01$), and the highest level (4.10 t ha^{-1}) was obtained with P2 dose. Dry matter yield decreased from 4.01 t ha^{-1} in the first year to 3.66 t ha^{-1} in the second year, and a statistically significant difference was found between dry matter yield values by the years ($p < .01$). It is known that the reaction of legumes to phosphorus is higher than other plants (Mitran et al., 2018) and phosphorus fertilizers increase the yield in cases of phosphorus deficiency (Sümer & Erten, 2022). However, in some cases, the efficiency of phosphorus for plants might be low due to the activity of soil microorganisms, even if the amount of phosphorus is sufficient. Because these bacteria increase the yield by transforming the phosphorus into a form that is available for plants (Chauhan et al., 2022; Matse et al., 2020; Öksel et al., 2022). Poultry manure application had a positive effect on the dry matter yield. In previous studies, it was reported that poultry manure application increased hay yield (Hoover et al., 2019; Lin et al., 2018).

Bacteria inoculation and poultry manure application increased the dry matter yield in the first year but caused a decrease in the second year. As a result of these different effects of bacteria and poultry manure on dry matter yield in different years, B × Y and PM × Y interactions were found to be significant ($p < .01$) (Figure 2A and B). With increasing phosphorus doses, there was a linear increase in dry matter yield in the first year, whereas

Table 3.
Chemical Composition of Poultry Manure

Parameter	Value
pH (1:5.0)	6.50
Organic matter (%)	22.00
Al (mg/kg)	315.26
B (mg/kg)	20.36
Ca (mg/kg)	18546.00
Cd (mg/kg)	0.092
Cr (mg/kg)	1.23
Cu (mg/kg)	36.12
Fe (mg/kg)	352.00
K (mg/kg)	12312.00
Mg (mg/kg)	3451.00
Mn (mg/kg)	172.35
Na (mg/kg)	956.00
Ni (mg/kg)	2136.00
P (mg/kg)	4845.00
Pb (mg/kg)	0.049
S (mg/kg)	452.13
Zn (mg/kg)	185.62

a higher level of increase was observed after the P1 dose in the second year. This different reaction suggests that the P × Y interaction was significant ($p < .01$) (Figure 2C). These results might be due to the changes in temperature and precipitation values between the years. While dry matter yield increased linearly in parallel with phosphorus doses under the B1 condition, a higher level of increase was observed after the P1 dose under the B0 condition. As a result of this different reaction, the B × P interaction was found to be significant ($p < .01$) (Figure 2D). It is known that plants benefit from fertilizers more effectively when using PGPR together with inorganic fertilizers (Abbas et al., 2013; Celik et al., 2020). While poultry manure application increased the dry matter yield under the B0 condition, it had no effect under the B1 condition. As a result of these different effects, B × PM interaction was found to be significant ($p < .01$) (Figure 2E).

The effects of PGPR inoculation and poultry manure applications on the crude protein ratio of the plant were insignificant. Besides that, phosphorus fertilizer application also significantly increased the crude protein ratio ($p < .01$).

In general, the crude protein ratio and mineral content increase with the use of phosphorus fertilizer (Belete et al., 2019), and it was reported in previous studies that phosphorous fertilizers increased the crude protein ratio in common vetch and forage pea (Kaynar, 2014; Yüksel & Türk, 2019). A statistically significant difference was also found between crude protein ratios over the years ($p < .01$). Application of poultry manure decreased the crude protein ratio under the B0 condition, whereas it increased the crude protein ratio when applied under the B1 condition. This reaction caused a significant B × PM interaction ($p < .05$) (Figure 3A). This different reaction might be because the bacteria showed a different activity in relation to different phosphorus concentrations in the soil (Gupta et al., 2015). Poultry manure application decreased the crude protein ratio in the first year but increased it in the

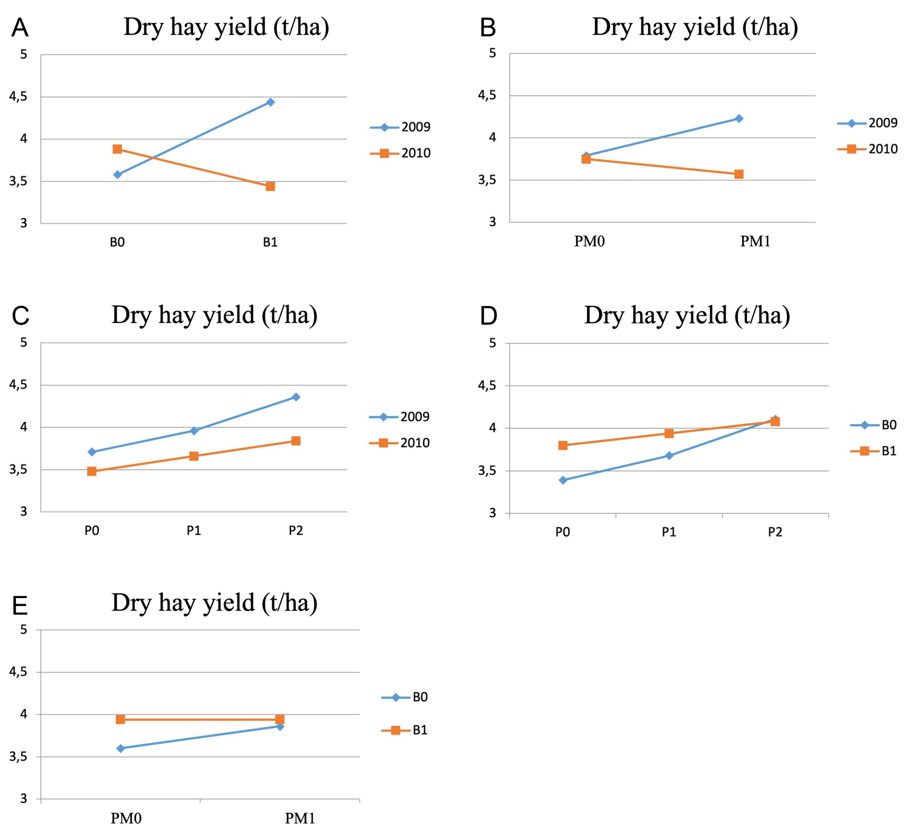

Figure 2.
A–E, Effects of Phosphorus-Solubulizing Bacteria, Poultry Manure, and Phosphorus Fertilizer Applications on Dry Matter Yield (t ha^{-1}) in Forage Pea; B × Y, PM × Y, P × Y, B × P, B × PM.

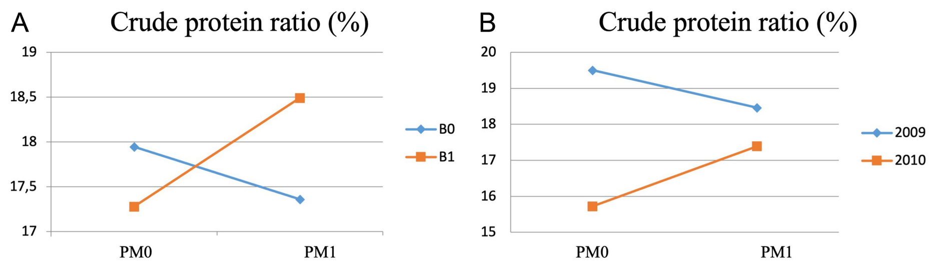

Figure 3.
A, B, Effects of Phosphorus-Solubulizing Bacteria, Poultry Manure, and Phosphorus Fertilizer Applications on Crude Protein Ratio (%) in Forage Pea; B × PM, PM × Y.

second year. As a result of this different reaction, the PM × Y interaction was found to be significant ($p < .01$) (Figure 3B).

Plant growth-promoting rhizobacteria inoculation caused a decrease in the NDF ratio of plants ($p < .05$), whereas poultry manure application increased it ($p < .05$). Moreover, the effect of phosphorus application on the NDF ratio was found to be statistically nonsignificant. A statistically significant difference was found between the years ($p < .01$). The results showed that the NDF ratio was lower than 41%, which is the upper limit for quality forage (Yavuz et al., 2009). Compared to the second year, the bacteria inoculation caused a more remarkable decrease in the NDF ratio in the first year. It resulted in a significant B × Y interaction (Figure 4A). The NDF ratio decreased after the P1 dose in the first year, whereas it increased in parallel with increasing phosphorus doses in the second year. As a result of this different reaction, the P × Y interaction was found to be significant ($p < .05$) (Figure 4B). High NDF and ADF ratios indicated increased lignification and consequently decreased the digestibility of hay (Budak & Budak, 2014).

According to the results, the effects of phosphorus, poultry manure applications, and PGPR inoculation on ADF ratio were found not to be statistically significant, and a statistically significant difference was found between the years ($p < .01$). Acid detergent fiber content of forage peas was found to be lower than 31%, which is the upper limit for quality roughage (Yavuz et al., 2009). However, bacteria inoculation and phosphorus application decreased the ADF content in the first year but increased it in the second year. This finding caused significant B × Y and P × Y interactions ($p < .05$) (Figure 5A and B). In addition,

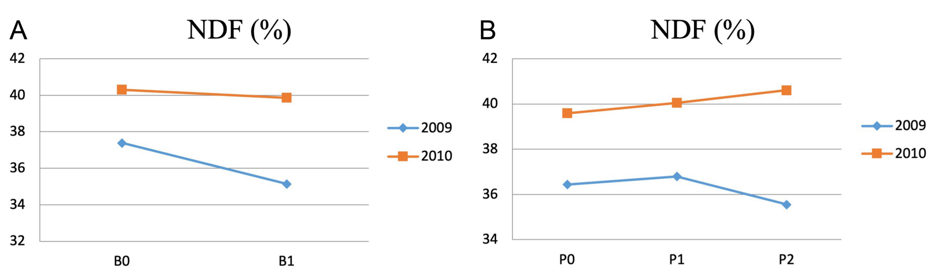

Figure 4.
A, B, Effects of Phosphorus-Solubulizing Bacteria, Poultry Manure, and Phosphorus Fertilizer Applications on NDF Ratio (%) in Forage Pea; B × Y, P × Y.

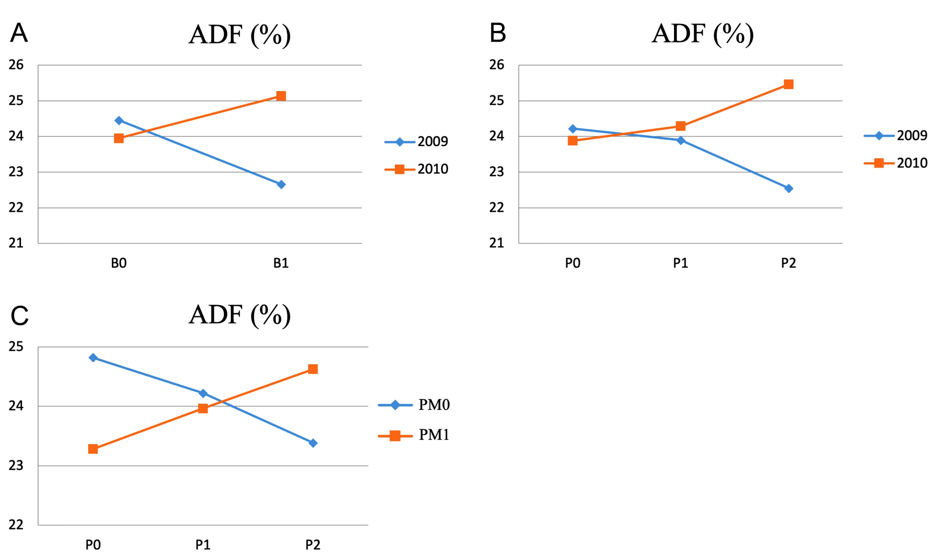

Figure 5.
A–C, Effects of Phosphorus-Solubulizing Bacteria, Poultry Manure, and Phosphorus Fertilizer Applications on ADF (%) in Forage Pea; B × Y, P × Y, PM × P.

the ADF ratio linearly increased in parallel with increasing phosphorus doses with poultry manure application, whereas it decreased after the P1 dose without poultry manure application. This different reaction caused a significant PM × P interaction ($p < .05$) (Figure 5C).

It is known that ADF and NDF ratios of forage peas, like other forage legumes, are generally lower in comparison to other plants (Osman et al., 2010). The reason for finding the NDF and ADF ratios of hay higher in the second year was probably because the temperature was higher in the second year than in the first year.

Conclusion and Recommendations

The combined application of organic and inorganic fertilizers increases soil productivity and yield and reduces the harmful effects of inorganic fertilizers on the environment. Thus, the combined use gains importance as an alternative way for sustainable soil productivity and sustainable agriculture. Hence, in the present study examining the effects of bacteria inoculation, poultry manure, and phosphorus fertilizer on the dry matter yield and yield components of forage peas, it was determined that the use of bacteria inoculation and poultry manure application in combination with phosphorus fertilizer resulted in a higher level of dry matter yield in comparison to using them solely.

Furthermore, the change in the results of bacteria inoculation and poultry manure over the years suggests that further studies, including different doses of poultry manure or PGPR inoculation together with different organic phosphorus sources, are needed.

Thus, to obtain the highest forage pea dry hay yield in Erzurum and similar ecological conditions with low and/or medium phosphorus content in the soil, it is recommended to the application of 100 kg ha^{-1} P_2O_5 in addition to 3 ton ha^{-1} poultry manure together with PGPR inoculation.

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Cold Plasma Technology and Its Effects on Some Properties of Milk and Dairy Products

Soğuk Plazma Teknolojisinin Süt ve Süt Ürünlerinin Bazı Özellikleri Üzerine Etkileri

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ABSTRACT

This review covers cold plasma techniques as a non-thermal processing technique and their effects on the microbiological and chemical properties of some dairy products, as well as sensory properties. Beforehand, the techniques used to generate cold plasma and its types and mode of action were also mentioned to make the reader become familiar with the subject. So far, limited results have shown that cold plasma techniques are able to reduce the number of some pathogens important to dairy technology such as *Escherichia coli*, *Staphylococcus aureus*, *Listeria monocytogenes*, etc., depending on the type of technique and application time. However, the effect of cold plasma application on physical, chemical, and sensory properties is still controversial. More research needs to be conducted to reveal the extent of the effectiveness of cold plasma techniques on the quality of dairy products.

Keywords: Cold plasma, corona discharge, dielectric barrier discharge, microwave discharge, plasma jet

ÖZ

Bu derleme, termal olmayan bir işleme tekniği olan soğuk plazma tekniklerini ve bunun bazı süt ürünlerinin mikrobiyolojik ve kimyasal özellikleri ile duyusal özellikleri üzerindeki etkilerini kapsamaktadır. Çalışmada öncelikle soğuk plazma üretmek için kullanılan tekniklerden ve soğuk plazma türlerinden ve etki biçimlerinden bahsedilmiştir. Şimdiye kadar gerçekleştirilen çalışmalardan elde edilen sınırlı sonuçlar, soğuk plazma tekniklerinin, tekniğin türüne ve uygulama süresine bağlı olarak *Escherichia coli*, *Staphylococcus aureus*, *Listeria monocytogenes* gibi süt teknolojisi için oldukça önemli olan bazı patojenlerin sayısını azaltabildiğini göstermiştir. Ancak soğuk plazma uygulamasının fiziksel, kimyasal ve duyusal özellikler üzerindeki etkisi halen tartışmalıdır. Soğuk plazma tekniklerinin süt ürünlerinin kalitesi üzerindeki etkinliğinin kapsamını ortaya koyabilmek için daha fazla araştırma yapılması gerekmektedir.

Anahtar Kelimeler: Soğuk plazma, korona deşarjı, dielektrik bariyer deşarjı, mikrodalga deşarjı, plazma jeti

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Introduction

Milk and dairy products are foods with high nutritional value, containing carbohydrates (lactose), fatty acids, and high-quality protein, as well as important micronutrients such as vitamins, minerals, and trace elements. The initial microbial load of the milk and the environmental factors such as the equipment used during milking and the environment in which the milking takes place can cause the raw milk to contain microorganisms at a level that may pose a health risk during the period until it is processed into the product. This microorganism load may also cause some sensory defects in milk and dairy products (Rathod et al., 2021). In addition, some enzymes such as lipase and alkaline protease in raw milk can cause structural and sensorial defects in milk and dairy products, leading to significant quality losses during processing, ripening, and storage of the product (Thirumdas & Annapure, 2020). Therefore, microorganisms and enzymes in raw milk must be inactivated at a certain level in order to ensure food safety, minimize sensory defects, and extend the shelf life of the product (Coutinho et al., 2018).

In the dairy industry, heat treatment techniques such as pasteurization, HTST (High temperature short time), LTLT (Low temperature long time), and UHT (Ultra high temperature) are generally applied for microorganism and enzyme inactivation, depending on the dairy product to be processed (Rathod et al., 2021). Such heat treatment applications are known as the most energy-consuming technologies in the food industry (Picart-Palmade et al., 2019) and may cause not only some nutritional losses in milk but the formation of undesirable sensory qualities such as bitterness and gelling in the final product (Misra et al., 2016; Rathod et al., 2021). In recent years, some novel techniques such as ohmic heating, high hydrostatic pressure, pulse electric field, and ultrasound have been developed in order to reduce the abovementioned effects (Coutinho et al., 2018). These technologies, which are generally called non-thermal techniques, aim at minimizing the negative effects on the nutritional value and quality characteristics of the products while meeting the necessary food safety and shelf life demands (Misra et al., 2016b). Cold plasma technology, on the other hand, is one of the newest techniques among these techniques. Unlike other non-thermal processes, it has some important advantages such as the need for shorter times in treatment, the need for no chemicals and water (Lee et al., 2021), and being applied at ambient temperature (Misra et al., 2016b).

In this review, the principle, mode of action of cold plasma technology, and its effects on microbiological, physicochemical, biochemical, and sensory properties of milk and dairy products are discussed.

Plasma Technology and Cold Plasma

Plasma application is based on exposing food or food surfaces to plasma, which is accepted as the fourth state of matter (Lee et al., 2021). Plasma is obtained by transforming a gas into an ionized gas containing atoms, ions, and electrons by providing sufficient energy (Misra et al., 2016a). There are several plasma techniques, each of which has different advantages or disadvantages.

By application temperature, it can be classified as a thermal or cold (low temperature) plasma technique. In the former technique, highly ionized species are in thermodynamic equilibrium with each other (Pankaj et al., 2018). Latter, on the other hand, is defined as plasma at room temperature due to the non-equilibrium between ions and unionized species, although the temperature of the electrons is high (Sharma & Singh, 2020). High pressure (>10^5 Pa) and very high energy (up to 50 MW) are needed to obtain thermal plasma. Besides, cold plasma is produced at 30–60°C and requires lower energy consumption compared to thermal plasma (Coutinho et al., 2018; Misra et al., 2016b). It is preferred especially in heat treatment-sensitive food products since ions and neutral molecules gain very low energy and remain stable at low temperatures in this application (Phan et al., 2017).

Considering the pressure conditions, this technique can be classified as high pressure, atmospheric pressure, and low-pressure plasma. Atmospheric plasma is generally preferred in practice because it eliminates the energy and cost required to create low or high pressure (Pankaj et al., 2018).

Cold plasma is produced by multiple techniques such as plasma jets, dielectric barrier discharge, corona discharge and microwave discharge (Corradini, 2020). All these discharges are initiated and sustained by electron collision processes under the influence of certain electric or electromagnetic fields (Misra et al., 2016a).

Although plasma jets (Figure 1A) may consist of a single electrode, they usually contain two electrodes and produce small "plasma flames" in the radio frequency range. The electrode gap

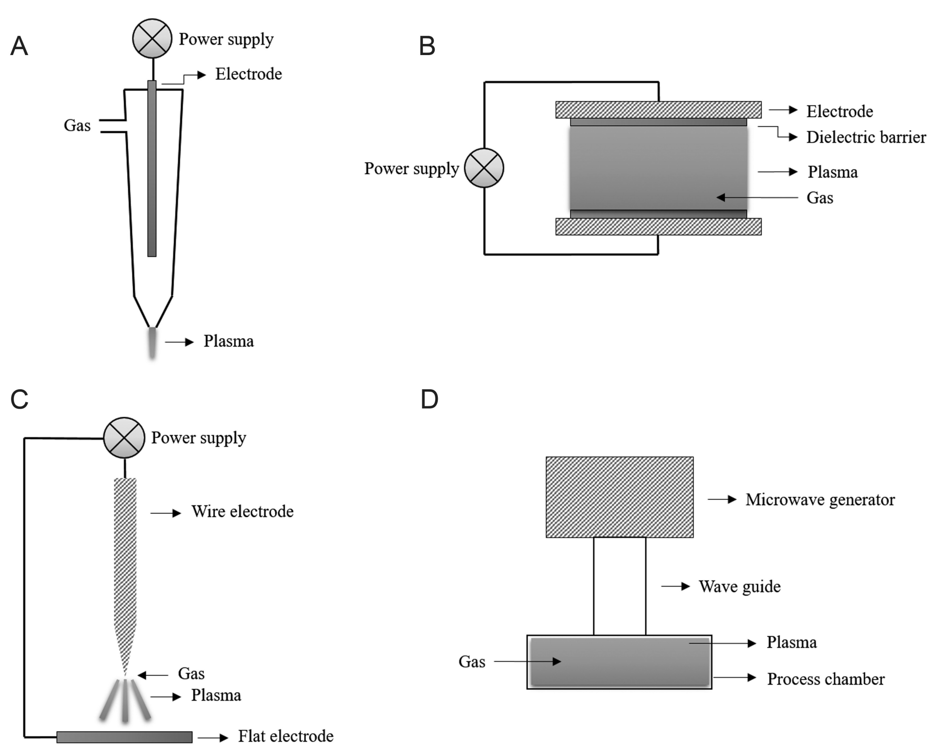

Figure 1.
Different Cold Plasma Systems: (A) Plasma Jet, (B) Dielectric Barrier Discharge, (C) Corona Discharge, and (D) Microwave Discharge (Modified from Coutinho et al., 2018; Misra et al., 2016a; Surowsky et al., 2015).

is usually a few millimeters, and the process gas (usually noble gases) is ignited at voltages of ~100 V. The biggest advantage of plasma jets is that they are small in size and can penetrate into narrow spaces (Surowsky et al., 2015).

In the dielectric barrier discharge (Figure 1B), plasma is produced between two electrodes separated by a dielectric. In this system, the process gas used, the distance between the electrodes and the electrical operation of the discharge are important process parameters. The biggest advantages of dielectric barrier discharges are that many different gases can be used to obtain this sort of plasma, relatively low gas flow is required, homogeneous discharges can be ignited for several meters, and can be adapted to different electrode geometries. However, depending on the distance between the electrodes, relatively high ignition voltages (10 kV) may be required in some cases. In such cases, it is necessary to take important measures by providing isolation (Surowsky et al., 2015). The dielectric barrier discharge is especially ideal for large surfaces (Coutinho et al., 2018).

Corona discharges (Figure 1C) are seen near large sharp electrode geometries under atmospheric pressure. There is an electric field large enough to accelerate the ionization level of the atoms or molecules of the gas surrounding the electrons. Cylindrical geometries or sharp, curved electrodes and flat electrodes are generally used in corona discharges. Being produced with simple devices with very low initial investment and operating costs appears to be an important advantage of this technique. However, it can be applied in small areas and non-uniformly is considered as a significant disadvantage (Coutinho et al., 2018; Surowsky et al., 2015).

Microwave discharges (Figure 1D) are produced without an electrode, unlike plasma jets, dielectric barrier discharges, and corona discharges. The microwaves produced by a magnetron are directed into the process chamber via a waveguide or a coaxial cable. Electrons in the process gas absorb these microwaves, leading to an increase in kinetic energy and, therefore, to the formation of ionization reactions with the collisions that occur. Depending on the microwave energy consumed here, neutral gas temperatures ranging from room temperature to about 1000 K can be reached. The biggest advantages of microwave discharges are that they can be installed without electrodes and can be ignited in the air or even with water vapor. In addition, their gas consumption is moderate and they can produce a high amount of reactive species depending on the discharge gas used. However, the necessity of using a series of discharges to ensure its applicability in large areas is a disadvantage of microwave discharges (Surowsky et al., 2015).

The properties of the produced plasma vary depending on factors such as the power source used, the parameters applied, and the composition of the gases (Pedrow et al., 2020). However, since dielectric barrier discharge and plasma jets are easier to construct, can operate continuously, and some configurations are commercially available, the use of cold plasma obtained from them in food products is more emphasized (Corradini, 2020; Misra et al., 2016).

Mode of Action of Cold Plasma

The effectiveness of cold plasma is basically based on the production of ultraviolet radiation, reactive oxygen species (ozone, hydrogen peroxide, singlet oxygen, peroxyl and hydroxyl radicals, etc.), and reactive nitrogen species (nitric oxide, peroxynitrite, peroxynitrous acid, etc.) (Misra & Jo, 2017; Misra et al., 2019). These reactive species formed cause some important physical, chemical, and microbiological changes in milk and dairy products. One of the most important changes is the deformation of the microbial cell surface, damage to the intracellular genetic material, and ultimately the death of the cell by lysis (Coutinho et al., 2018; Timmons et al., 2018). In addition, many different atoms, metastable, radical, electronically, and vibrationally excited molecules, including short- and long-lived neutral reactive species, can also contribute to the antimicrobial effect (Misra & Jo, 2017).

Also, plasma-reactive species (free radicals) have the potential to inactivate enzymes (Thirumdas et al., 2015). These reactive species cause modifications in amino acids through chemical reactions such as oxidation, sulfonation, and hydroxylation. It is stated that cold plasma specifically targets the secondary structure of enzymes (α-helix and β-sheet) (Thirumdas & Annapure, 2020). Binding and catalysis are inhibited due to the structural change seen in enzyme active sites with the exposure of proteins to radicals (Bubler et al., 2017; Khani et al., 2017). Rodacka et al. (2016) reported that the greatest effect on enzyme inactivation was seen in the presence of reactive oxygen species.

Plasma-produced reactive oxygen species, such as hydroxyl radicals, hydrogen peroxide, and superoxide anions (Attri et al., 2015), can also interact with lipids in foods and cause lipid oxidation (Gavahian et al., 2018). This situation has the potential to cause some undesirable changes such as deterioration of sensory properties, especially in dairy products with high fat content such as cream and butter. The primary target of reactive oxygen species is the methyl groups of fatty acids. Especially fatty acids with double bonds are more sensitive to reactive oxygen species. Linoleic acid (18:2) containing two double bonds and α-linolenic acid (18:3) containing three double bonds are the most sensitive fatty acids (Gavahian et al., 2018).

Some researchers expect an increase in the acidity of the product due to the chemical interactions between reactive species such as hydrogen peroxide and nitric acid formed during plasma production (Thirumdas & Annapure, 2020). However, no acidity change was observed in other studies (Gurol et al., 2012; Segat et al., 2016). This is thought to be due to the difference in the plasma source used and the applied process parameters.

The Effects of Cold Plasma on Milk and Dairy Products

There are a limited number of studies examining the effects of cold plasma application on the physical, chemical, and microbiological properties of milk and dairy products (Table 1).

The majority of these studies are on the inhibition of the most common pathogens in milk and dairy products. Cold plasma significantly reduces the number of pathogens such as *E. coli* (Gurol et al., 2012; Kim et al., 2015; Lee et al., 2012), *E. coli* O157:H7 (Yong et al., 2015), *Staphylococcus aureus* (Lee et al., 2012), *Listeria monocytogenes (*Kim et al., 2015; Yong et al., 2015), *Salmonella* Typhimurium (Kim et al., 2015; Yong et al., 2015), *Listeria innocua* (Wan et al., 2019), and *Cronobacter sakazakii* (Chen et al., 2019) in products such as milk, cheese, milk powder, and whey beverages, depending on the technique applied, the type of gas used, and the application time. In products with high surface roughness, such as cheese, it is thought that the microstructure provides a suitable environment for bacterial cells to adhere to the surface and reduces the effectiveness of the process by protecting the bacteria from the effects of cold plasma (Wan et al., 2019).

Table 1.
The Studies on the Effects of Cold Plasma Application on Some Properties of Milk and Dairy Products

Sample	Gas	Cold Plasma	Treatment Time	Microbial Activity	Enzyme Inactivation	Physicochemical and Biochemical Properties	Color Values	Sensory Properties	Reference
Whole milk, semi-skimmed milk, skimmed milk	Air	Corona discharge	0, 3, 6, 9, 12, 15, and 20 minutes	*Escherichia coli* 3 minutes 54% ↓	n/a	pH ↔	*L**, *a**, *b** ↔	n/a	Gurol et al. (2012)
Sliced cheese	He He/O_2	Dielectric barrier discharge	1–15 minutes	*E. coli*—0.05–1.98 log ↓ *S. aureus*—0.05–0.91 log ↓	n/a	n/a	*L** ↓ *b** ↑	Appearance, flavor, odor, total acceptability ↓	Lee et al. (2012)
Whole milk	Air	Dielectric barrier discharge	5 and 10 minutes	*E. coli*, *L. monocytogenes*, *Salmonella typhimurium* 10 minutes 2.40 log cfu/mL ↓	n/a	pH ↓ Lipid oxidation ↔	*L**, *b** ↑ *a** ↓	n/a	Kim et al. (2015)
Raw milk	Air	Corona discharge	0, 3, 6, 9, 12, 15, and 20 minutes	n/a	n/a	FFA content ↔ Lipid composition ↔ Total aldehyde content—20 minutes ↑ Toplam ketone and alcohol content ↔	n/a	n/a	Korachi et al. (2015)
Sliced Cheddar cheese	Air	Dielectric barrier discharge	0, 2.5, 5, and 10 minutes	*E. coli* O157:H7, *L. monocytogenes*, *Salmonella typhimurium* 10 minutes 3.2, 2.1, and 5.8 log cfu/g ↓	n/a	pH ↓ Thiobarbituric acid-reactive species ↑	ΔE ↔ *L** ↓ *b** ↑	Appearance ↔ Odor-aroma and total acceptability ↓ Off-odor ↑	Yong et al. (2015)
Alkaline phosphatase solution	Air	Dielectric barrier discharge	15 seconds–5 minutes	n/a	Alkaline phosphatase 180 seconds 90% ↓	pH ↔	n/a	n/a	Segat et al. (2016)
Süt yağı (tereyağı)	Air	Dielectric barrier discharge	3–30 minutes	n/a	n/a	Secondary oxidation products—30 minutes ↑ Oleic, palmitoleic, and linoleic acid—30 minutes ↓	n/a	n/a	Sarangapani et al. (2017)
Non-fat milk powder	N	Corona discharge	20–120 seconds	*C. sakazakii* 1.17–3.27 log ↓	n/a	Amino acid composition ↔ phenolic acid content ↔	*L**, *a**, *b** ↔	n/a	Chen et al. (2019)
Whey beverage	N	Corona discharge	5, 10, and 15 minutes	n/a	n/a	Bioactive and volatile compound contents ↑ Short times: Vitamin C ↑ Antioxidant activity ↑ Carotenoid content ↓ Long times: Vitamin C and volatile compound ↓ Carotenoid content ↑ ACE inhibitor activity ↑	n/a	n/a	Silveira et al. (2019)
Tryptic soy agar (TSA), Queso Fresco cheese, cheese model	Air	Dielectric barrier discharge	5 minutes	*Listeria innocua* 1.6–5.0 log ↓	n/a	n/a	n/a	n/a	Wan et al. (2019)
Gel	Air	Plasma jet	0–120 seconds	*S. aureus* and *L. monocytogenes* 120 seconds 1–2 log ↓	n/a	n/a	n/a	n/a	Lee et al. (2021)
Whey beverage	Air	Corona discharge	0, 5, 10, and 15 minutes	n/a	n/a	HMF value ↓ Antioxidant activity ↑ ACE inhibitor activity ↑	*L**, *a**, *b** ↔	**Acceptability** ↑	Ribeiro et al. (2021)

n/a: not applicable.

Cold plasma application is also effective on pH, minor components, enzyme, and volatile components of milk and dairy products mostly depending on the application time. The application of cold plasma (dielectric barrier discharge) for 5 and 10 minutes in whole milk decreased the pH values with no major changes in lipid oxidation (Kim et al., 2015). It was also observed that the application of cold plasma (dielectric barrier discharge) for different times (0, 3, 6, 9, 12, and 15 minutes) in raw milk increased the total aldehyde content after 20 minutes of application (Korachi et al., 2015). Similarly, the thiobarbituric acid reactive substance content, which is an indicator of lipid oxidation, increased in sliced Cheddar cheeses, by 30% after an additional 7.5 minutes of plasma application (Yong et al., 2015). In another study (Sarangapani et al., 2017), when milk fat was treated with atmospheric cold plasma (dielectric barrier discharge) for 3–30 minutes, it was observed that secondary oxidation products were released in the samples with only 30 minutes of application. With the release of oxidation products (2-nonenal, azelaic acid, 9-oxononanoic acid, nonanoic acid, and octanoic acid), a decrease in the amount of oleic, palmitoleic, and linoleic acids occurred. Cold plasma application increased the bioactive and volatile component content of guava-flavored whey samples (Silveira et al., 2019). Its application at low flow rates and for short periods increased the vitamin C content and antioxidant activity of the samples but decreased the carotenoid content, resulting in a less acceptable fatty acid profile. On the other hand, higher flow rate and application times decreased the vitamin C and volatile component content of the samples, while increasing the carotenoid content and ACE (angiotensin-I-converting enzyme)-inhibitory activity. Cold plasma application had a reducing effect on the HMF (hydroxymethylfurfural) value of the xylooligosaccharide-added whey beverage, but increased the antioxidant and ACE-inhibitory activities, compared to the pasteurization process, and these effects were enhanced with the increase of the application time (Ribeiro et al., 2021). In skimmed milk powder, no changes in the amino acid composition or phenolic acid content occurred with cold plasma application for 120 seconds (Chen et al., 2019).

Limited studies revealed that cold plasma applications have different effects on the sensory properties of milk and dairy products. On one hand, it negatively affects the taste, odor, and overall acceptability of cheese (Lee et al., 2012; Yong et al., 2015), on the other hand, there was a positive effect in whey beverages containing oligosaccharides (Ribeiro et al., 2021). Some researchers reported no noticeable changes in color parameters in milk samples containing different amounts of fat (Gurol et al., 2012), cheese (Lee et al., 2012; Yong et al., 2015), milk powder (Chen et al., 2019) and whey beverage (Ribeiro et al., 2021), the changes in, while others (Kim et al., 2015) reported an increase in the L^* and b^* values of the dairy products samples and a clear decrease in the a^* value in whole milk. In contrast, no noticable effect of cold plasma was observed in color parameters in milk samples containing different amounts of fat (Gurol et al., 2012), cheese (Lee et al., 2012; Yong et al., 2015), milk powder (Chen et al., 2019) and whey beverage (Ribeiro et al., 2021).

When the cold plasma technique is considered as a sanitation application in the dairy industry, it has been shown to have a lower degree of effectiveness than peracetic acid, a widely used chemical in sanitation (Lee et al., 2021). With the application of peracetic acid, a 7-log reduction was recorded in the count of two microorganisms (three different strains of *S. aureus* and one strain of *L. monocytogenes*) in a short time (10 seconds). Cold plasma application, on the other hand, yield a very low bactericidal effect, only a 1–2 log reduction was achieved after 120 seconds of application. It is pointed out that RNA and DNA damage occurred in cells and esterase activity decreased with the application of peracetic acid, while cold plasma application had no such effect on the mentioned parameters.

The enzyme inactivation efficiency of cold plasma was investigated in a solution prepared using a commercial alkaline phosphatase enzyme, which is specific to milk and obtained from bovine intestinal mucosa (Segat et al., 2016). The plasma obtained by dielectric barrier discharge was applied at three different voltages, 40, 50, and 60 kV, between 15 seconds and 5 minutes. The results indicated that enzyme inactivation was achieved by 45%–50% at the end of 120 seconds and by 90% at the end of 180 seconds at all applied voltages. In the meantime, no change in the pH of the solution was observed and the highest temperature recorded during the application was 30°C.

Conclusion and Recommendations

Cold plasma technology, which is considered one of the newest among non-thermal (thermal) techniques, has special importance especially for milk and dairy products as it has significant advantages compared to thermal methods. However, studies on the subject have generally focused on the antimicrobial effect of cold plasma, and the changes in the physical, chemical, and sensory properties of the final product have not been adequately addressed until today. The results of the studies, some of which have been summarized in this review, showed that cold plasma has different effects on the microbiological, physicochemical, biochemical, and sensory properties of milk and dairy products. The type and concentration of reactive species that can be found in the plasma vary depending on many factors such as the gas or gas mixtures in which the plasma is induced, the configuration of the source used in the production, and the applied voltage and time. Therefore, obtaining different results in studies is closely related to the method of obtaining the applied plasma, the process parameters, and also the microorganism species examined.

As a result, more studies are still required to reveal the changes in milk and dairy products due to cold plasma application. In particular, the examination of fat oxidation and therefore the volatile compounds originating from fat emerges as a new research topic as a potential for acceleration of cheese ripening.

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