Effects of Different Maturity Stages and Cultivars on Nutrient Composition and Rumen Degradation Characteristics of Whole-Plant Wheat Postprint

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Abstract

This study aimed to investigate the effects of different maturity stages and varieties on the nutritional composition and rumen degradation characteristics of whole-plant wheat, thereby providing data reference for its application in dairy cow diets. The experiment utilized two wheat varieties, Shannong 22026 (SN22026) and Shannong 82567 (SN82567), with the sample collection period spanning from late March to mid-June 2015. The experiment determined the contents of dry matter (DM), crude protein (CP), starch, crude ash, organic matter, neutral detergent fiber (NDF), acid detergent fiber (ADF), acid detergent lignin (ADL), and relative feed value of whole-plant wheat at different maturity stages, and measured the rumen degradation rate of wheat using three Holstein dairy cows (approximately 500 kg body weight) fitted with rumen fistulas. The results showed that: 1) The DM content of whole-plant wheat at the wax-ripe stage was significantly higher than that at other stages ($P<0.05$); the CP content of whole-plant wheat gradually decreased during the maturation process and remained stable after the flowering stage; with the maturation of wheat, the NDF, ADF, and ADL contents of whole-plant wheat exhibited a trend of first increasing and then decreasing. 2) The gross energy per unit DM of whole-plant wheat showed a declining trend during maturation, while net energy for lactation exhibited a trend of first decreasing and then increasing. 3) The effective degradation rates of DM, CP, and NDF in whole-plant wheat were highest at the jointing stage, significantly decreased at the heading and flowering stages ($P<0.05$), and significantly increased again at the milk-ripe and wax-ripe stages ($P<0.05$). 4) The rumen degradable protein (RDP) content of whole-plant wheat was highest at the jointing stage, significantly higher than that at other stages ($P<0.05$); it significantly decreased at the heading stage

(P<0.05), reached its minimum at the flowering stage (P<0.05), and gradually increased after the flowering stage (P > 0.10); whereas the rumen undegradable protein content gradually declined during wheat maturation, being lowest at the wax-ripe stage and significantly lower than that at other stages (P<0.05). Therefore, comparison between the two whole-plant wheat varieties in this trial showed significant differences only in a few parameters. Whole-plant wheat at each maturity stage exhibited high feeding value, yet significant differences were observed in nutritional value, yield, and rumen degradation characteristics across different maturity stages.

Full Text

Effects of Different Maturity Stages and Varieties on Nutritional Components and Rumen Degradation Characteristics of Whole Crop Wheat

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Abstract

This study investigated the effects of different maturity stages and varieties on the nutritional components and rumen degradation characteristics of whole crop wheat to provide data reference for its application in dairy cattle diets. Two wheat varieties, ShanNong 22026 (SN22026) and ShanNong 82567 (SN82567), were used, with samples collected from late March to mid-June 2015. The experiment measured dry matter (DM), crude protein (CP), starch, crude ash, organic matter, neutral detergent fiber (NDF), acid detergent fiber (ADF), acid detergent lignin (ADL) contents, and relative feed value (RFV) at different maturity stages. Rumen degradability was determined using three rumen-fistulated Holstein cows weighing approximately 500 kg. The results showed that: (1) DM content in whole crop wheat at the dough stage was significantly higher than at other stages (P<0.05). CP content gradually decreased during maturation and remained stable after the flowering stage. NDF, ADF, and ADL contents showed a trend of initially increasing then decreasing with maturity. (2) Gross energy per unit DM decreased during maturation, while net energy for lactation initially decreased then increased. (3) Effective degradabilities of DM, CP, and NDF were highest at the jointing stage, significantly decreased at heading and flowering stages (P<0.05), and significantly increased again at milk and dough stages (P<0.05). (4) Rumen degradable protein (RDP) content was highest at the jointing stage, significantly higher than other stages (P<0.05), decreased significantly at heading stage (P<0.05), reached its lowest at flowering stage (P<0.05), and gradually increased thereafter (P>0.10). Rumen undegradable protein content gradually decreased during maturation, with the lowest value at dough stage, significantly lower than other stages (P<0.05). In conclusion, the two wheat varieties showed significant differences in only a few indices. While whole crop wheat at each maturity stage had high feeding value, significant differences existed in nutritional value, yield, and rumen degradation characteristics among different maturity stages.

Keywords: whole crop wheat; dairy cow; nutritional components; rumen degradation rate

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Wheat is one of the most widely cultivated crops worldwide. Due to its high digestible fiber and energy content, whole crop wheat is suitable as a high-quality forage crop for high-yielding dairy or beef cattle, with feeding value approaching that of corn silage. Whole crop wheat has high nutritional value and is widely used in dairy feed in Israel, Turkey, and some regions of the United States. The 2016 Central No. 1 Document proposed expanding the grain-to-forage pilot program and accelerating the construction of a modern forage and feed system. In recent years, with the development of China' s dairy industry, domestic high-quality roughage has struggled to meet the needs of dairy farms. Therefore, fully developing and utilizing local roughage resources is the general trend, and the application of wheat in dairy production has gradually attracted attention.

To apply whole crop wheat in dairy feed, it is essential to understand the characteristics and changing patterns of its nutritional value during growth to determine the optimal harvesting period. However, many research results on wheat show discrepancies, and currently, there are few studies on whole crop wheat in China, with no reports on its rumen degradation rate. Therefore, this experiment aimed to investigate the changing patterns of nutritional components and rumen degradation characteristics during the growth of whole crop wheat, providing data reference for its application in dairy diets. It is hoped that this study can offer some reference for developing local roughage resources and reducing imported roughage.

1.1 Sample Collection

The wheat used in this experiment was sown on October 10, 2014, in two plots at the experimental field of the College of Agronomy, Shandong Agricultural University. The wheat varieties in the two plots were ShanNong 22026 (SN22026) and ShanNong 82567 (SN82567), with a seeding rate of 150,000 plants per mu (1 mu 666.67 m^2) in Tai' an, Shandong.

Samples were collected from late March (jointing stage) to mid-June (mature harvest) 2015, over a total of 11 weeks: jointing stage (weeks 1, 2), heading stage (weeks 3, 4), flowering stage (weeks 5, 6), milk stage (weeks 7, 8, 9), and dough stage (weeks 10, 11). Sampling was conducted once every Thursday. Starting 2 m from the field edge, plants were sampled longitudinally with random collection while avoiding adjacent plants. One hundred plants were collected from each plot each time. Wheat samples from each plot were divided into two portions for determining nutritional component content and rumen degradation parameters.

After collection, samples were immediately placed in an electric thermostatic oven at 65°C and dried to constant weight, then rehydrated for 24 h to determine initial moisture content. The air-dried samples were ground using a plant sample grinder to 40-mesh and 7-mesh sizes for determining routine nutritional components and rumen degradation parameters, respectively.

1.2 Rumen Degradability Measurement

Rumen degradability was measured using the nylon bag technique. Wheat samples from the two varieties sown in two plots were divided into two portions each. Approximately 3 g of 7-mesh whole crop wheat samples and nylon bags (pore size: 50 m, size: 8 cm × 12 cm) were accurately weighed using an electronic analytical balance, and samples were placed in the nylon bags. The bags containing samples were fixed on rubber stoppers and placed in nylon net bags (approximately 50 cm long).

The experimental animals were three healthy mid-lactation multiparous Holstein cows weighing approximately 500 kg, fitted with permanent rumen fistulas, with an average milk yield of 25 kg/d. They were milked twice daily (06:30 and 18:30) and fed twice daily (08:30 and 15:30) with free access to feed and water. Diet composition is shown in Table 1 .

Table 1 Composition of the diet (DM basis) %

Ingredients	Content
Corn	
Wheat bran	
Soybean meal	
Alfalfa hay	
Oaten hay	
Wild-rye hay	
Whole corn silage	
Premix	
Total	

One kg of premix contained the following: VA 160,000 IU, VD3 30,000 IU, VE 300 mg, VK3 30 mg, P 80 mg, Mn 550 mg, Zn 750 mg, NaCl 80 mg, Ca 200 mg, Cu 400 mg, Fe 1,800 mg.

One hour before morning feeding, nylon net bags were placed in the rumen, with the other end fixed to the cow’ s rumen fistula. Each sample was divided into three portions and placed in the rumens of three cows. Based on the required residual sample amount for measurement, a certain number of nylon bags were removed at corresponding time intervals. Sample incubation times were 2, 4, 8, 12, 24, 48, and 72 h, with two replicates per time point (one sample per bag). After removal, bags were immediately rinsed with clean water until the water ran clear, strictly preventing sample loss. Cleaned bags were dried in an electric thermostatic oven at 65°C to constant weight and then weighed. Nutritional components in residual samples were analyzed, with calculation indices for each variety averaged across maturity stages.

1.3 Degradation Parameter Calculation

Based on the real-time rumen degradation rate of target components in samples at time t, the exponential curve model proposed by Feng Yanglian [5] was used with the nonlinear regression procedure in SAS 8.2:

$$P = a + b(1 - e^{-ct})$$

Where:
P = rumen degradation rate (%) at time point t (h)
a = rapidly degradable fraction (%)
b = slowly degradable fraction (%)
c = degradation rate of b (%/h)

1.4 Effective Degradability Calculation

Using the calculated values of a, b, and c, effective degradability was calculated as follows:

$$ED = a + \frac{bc}{c + K_p}$$

Where:
ED = effective degradability (%)
K_p = rumen outflow rate (%/h)

Rumen outflow rate was predicted using the equation from NRC (2001):

$$K_p = 3.362 + 0.479X_1 - 0.007X_2 - 0.017X_3$$

Where:
K_p = rumen outflow rate (%/h)
X_1 = dry matter intake as a percentage of body weight (%)
X_2 = concentrate proportion in the experimental diet (%)
X_3 = neutral detergent fiber (NDF) proportion in diet DM (%)

The experimental cows were medium-weight Holstein cows with DM intake at 3.4% of body weight, concentrate content at 50% of diet, and NDF content at 25% of diet DM. Based on these parameters, K_p was calculated as 4.2%/h.

1.5 Relative Feed Value (RFV) Calculation

RFV is a widely accepted forage quality indicator that has become a common tool for determining hay quality in the U.S. hay market. Developed by the Hay Marketing Task Force of the American Forage and Grassland Council, RFV is estimated from acid detergent fiber (ADF) and NDF using the following formulas:

$$DDM = 88.9 - 0.779 \times ADF$$
$$DMI = \frac{120}{NDF}$$
$$RFV = \frac{DDM \times DMI}{1.29}$$

Where:
DMI (dry matter intake) = DM intake of roughage, expressed as percentage of body weight (BW)
DDM (digestible dry matter) = digestible DM, expressed as percentage of DM
The divisor 1.29 represents the expected DDM (% of BW) for full-bloom alfalfa based on extensive animal trial data, used to normalize full-bloom alfalfa RFV to 100.

1.6 Rumen and Small Intestine Index Calculation

Calculations referenced *Nutrient Requirements and Feed Composition of Dairy Cows* edited by Feng Yanglian [7]. Energy from rumen fermentation was expressed as fermentable organic matter (FOM) and digestible organic matter (DOM), affecting microbial crude protein (MCP) yield. In China’ s small intestinal protein system, each kg of FOM supports synthesis of 136 g MCP (MCP_E). MCP yield supported by feed nitrogen sources was calculated from RDP yield and its conversion efficiency to MCP. The minimum of these two values represents the theoretical MCP yield (MCP_N).

$$Rumen\ Energy\ Nitrogen\ Balance (RENB) = MCP_E - MCP_N$$

MCP(FOM) = MCP yield calculated based on FOM
MCP(RDP) = MCP yield calculated based on RDP
Conversion efficiency of RDP to MCP for individual feeds and diets was calculated at 90%, i.e., MCP = RDP × 0.9.

MCP synthesis supported by feed energy:

$$MCP_E(g) = 136 \times FOM(kg)$$

MCP synthesis supported by feed RDP:
Efficiency of converting Rumen Degradable Nitrogen (RDN) to Microbial Nitrogen (MN) can be predicted from the ratio of RDN (g) to feed FOM (kg) using the regression formula:

$$MN/RDN = 3.6259 - 0.8457 \ln(RDN/FOM)$$

$$MCP_N = RDN \times (MN/RDN)$$

Small intestinal protein = feed RUP + rumen MCP
Small intestinal digestible protein = feed RUP × small intestinal digestibility + rumen MCP × small intestinal digestibility

Small intestinal protein digestibility: MCP digestibility = 0.7, feed undegraded protein digestibility = 0.65. Conversion efficiency of small intestinal digestible protein: 0.6 for growing cattle, 0.7 for lactating cows.

1.7 Whole Crop Wheat Sample and Rumen Degradation Residue Analysis

DM content was determined according to GB 6435—1986, CP according to GB/T 6432—1994, crude ash according to GB/T 6438—1986, and crude fat (EE) according to GB/T 6433—2006. NDF, ADF, and ADL were determined using the method of Van Soest (1991). Starch content was determined by anthrone colorimetry following *Biochemical Experiments* by Chen Junhui. Non-fibrous carbohydrate (NFC) was calculated as:

$$NFC(\%) = 100 - (CP + NDF + EE + Ash)$$

Based on measured CP, ash, EE, NDF, and ADF contents, gross energy (GE) and net energy for lactation (NEL) were calculated using formulas from the French National Institute for Agricultural Research (INRA) (1978, 1988, 2000):

$$GE = 17.3 + 0.0617CP + 0.2193EE + 0.0387CF - 0.1867Ash + 0.19$$

$$NEL = ME \times K_l$$

$$K_l = 0.60 + 0.24 \times (ME/GE - 0.57)$$

Where:
CF = crude fiber content
ME = metabolizable energy

1.8 Statistical Analysis

Data were preprocessed using Excel 2016, then analyzed using SAS 8.2 software for linear model ANOVA and multiple comparisons. P<0.05 indicated significant difference, P>0.10 indicated no significant difference, and 0.05≤P$ $0.10 indicated a significant trend.

2.1 Effects of Different Maturity Stages and Varieties on Nutritional Components of Whole Crop Wheat

As shown in Table 2 , DM content in whole crop wheat gradually increased with maturity, with the rate of increase accelerating, particularly at the dough stage where DM content increased significantly (P<0.05). CP content gradually decreased during maturation, being highest at the jointing stage and significantly lower at heading and flowering stages (P<0.05), then stabilizing after flowering. NDF, ADF, and ADL contents showed a trend of initially increasing then decreasing with maturity; NDF peaked at heading stage, while ADF and ADL peaked at flowering stage. NFC content showed an opposite trend of initially decreasing then increasing, while starch content remained stable until flowering stage and increased significantly thereafter (P<0.05). No significant differences were observed between varieties (P>0.10).

Table 2 Effects of different maturity stages and breeds on nutritional components of whole crop wheat

Items	Maturity stage					Breed	P-value
	Jointing	Heading	Flowering	Milk	Dough	SN22026	SN82567
DM/%	16.65c	19.97c	22.67bc	28.78b	77.73a	<0.0001	
CP/%DM	21.00a	15.19b	12.34c	11.95c	11.07c		
NDF/%DM	47.43c	63.57a	58.01b	56.95b	55.76b		
ADF/%DM	28.12b	35.84a	34.81a	26.69bc	22.92c		
ADL/%DM	2.33d	5.00ab	5.84a	4.23bc	3.63c		
NFC/%DM	15.52c	7.84d	16.04c	20.73b	25.40a		
Starch/%DM	8.54c	6.91c	7.88c	18.66b	22.59a		

In the same row, values with different small letter superscripts mean significant difference (P<0.05), while with the same or no letter superscripts mean no significant difference (P>0.10). The same as below.

2.2 Effects of Different Maturity Stages and Varieties on Energy, Yield, and RFV of Whole Crop Wheat

As shown in Table 3 , GE per unit DM of whole crop wheat decreased during maturation. NEL showed a trend of initially decreasing then increasing, being lowest at heading and flowering stages, significantly lower than other stages

(P<0.05), and highest at milk and dough stages, significantly higher than other stages (P<0.05). DM yield per plant increased with maturity, being lowest at jointing stage, significantly lower than other stages (P<0.05), and highest at milk and dough stages, significantly higher than other stages (P<0.05). Whole crop wheat had the highest RFV at jointing stage, which decreased significantly at heading and flowering stages (P<0.05), then gradually increased at milk and dough stages (P>0.10). No significant differences in energy, yield, or RFV were observed between varieties (P>0.10).

Table 3 Effects of different maturity stages and breeds on energy, yield and RFV of whole crop wheat

Items	Maturity stage					Breed	P-value
	Jointing	Heading	Flowering	Milk	Dough	SN22026	SN82567
GE/(MJ/kg)	18.08a	17.75bc	17.75bc	17.92ab	17.58c		
NEL/(MJ/kg)	5.86b	4.94c	5.11c	6.03a	6.32a		
DM yield/(g/plant)	6.15c	13.74b	17.22b	28.87a	29.61a		
Relative feed value	132.10a	89.25d	99.11cd	111.32bc	118.53ab		

2.3 Effects of Different Maturity Stages and Varieties on Rumen Degradation Characteristics of Whole Crop Wheat

As shown in Table 4 , different maturity stages significantly affected rumen degradation rate (P<0.05). Effective degradabilities of DM, CP, and NDF were highest at jointing stage, significantly decreased at heading and flowering stages (P<0.05), and significantly increased again at milk and dough stages (P<0.05). GE effective degradability showed irregular patterns, being highest at jointing stage, significantly higher than other stages (P<0.05), and lowest at heading and dough stages, significantly lower than other stages (P<0.05). Organic matter degradability was relatively high at jointing stage, significantly decreased at heading and flowering stages (P<0.05), and significantly increased at milk and dough stages (P<0.05).

Table 4 Effects of different maturity stages and breeds on characteristics of rumen degradation rate of whole crop wheat (%)

Items	Maturity stage					Breed	P-value
	Jointing	Heading	Flowering	Milk	Dough	SN22026	SN82567

Items	Maturity stage					Breed	P-value
Effective degradability of DM	64.02a	49.10c	46.80d	51.07b	50.66b	52.93a	51.85b
Effective degradability of CP	67.86a	58.54b	49.35c	57.17b	65.91a	62.04a	57.49b
Effective degradability of NDF	44.08a	34.23b	24.80d	29.40c	25.41d		
Effective degradability of GE	61.21a	45.64c	42.52d	48.02b	44.67c	48.97a	47.85b
OM degradability	53.69b	43.28c	45.45c	57.02b	62.36a		

2.4 Effects of Different Maturity Stages and Varieties on RDP and Small Intestinal Protein Contents of Whole Crop Wheat

As shown in Table 5 , RDP content in whole crop wheat was highest at jointing stage, significantly higher than other stages ($P<0.05$), decreased significantly at heading stage ($P<0.05$), reached its lowest at flowering stage ($P<0.05$), and gradually increased thereafter ($P>0.10$). Rumen undegradable protein (RUP) content gradually decreased with maturity, being lowest at dough stage, significantly lower than other stages ($P<0.05$). MCP yield calculated based on FOM and RDP both showed a trend of initially decreasing then increasing, with the former peaking at dough stage and the latter at jointing stage. Rumen energy nitrogen balance (RENB) was negative at jointing and heading stages, positive at flowering and later stages, and closest to zero at flowering stage. Small intestinal protein and small intestinal digestible protein contents gradually decreased with maturity, being highest at jointing stage, significantly higher than other stages (P<0.05), and lowest at dough stage.

Table 5 Effects of different maturity stages and breeds on rumen degradation protein and small intestinal protein contents of whole crop wheat

Items	Maturity stage					Breed	P-value
	Jointing	Heading	Flowering	Milk	Dough	SN22026	SN82567
RDP/(g/kg)	143.04a	89.16b	61.08c	68.38bc	73.01bc	66.97a	62.74a
RUP/(g/kg)	62.32a	51.15d	37.73c				
MCP(FOM)/(g/kg)	64.91c	52.23d	55.80b	71.84b	79.93a		
MCP(RDP)/(g/kg)	128.74a	80.25b	54.97c	61.55bc	65.71bc	85.98a	70.50b
RENB/(g/kg)	-63.83c	-28.02b	0.82a	10.29a	14.22a	-19.57b	-7.03a
Small intestinal protein/(g/kg)	195.70a	142.99b	117.30c	112.69cd	103.44d	141.66a	127.18b
Small intestinal digestible protein/(g/kg)	133.64a	96.95b	78.99c	76.33c	70.52c	96.38a	86.19b

3.1 Effects of Different Maturity Stages and Varieties on Nutritional Components of Whole Crop Wheat

Based on wheat grain development and weight gain characteristics during grain filling, wheat development from flowering to maturity can be divided into three stages: grain formation, grain filling, and rapid dehydration. Grain formation determines endosperm cell number, closely related to final grain weight. During this period, rapid grain volume expansion occurs with highest water content and slow DM accumulation. After grain formation, weight gain accelerates into the grain filling stage, which continues until maximum grain dry weight is reached, during which nutrients rapidly transfer from the plant to the grain. During grain filling, volume continues to increase until peaking, then enters rapid dehydration—a short period with rapid water loss. After entering the dough stage, wheat leaves and stems yellow and dry, and from late dough to full maturity, whole crop wheat DM content gradually increases. Crovetto et al. [3] found that DM content increased with maturity when testing wheat at booting, flowering, milk, and dough stages. Qin Mengzhen et al. [8] also reported that DM content increased (moisture decreased) with maturity, consistent with our findings.

CP content decreased with maturity as photosynthesis weakened, inhibiting protein synthesis. Throop [9], Qin Mengzhen et al. [8], Crovetto et al. [3], and Xie et al. [4] all reported that plant maturity decreased whole crop wheat CP content, though Oltjen et al. [10] reported higher CP content in dough-stage whole crop wheat silage than in milk-stage.

Cellulose components (NDF, ADF, and ADL) varied across maturity stages. Numerous studies show that cell wall components increase with plant maturity. In this experiment, cellulose components initially increased then decreased, with lower fiber content at milk and dough stages after flowering, likely because starch deposition in grains after grain formation relatively decreased cellulose content. Crovetto et al. [3] reported that NDF and ADF remained stable from heading to milk stage then decreased at dough stage, while ADL gradually increased. Xie et al. [4] found that crude fiber, NDF, and ADF at milk stage were significantly lower than at flowering and dough stages.

NFC content showed a trend of initially decreasing then increasing, while starch remained stable until flowering then increased significantly. This indicates that non-starch carbohydrates in NFC decreased before flowering, while after flowering most carbohydrates transferred to grains as starch. Beck et al. [11] also found higher NFC content in dough-stage whole crop wheat hay than in boot-stage hay for beef calves, with higher wash fiber but lower NFC in hay than silage at boot stage, possibly because water-soluble carbohydrates were consumed during curing, incorporated into NDF through Maillard reactions, or lost to air exposure. Such losses decreased at milk and dough stages because most NFC existed as more stable starch in wheat grains.

3.2 Effects of Different Maturity Stages and Varieties on Energy, Yield, and RFV of Whole Crop Wheat

Feed GE is the heat released from oxidation of organic matter per unit DM, determined by the ratio of carbon, hydrogen, and oxygen. GE magnitude depends on organic matter content per unit DM and the C:H:O ratio. GE per unit DM decreased during maturation but remained high at all stages. Crovetto et al. [3] also reported high GE at all stages that gradually decreased with maturity, consistent with our results. Notably, their GE values were higher than ours and even higher than INRA [12] reports for similar maturity stages, possibly due to regional differences or measurement methods.

Ruminant energy digestion and utilization is more complex than in monogastric animals, affected by rumen microbial fermentation, digestive tract absorption, and organ conversion efficiency. Moreover, dairy cows show large variation in feed utilization efficiency. Therefore, dairy feed evaluation requires net energy (NE) correction beyond digestible or metabolizable energy. NEL evaluation is complex, generally based on regression relationships between measured NEL and digestible or metabolizable energy from representative feeds. In this experiment, NEL per unit DM was lowest at heading and flowering stages and highest at milk and dough stages, mainly because starch deposition in later maturity increased non-fibrous nutrients and decreased cellulose content, as high-NDF feeds have lower NE than low-NDF feeds.

DM yield per plant increased with maturity, particularly rapidly at milk and dough stages, primarily from increased biological yield and nutrient deposition. Calculated yields per mu were high but unattainable in practice due to seed germination rate, stubble height, and processing losses. Our results align with numerous studies: Edmisten et al. [13] reported that grain contributed 56% of wheat DM yield at dough stage; Coblentz et al. [14] reported that wheat spikes contributed 58% and 60% of DM at dough and grain maturity stages; Ashbell et al. [15] found that DM yield increased by about 40% from milk to dough stage in Israeli wheat. This demonstrates that after spike emergence, wheat grains contribute substantially to overall forage nutritional quality during grain filling.

Whole crop wheat had highest RFV at jointing stage, which decreased at heading and flowering stages then increased at milk and dough stages. Xie et al. [4] produced silage from whole crop wheat at flowering, milk, and dough stages, obtaining highest RFV at milk stage, followed by dough and flowering stages. Our finding of higher RFV at dough than milk stage differs from Xie et al. [4], possibly due to different processing methods. When made into hay, water-soluble compounds are lost during curing or incorporated into NDF through Maillard reactions. During ensiling, lactic acid fermentation converts carbohydrates to lactic acid, causing nutrient loss and dissolving potential nutrients into silage, altering feed nutritional value.

In this experiment, variety did not affect nutritional components, possibly because the two wheat lines had similar genetic characteristics.

3.3 Effects of Different Maturity Stages and Varieties on Rumen Degradation Characteristics of Whole Crop Wheat

DM degradability is an important factor affecting DM intake in ruminants. Roughage DM degradability in the rumen increases with incubation time but varies among forages of different quality. Fiber content (cellulose content and lignification degree) affects degradation characteristics. Generally, cellulose degrades slower than NFC, while lignin is difficult to digest and can bind with other nutrients, reducing their degradability. As wheat grew, stem and leaf proportions increased, tissues aged, cell wall components increased, and cellulose content rose, slowing nutrient degradation and reducing DM degradability. After grain filling began, starch deposition transferred more nutrients to easily degradable grains, and increased starch content with decreased cellulose proportion in later maturity greatly improved rumen degradability.

Protein in forages is utilized by rumen microorganisms to produce MCP, which is then digested and absorbed in the small intestine. Protein fermentation difficulty and rumen retention time determine degradability [16]. Forage protein mainly exists as nitrogenous compounds in cell contents, while cell wall cellulose structure affects protein degradation rate. Plant maturation and lignification affect nitrogen release and decomposition. Feed protein can be divided into rapidly degradable, slowly degradable, and non-degradable fractions, with different proportions among feeds represented by parameters a, b, and c in the regression equation. Whole crop wheat at different maturity stages had minimal non-degradable fractions, indicating that most protein was rumen-degradable. Results showed that CP effective degradability was greatly affected by maturity stage. Leng Jing et al. [17] and Liu Dalin et al. [18] reported that high CP content favored degradation, consistent with our pre-flowering results but opposite post-flowering. This is mainly because after flowering, most protein transferred to grains with low fiber and lignification, making it more degradable.

NDF degradability is an important indicator for evaluating roughage quality. Dietary NDF plays a crucial role in maintaining normal rumination and rumen health. NDF composition affects rumen degradability, which varies among feed ingredients. As plants mature, leaf-to-stem ratio and stem lignification (affecting fiber digestibility) change, influencing hay fiber digestibility and protein components [19-20]. Lignin affects the extent and rate of forage fiber digestion [21-23], depending on its content and composition [24-25], tissue distribution [24], and phenolic functions [27]. Due to its phenolic components, lignin cannot be digested anaerobically and reduces the proportion of potentially digestible fiber [28]. Therefore, NDF effective degradability was highest at jointing stage, decreased with maturity, and was significantly lower at milk stage than at jointing and heading stages but higher than at dough stage. This may be because dough-stage wheat had yellowed, with higher lignification and hardened grains potentially reducing NDF degradability.

GE effective degradability changed with maturity similarly to NDF content, indicating that NDF content affects energy degradation in the rumen.

Fermentation products in the rumen and digestion products in the small intestine differ, and many studies show that rumen FOM yield is proportional to volatile fatty acid (VFA) and MCP production [29-30]. Therefore, organic matter degradability in the rumen (FOM/OM) is an important parameter for feed quality evaluation. Whole crop wheat had relatively high organic matter degradability at jointing stage, which decreased at heading and flowering stages then increased significantly at milk and dough stages. This indicates that organic matter became more degradable after grain filling, likely because nutrients, especially non-fibrous components, gradually transferred to grains and increased their proportion in total DM. This supports findings by Jiang Jun et al. [31] and Xu Ping et al. [32], who reported that apparent rumen organic matter degradation increased with dietary concentrate content, and whole-tract organic matter digestibility also increased with more concentrate. However, some studies show that rumen and whole-tract organic matter digestibility are unaffected by dietary organic matter content [33-35]. The increased degradability after grain filling may also occur because easily degradable nutrients like starch in grains provide energy for rumen microbial growth. Russell et al. [36] found that rumen microbial growth accelerates with carbohydrate fermentation rate, and abundant microbes can in turn degrade more organic matter.

3.4 Effects of Different Maturity Stages and Varieties on RDP and Small Intestinal Protein Contents of Whole Crop Wheat

Traditional protein systems cannot fully explain ruminant protein digestion and metabolism. Dietary protein undergoes rumen degradation before entering the small intestine, where its structure and quantity have changed. Protein entering the small intestine includes undegraded dietary protein and rumen MCP. Considering microbial degradation and utilization requires evaluation using the small intestinal protein system.

Dietary protein in the rumen, functionally divided into RDP and RUP, affects rumen fermentation. RDP provides necessary peptides, amino acids, and ammonia for microbial growth and MCP synthesis, while RUP bypasses rumen degradation (or is undergraded by microbes) and enters the small intestine directly for digestion and absorption with MCP, representing an important protein nutrition pathway. Studies show that 60% of dairy cow protein requirements are provided by RDP and 40% by RUP [37]. Balancing RDP:RUP ratio meets microbial needs while providing adequate small intestinal amino acids (RUP is the second major source). Whole crop wheat at jointing stage had high RDP and RUP contents, indicating high total protein with both high microbially available and unavailable fractions. In later maturity, RDP increased while RUP decreased, indicating more protein became degradable by rumen microbes and less bypassed to the small intestine.

Different RDP contents among feeds cause variation in MCP synthesis. High-protein feeds have higher RDP than high-energy feeds, yielding higher MCP based on RDP, while high-energy feeds yield high MCP based on FOM. Therefore, RENB evaluation can simultaneously meet microbial needs for RDP and FOM, enabling more rational diet formulation. RENB = 0 indicates good balance; negative values indicate RDP excess and energy (FOM) deficiency, requiring more energy; positive values indicate RDP deficiency and energy excess, requiring more RDP. Our results showed RDP was sufficient before flowering but FOM was insufficient, with the opposite after flowering, and good energy-nitrogen balance at flowering stage (RENB 0). Correspondingly, small intestinal protein and digestible protein contents were high when RDP was in excess (jointing and heading stages, RENB<0), and decreased when energy was in excess (flowering, milk, and dough stages, RENB>0), though degradable energy was high in these stages.

4 Conclusion

1. Differences between the two whole crop wheat varieties were minor, with significant differences in only a few indices. While whole crop wheat at each maturity stage had high feeding value, significant differences existed in nutritional value, yield, and rumen degradation characteristics among maturity stages.

2. From perspectives of nutritional value and rumen degradation characteristics, jointing, milk, and dough stages were superior to heading and flowering stages, with milk and dough stages having higher DM yield. In North China, early harvesting can reduce disease, pest, and severe weather risks while benefiting subsequent corn planting and yield.

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