Review Article

Nutritional value, bioactivity, and application potential of Jerusalem artichoke (*Helianthus tuberosus* L.) as a neotype feed resource

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ABSTRACT

The large-scale development of herbivorous animal husbandry in China has increased the demand for forage products. However, due to scarce land resources and poor soil quality, forage is in short supply. In particular, high-quality forage in China heavily relies on imports. The contradiction between supply and demand for forage grass products is increasingly notable. Therefore, the development of indigenous new forage resources with a strong ecological adaptability and a high nutritional value is a key to solving this problem. Jerusalem artichoke (JA, *Helianthus tuberosus* L.), a perennial herb of the genus *Helianthus*, has advantageous growth traits such as resistance to salinity, barrenness, drought, cold, and disease. The contents of crude protein, crude fiber, and calcium in the optimal harvest period of forage-type JA straw are comparable to those of alfalfa hay at the full bloom stage and the straw of ryegrass and corn at the mature stage. Inulin in JA tubers is a functional ingredient that has prebiotic effects in the gastrointestinal tract of monogastric animals and young ruminants. In addition, some bioactive substances (e.g. flavonoids, phenolic acids, sesquiterpenes, polysaccharides, and amino acids) in JA leaves and flowers have antibacterial, anti-inflammatory, and antioxidant functions as well as toxicities to cancer cells. These functional ingredients may provide effective alternatives to antibiotics used in livestock production. In this review, we summarized the potentials of JA as a feed ingredient from the aspects of nutritional value and fermenting characteristics of the straw, the functions of physiological regulation and disease prevention of inulin in the tubers, and bioactive substances in the leaves and flowers.

1. Introduction

Soil salinization, alkalization, and desertification are some key factors leading to the scarcity of pasture resources. Jerusalem artichoke (JA, *Helianthus tuberosus.* L) is a plant with strong stress resistance and considerable nutritional value. It is a perennial herb of the family Asteraceae originally from North America (Cardellina, 2015). Pictures of the whole plant, tubers, leaves, and flowers of JA are shown in Fig. 1.

The functional and bioactive ingredients in the tubers and aerial parts (stems, leaves, and flowers) of JA are beneficial to animal health (Kays and Nottingham, 2007). The inulin in the tuber has been widely reported to be effective in promoting the growth of probiotics, such as *Bifidobacteria* and *Lactobacillus*, regulating intestinal flora, and improving the immune function of animals (Rowland et al., 1998; Kaur and Gupta, 2002). Moreover, the aerial part contains several bioactive substances, such as flavonoids, phenolic acids, terpenoids, and some amino acids (AA), which exhibit antioxidant, anti-inflammatory, antitumor, and antibacterial activities (Pan et al., 2009; Yuan et al., 2012).
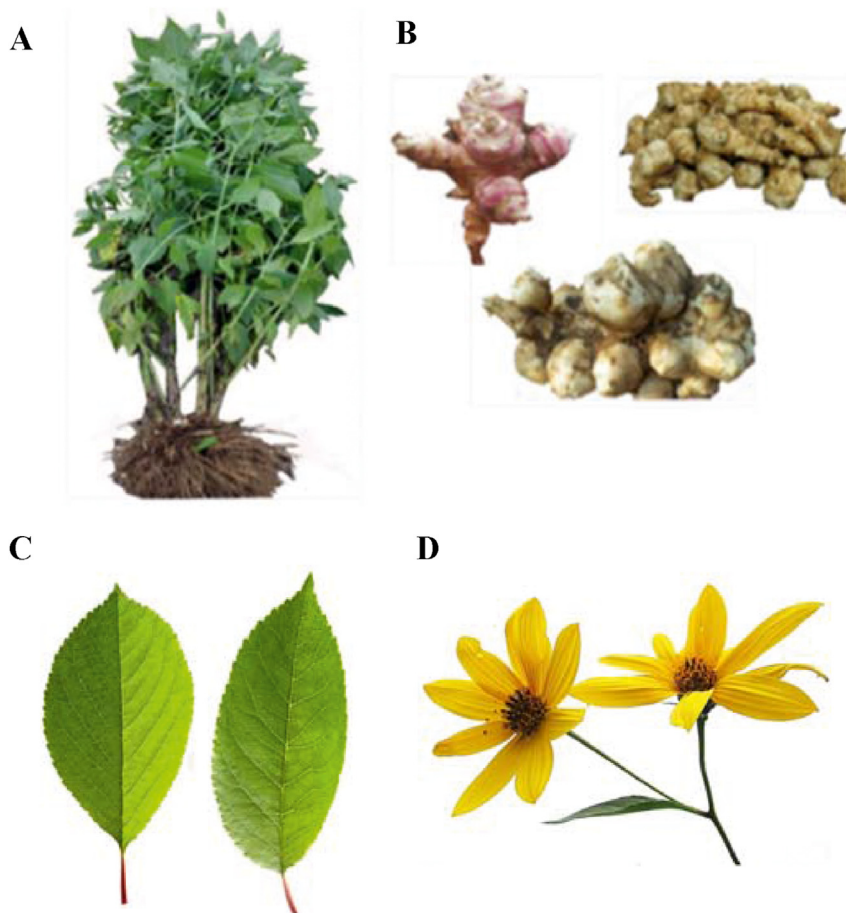
Fig. 1. Jerusalem artichoke (*Helianthus tuberosus* L.): (A) whole plant, (B) tubers, (C) leaves, and (D) flowers.

However, information about the nutritional compositions of JA in the literature is still limited. Additionally, the existing parameters are not consistent because of the effects of different varieties (Kou et al., 2014), growth stages (Saengthongpinit and Sajjaanantakul, 2005), and the storage method and temperature (Honorata et al., 2008). Moreover, the utilization of functional components and bioactive substances in JA in animal production still needs further investigation. Therefore, this paper reviewed the practical application potential of JA in animal production from the aspects of its nutritional composition, functional ingredients, and bioactive effects.

2. Nutrient composition

2.1. Dry matter

The dry matter (DM) content is closely correlated with the growth stages of JA. The main growth stages include the elongation stage (4 to 10 wk after emergence), bud stage (11 to 14 wk after emergence), initial bloom stage (15 to 17 wk after emergence), full-bloom stage (17 to 19 wk after emergence), tuber expansion stage (20 to 24 wk after emergence), and harvest stage (25 to 28 wk after emergence) (Cardellina, 2015). Li et al. (2016) reported that the DM of the leaves, stems, and branches continued to increase from emergence and peaked at the 19th wk, and then gradually decreased.

On the other hand, the accumulation of DM in tubers undergoes 3 stages: 1) a slow accumulation stage from 11 to 17 wk after emergence, during which the tubers begin to form, 2) a rapid redistribution from the aerial parts to tubers from 18 to 19 wk after emergence, and 3) a stabilization stage from 20 to 25 wk after emergence, during which the DM of tubers accumulates continuously but slowly (Mclaurin et al., 1999) (Fig. 2). During this period, the accumulation of DM is derived from an increase in the biomass of tubers. From 17 to 19 wk after emergence, the tubers begin to form and rapidly expand and the number of tubers also increases. At this stage, DM begins to redistribute rapidly from the aerial parts to the tubers. The DM accumulation rate of the tubers is 50.9 g/wk per plant (Mclaurin et al., 1999). From 20 to 25 wk after emergence, the number of tubers continues to increase but slowly stabilized. The increase of DM in tubers indicates the swelling rate of tubers, which reaches 59.5 g/wk per plant at maximum (Zhong et al., 2007). At the time of harvesting, the dry weight production of the tubers reaches14.4 t/ha (Zhong et al., 2007).

2.2. Crude protein and amino acids

According to previous studies, the crude protein (CP) content of the tubers ranges from 2% to 12% DM (Zaldarienė et al., 2013; Huang et al., 2004) (Table 1), and the CP of the aerial parts is between 5% and 21% DM (Hay and Offer, 1992; Bacon and Edelman, 1951)
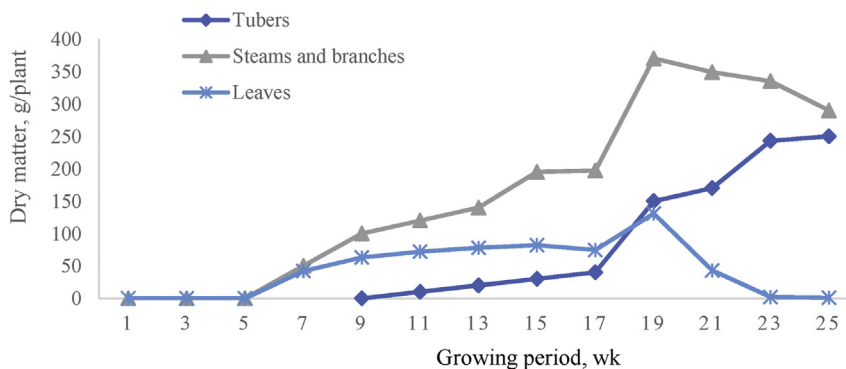
Fig. 2. Dynamics of dry matter accumulation in leaves, stems, and tubers of Jerusalem artichoke during the growing period.

Table 1
Composition of tubers of different varieties of Jerusalem artichoke (JA) (DM basis unless otherwise stated).[1]

Item	Varieties						
	A	R	S	T	L	Q	N
Nutrients, %							
DM, % (fresh weight)	23.2	19.3	22.8	19.8	27.2	22.4	18.8
CP	7.79	6.74	5.12	12.1	9.81	10.16	3.47
Total sugars	81.0	76.8	82.5	68.6	81.2	71.6	74.9
Glucose	0.21	0.21	—	—	—	—	—
Sucrose	8.13	9.56	9.19	8.54	6.05	3.61	6.82
Fructose	0.50	0.80	1.58	0.34	0.48	0.27	1.02
Inulin	75.2	66.2	71.7	71.5	74.7	67.7	67.1
Total starch	0.55	1.60	—	—	—	1.95	—
Total fat	0.83	0.90	0.60	1.57	—	2.71	—
Ash	5.50	6.75	4.85	5.34	5.63	—	8.40
Minerals and trace elements, mg/100 g							
Ca	114	105	136	70.7	57.4	—	157
K	21.0	21.8	25.4	—	4.09	—	11.3
Mg	72.7	90.9	85.4	72.7	56.5	81.0	64.5
P	2,545	2,614	2,155	—	2,210	1,928	2,854
Na	13.6	16.0	—	6.06	4.02	8.57	—
Fe	15.5	3.21	—	17.2	1.84	10.0	2.69
Cu	0.55	0.43	—	0.61	—	—	—
Zn	0.00	0.53	—	60.6	0.69	1.90	—
Amino acids, mg/100 g							
Asp	258	169.5	210	229	620	115	312
Thr	148	155	136	161	220	174	196
Ser	251	252	163	232	190	188	169
Glu	—	242	—	415	990	—	152
Pro	—	—	217	—	340	169	—
Gly	367	369	—	174	200	511	315
Ala	39.0	24.0	17.0	23.0	210	161	24.0
Val	24.0	25.0	—	32.0	40	719[2]	
Met	—	215	—	—	60.0	159	
Ile	30.0	34.0	25.0	—	170	66.0	51.0
Leu	52.0	56.0	52.0	—	280	44.0	42.0
Tyr	6.30	6.10	73.0	8.00	90.0	623[2]	5.00
Phe	64.0	89.0	64.1	111	160	19.0	
Lys	38.0	39.0	37.0	41.0	300	47.0	52.0
His	53.0	56.0	39.0	38.0	220	—	—
Arg	2,364	2,267	1,738	2,151	1,450	2,553	805

—, not detected.
[1] Sources: (A) Albik'; (R) 'Rubik'; (S) 'Sauliai' from Lithuania harvested at 16, 18, and 20 wk after planting (Zaldariene et al., 2013), (T) JA from Thailand harvested at 18 wk after planting (Saengthongpinit and Sajjaanantakul, 2005); (L) JA from Langfang, Hebei, China, harvested at 17 to 19 wk after emergence (China Feed Database, 2019); (Q) JA from Qinghai, China, harvested at 11 to 14 wk after emergence (Huang et al., 2004); (N) JA from Nanjing, China, harvested at 16 to 18 wk after emergence (Kou et al., 2014).
[2] Hydrolyzed amino acid.

Table 2
Composition of leaves and stems of different Jerusalem artichokes (JA).[1]

Ingredients	Varieties					
	A	R	S	T	L	Q
Nutrients, %, DM basis						
CP	10.2	9.79	21.4	5.65	15.2	9.59
Total sugars	18.3	21.8	17.3	14.8	19.5	14.1
Fructose	0.26	0.27	0.26	0.18	—	0.13
Glucose	0.74	—	0.73	0.46	—	0.51
Sucrose	0.08	0.16	0.04	0.04	—	1.28
CF	21.0	23.9	26.1	25.6	27.4	24.3
Lignin	13.6	17.9	18.0	—	—	21.1
Ash	9.68	11.57	13.4	10.88	11.7	13.6
Fat	4.18	1.69	—	1.52	6.14	5.85
Minerals and trace elements, mg/100 g						
Ca	—	291	102	320	760	—
K	3,600	4,500	—	—	—	—
Mg	—	—	690	60.0	—	447
P	105	—	34.0	7.00	26.0	—
Na	5.10		7.00	4.00	—	—
Zn	4.40	6.90	—	—	—	7.20
Fe	—	—	8.00	<0.10	—	—
Mn	—	5.30	—	—	—	—

CF = crude fiber.
[1] Sources: (A) Albik'; (R) 'Rubik'; (S) 'Sauliai' from Lithuania harvested at 16, 18, and 20 wk after planting (ZAldariene et al., 2013), (T) JA from Thailand harvested at 18 wk after planting (Saengthongpinit and Sajjaanantakul, 2005); (L) JA from Langfang, Hebei, China, harvested at 17 to 19 wk after emergence (China Feed Database, 2019); (Q) JA from Qinghai, China, harvested at 11 to 14 wk after emergence (Huang et al., 2004); (N) JA from Nanjing, China, harvested at 16 to 18 wk after emergence (Kou et al., 2014).

(Table 2). Zaldariene et al. (2013) reported that the highest yields of CP in the whole plant were 2,258 to 3,718 kg/ha (6 wk before the tuber harvest), 3,451 to 4,685 kg/ha (2 wk before tuber harvest), and 1,643 to 2,095 kg/ha (in tuber harvest), respectively. The tubers contain 13 to 16 AA and the top 4 AA are Arg, Gly, Asp, and Glu (Cieślik et al., 2011) (Table 1). Moreover, the ratio of essential amino acids to total AA (EAA:TAA ratio) in the tubers is 47.5%, and the ratio of EAA to nonessential AA (EAA:NEAA ratio) in the tubers is 90.7% (Cieślik et al., 2011). This finding is similar to the ideal AA pattern (EAA:TAA ratio = 40% and EAA:NEAA ratio > 60%) in the animal-origin or plant-origin food recommended by the Food and Agriculture Organization (FAO) and World Health Organization (WHO) (Agriculture Organization, 2009), indicating that the tubers is a good source of high-quality protein. Compared with common

roughage, such as alfalfa, ryegrass, and corn straw for ruminants, JA possesses appreciable CP content (Cardellina, 2015; NRC, 2001). The CP of JA leaf powder is 19% DM, which is equivalent to that of alfalfa hay at the early flowering stage. Although the CP content of the whole plant of JA (10% DM) is 3% DM lower than that of alfalfa hay at the mature stage, it is similar to those of alfalfa stem (11% DM) and ryegrass (10% DM).

Source, variety, and growth stage considerably influence the AA composition of tubers. Kou et al. (2014) investigated 29 varieties of JA tubers from France (14), Denmark (11), and China (4) and found a sample from France with the highest content of EAA, which could reach 610 mg/100 g DM. Generally, the content of EAA (especially Met and Lys) in the JA tubers of the red variety is several times higher than those of chicory and potato tubers, and the EAA:TAA ratio is more balanced (Cieślik et al., 2011). Additionally, the contents of Arg and Asp are most abundant at the tuber expansion stage (Saengthongpinit and Sajjaanantakul, 2005).

2.3. Sugar

Jerusalem artichoke tuber has a rich content of soluble dietary fiber and its prime carbon is stored in inulin (43% to 83% DM), which is a fructo-oligosaccharide (FOS). However, the main carbohydrate of other crops (e.g., wheat and corn) is stored in starch (Kays and Nottingham, 2007). The other sugars in JA include fructose, sucrose, and glucose. Maintaining the inulin content and decreasing the content of reducing sugars (e.g., glucose and fructose) during storage are vital to ensure the quality of tubers (Schubert and Feuerle, 2010). The degree of polymerization (dp) is critical to the function of inulin. As depolymerization proceeds, more fructose and glucose are produced (Kays and Nottingham, 2007). Depolymerization is affected by 2 enzymes, fructanexohydrolase and fructan-fructosyltransferase, which activities are inhibited at low temperature (0 to 2 °C) and the hydrolysis rate is significantly decreased (Honorata et al., 2008). In addition, by controlled atmosphere storage has been shown to inhibit depolymerization. The primary benefit of it is to reduce the respiration/metabolic rate, thus effectively reducing the enzyme activity. The degradation rate of inulin is significantly inhibited when the tubers are stored in low O_2 and high CO_2 surroundings, such as 22.5% CO_2 and 20% O_2 (Singh and Goswami, 2006). Furthermore, although irradiation has been proved to facilitate the storage potential of fruits and vegetables by reducing insects, pathogens, and germination loss, the exposure to high radiation (8,000 to 16,000 rad X-rays) greatly accelerates the depolymerization of inulin (Jonard and Parrotmlché, 1970).

2.4. Other nutrients

There is little fat content in the tubers, except for trace monounsaturated and polyunsaturated fatty acids, and no saturated fatty acids are observed (Kays and Nottingham, 2007). The contents of total fat in different varieties of JA are shown in Table 1. The total ash content in the aerial parts (6% to 13% DM) is approximately 2 to 3 times higher than that of tubers (Saengthongpinit and Sajjaanantakul, 2005). In terms of minerals, Ca, K and Mg are quite stable in JA, their concentrations in the aerial parts are approximately 4.5, 3 and 6.5 times than those in tubers, respectively (Tables 1 and 2). Seiler and Campbell (2004) further confirmed that insufficient P in JA resulted in a high Ca-to-P ratio ranging from 4.8:1 to 37.4:1 at the flowering stage. Therefore, additional P or other feeds with rich P content are necessary while JA is fed to animals in a larger proportion of diets. Furthermore, the contents of Na, K, P, Ca, and Mg and Ca-to-P ratio are affected by the genotypes of JA, suggesting the possibility of

improvement through hybridization and selection (Seiler, 1988). Many studies have shown that alfalfa is a good source of Ca for cows (Ai et al., 2002). Latest data have proven that the Ca content in JA straw can be comparable to that in alfalfa, corn straw, and ryegrass (China Feed Database, 2019). The Ca content in the whole plant of JA is from 10% to 17% DM, which is higher than that of alfalfa (6% to 15% DM), corn straw (2% to 7% DM), and ryegrass (6% to 8% DM). The P content in the whole plant of JA is from 0.16% to 0.45% DM, whereas it is 0.18% to 0.30% DM in alfalfa, 0.19% to 0.26% DM in corn straw, and 0.09% to 0.30% DM in ryegrass (NRC, 2001). Moreover, the crude fiber (CF) content of JA is moderate. Ruminants can effectively digest roughage, which provides approximately 70% to 80% of their energy requirements through rumen fermentation. The utilization efficiency of roughage depends on the content and structure of CF. The CF content (31% DM) of the whole JA is close to that of alfalfa hay (30% DM) in the middle flowering period and ryegrass (33% DM) (China Feed Database, 2019).

There are abundant vitamin C (7 to 26 mg/100 g DM), carotenoids (48 to 131 mg/100 g DM), and folic acid (53 to 87 μg/100 g DM) in the tubers of JA. However, the vitamin concentration is highly influenced by the growth stage, moisture content, cutting time, and storage method. The lignin content in the JA straw is commonly low from 11 to 14 wk after emergence. Hence, harvest at bud stage has no effect on palatability (Kays and Nottingham, 2007; Cardellina, 2015).

3. Application of Jerusalem artichoke as feed

3.1. Potential as a high-quality roughage

The net energy for lactation (NE_L) of JA straw (6.11 MJ/kg DM) is higher than that of corn straw (5.15 MJ/kg DM), eared corn straw (6.07 MJ/kg DM), rye straw (3.97 MJ/kg DM), alfalfa hay (4.52 to 5.44 MJ/kg DM), and alfalfa stem (4.23 MJ/kg DM) (NRC, 2001). Furthermore, the leaves of JA are thin and fragile and the stems can also be broken into small particles, resulting in faster rumen degradation and absorption (Hay and Offer, 1992). Ersahince and Kara (2017) reported that JA herbage at the vegetative stage could increase true DM disappearance, true organic matter disappearance, in vitro gas yield, and total volatile fatty acid (VFA) concentrations in both horse and ruminant rumen fluids. Papi et al. (2019) reported that DM intake increased linearly by the substitution of alfalfa with dry JA, which may be attributed to the better palatability and acceptability of JA. The above studies prove that JA has a potential to be used as a good quality forage because of its moderate nutrient composition and satisfactory digestibility for ruminants.

Moreover, the aerial parts of JA have a strong reproductive ability, which can be harvested 3 to 4 times a year (Cardellina, 2015). Biomass production of fresh and air-dried plants can be from 108 to 134 t/ha and 42 to 73 t/ha, respectively (Long et al., 2016), making this plant an ideal resource for silage.

3.2. Jerusalem artichoke silage

3.2.1. Ensiling characteristics

The FOS in stems and branches are favored substrates for lactic acid bacteria fermentation (Koczon et al., 2019). Meneses et al. (2007) reported that the DM content of JA straw before making silage was 295 g/kg, which was in line with the results of several other crops (e.g., wheat, oats, and corn) (250 to 300 g/kg) measured by Wilkins (1982). The DM content of JA silage after fermentation for 50 d is 275 g/kg, which is also well within the high-quality silage reference range (280 ± 10 g/kg) (Mcdonald et al., 1966). Furthermore, the maximum lactic acid content (32.4 g/kg of DM) appears

at 21 d after ensiling. Finally, this value decreases to 20.1 g/kg DM, composing 57.9% of the total organic acid (Meneses et al., 2007), which coincides with the optimal lactic acid concentration in superior silage (50.1% to 60% of the total organic acid) recommended by Mcdonald et al. (1966). Chabbert et al. (1983) suggested that the silage quality would become poor if the ammonia nitrogen (NH$_3$–N) content exceeded 7 g/kg DM. The NH$_3$–N content of JA silage is from 0.20 to 0.80 g/kg DM, which is considerably lower than 7 g/kg DM (Meneses et al., 2007), indicating little degradation of protein during fermentation. The pH of JA silage is over 4.6 (Koczon et al., 2019), indicating weak acidogenesis through direct ensiling. Thus, it is necessary to mix corn or *Lactobacillus* together with JA to enhance the ensiling process (Kononoff et al., 2003). Liu et al. (2017) designed a mixture of corn straw and JA straw in ratios of 10:0, 6:4, 2:8, and 0:10 for ensiling and found that the pH and fiber content in the mixed forages decreased with the increase of JA straw, whereas the NDF degradability and relative feed value increased.

Therefore, JA straw has a potential to be a high-quality silage due to advantages such as high biomass yield, abundant FOS, suitable DM, lactic acid content, and extremely low NH$_3$–N concentration. Moreover, the silage quality can be improved by mixing JA with acid-producing bacteria or high acid-producing feedstuffs.

3.2.2. Feeding value

In comparison with other major silages, JA silage has relatively higher CP and Ca and lower NDF contents. The CP (11.6% DM) of JA silage is higher than that of corn silage (8.80% DM) and close to that of oat silage (12.9% DM) and barley silage (12% DM). The Ca content (1.36% DM) of JA silage is comparable to that of legume forage silage (1.34% DM) and significantly higher than that of corn silage (0.28% DM) (NRC, 2001; China Feed Database, 2019). The NDF content of JA silage (43.9% DM) is lower compared with other silages, such as yellow corn silage (45.0% DM), barley silage (56.3% DM), and oats silage (60.6% DM) (Table 3). High levels of NDF in diets can decrease the consumption of the nonfibrous carbohydrates and the synchronization of energy and nitrogen (Pinho et al., 2019). As shown in Table 4, the digestible energy and metabolizable energy of JA silage for lactating cows (11.9 and 9.20 MJ/kg DM, respectively) are comparable to those of corn silage (12.5 and 9.75 MJ/kg DM, respectively). The NE$_L$ (7.78 MJ/kg DM) of tubers in dairy cows is similar to that of potato (7.74 MJ/kg DM) and higher than that of sugar beet (6.15 MJ/kg DM) (Table 4). Papi et al. (2017) demonstrated that substituting maize silage with JA silage (200 g/kg DM) had no adverse effect on the growth of lambs. Razmkhah et al. (2017) performed to assess the effects of dietary substitution of different levels of JA silage for corn silage on sheep rumen fermentation. The result showed that, with replacing corn silage by JA silage, the ruminal NH$_3$–N concentration tended to decrease and VFA tended to increase, but rumen protozoa and pH remained unchanged. Moreover, it also had no adverse effects on DMI and DM

Table 4
Comparison of digestible energy (DE), metabolizable energy (ME) and net energy for lactation (NE$_L$) of dairy cows in Jerusalem artichoke and other main feeds (MJ/kg DM).

Feed name	DE	ME	NE$_L$
Jerusalem artichoke silage (squaring stage)[1]	11.9	9.20	–
Jerusalem artichoke tuber[2]	10.1	–	7.78
Corn yellow silage (normal, 32% to 38% DM)[3]	12.5	9.75	6.07
Barley silage[3]	11.2	8.49	5.19
Oats silage (head)[3]	10.6	7.99	4.81
Ryegrass silage (annual, vegetative stage)[3]	11.4	8.70	5.36
Sorghum silage (feed)[3]	10.1	7.49	4.48
Wheat silage (head)[3]	10.7	7.99	4.85
Potato[3]	14.7	11.9	7.74
Beet sugar (dried)[3]	12.7	9.87	6.15

[1] Adapted from Liu et al. (2017); Zhao et al. (2006).
[2] Adapted from Hay and Offer (1992).
[3] Adapted from NRC (2001).

digestibility. Zhao et al. (2006) stated that 1 kg DM of JA silage ('Kulista czerwona' variety) could provide 9.25 MJ digestible energy to lambs. Thus, it can be seen that the aerial parts of the JA can be used as a potential resource to produce silage for ruminants.

4. Function and application of the main components of Jerusalem artichoke

4.1. Function and application of inulin in monogastric animals

Inulin is a linear polysaccharide linked by 31 β-D-fructofuranose and 1 to 2 glucopyranose residues with a glucose residue at the end. The chemical structure determines its hydrolytic resistance to enzymes in the digestive track (Rowland et al., 1998). As a plant polysaccharide, the physiological activity of inulin is closely related to dp. The inulin dp ranges from 2 to 60 (Kays and Nottingham, 2007). Ito et al. (2011) compared the bioactivity of inulin with 7 different dp and found that dp has negative relationship with activity. Inulin has been well recognized as a prebiotic that can effectively regulate intestinal microbiological balance and immune response, thereby improve animal performance (Kaur and Gupta, 2002). To date, the application of inulin has mainly focused on monogastric animals, with little research available in ruminants.

4.1.1. Regulation of intestinal microflora and intestinal environment

The effect of inulin on the intestinal microflora is mainly achieved by direct and indirect pathways: 1) Specific binding of inulin to lectin on the pathogen cell surface competitively inhibits the binding of the pathogen to the surface of the intestinal mucosa (Valdovska et al., 2014); 2) Inulin could be digested and utilized by beneficial bacteria (e.g., *Bifidobacterium* and *Lactobacillus*) present in the colon to produce VFA, lowering the intestinal pH and redox potential and therefore inhibiting harmful bacteria, such as

Table 3
Comparison of silage nutrients between Jerusalem artichoke and several main feeds (%, DM).

Silage	DM	CP	EE	Ash	NDF	ADF	Lignin	Ca	P
Jerusalem artichoke silage (squaring stage)[1]	25.8	11.6	1.60	5.90	43.9	31.7	7.50	1.36	0.20
Yellow corn silage, normal (32% to 38% DM)[2]	35.1	8.80	3.2	4.30	45.0	28.1	2.60	0.28	0.26
Barley silage[2]	35.5	12.0	3.5	7.50	56.3	34.5	5.60	0.48	0.30
Oats silage (head)[2]	34.6	12.9	3.4	9.80	60.6	38.9	5.50	0.52	0.31
Ryegrass silage (annual, vegetative stage)[2]	29.7	16.1	3.80	9.60	57.8	34.9	4.50	0.43	0.42
Sorghum silage (feed)[2]	28.8	10.8	3.60	10.9	63.3	40.7	5.90	0.64	0.24
Wheat silage (head)[2]	33.3	12.0	3.20	8.60	59.9	37.6	5.80	0.38	0.29

[1] Adapted from Liu et al. (2017).
[2] Adapted from NRC (2001).

Escherichia coli and *Salmonella* (Kaur and Gupta, 2002). Also, *Bifidobacterium* can secrete a large amount of extracellular glycosidase to degrade the intricate polysaccharides produced by intestinal mucosal epithelial cells, further preventing the adsorption of pathogens and their toxins on intestinal mucosal epithelial cells (Zhang et al., 2016). Adding inulin at 0.2% DM to piglets feed can significantly reduce the number of rectal fecal *E. coli* and increase the number of *Lactobacillus* (Valdovska et al., 2014). Adding inulin at 6 g/kg DM in the broiler chicken diet can significantly increase the cecal mucosal crypt depth and cell density (Nabizadeh, 2012).

4.1.2. Improving intestinal tissue morphology

The main degradation products of inulin after microbial fermentation are short-chain fatty acids (SCFA), which serve as the dominating energy source for the proliferation of intestinal mucosal cells and increase antimicrobial peptide production (Munjal et al., 2012). Chronic or indirect SCFA deficiency will result in intestinal flora utilizing the mucosal glycoprotein secreted by the host as a nutrient source, erode the intestinal mucosal barrier, and further prompt more pathogens to enter the intestinal epithelium, consequently contributing to fatal colitis (Desai et al., 2016). Moreover, inulin can increase crypt depth, cell density, and cecal wall weight (Ortiz et al., 2009). Nabizadeh (2012) added inulin (6 g/kg DM) to a broiler chicken diet and found that the villus length of the small intestine and crypt depth were 12.3% and 18.2% higher than those of the control group, respectively. The thickness of the intestinal wall was reduced by 27.1%, which made the intestinal mucosa thin, promoted the absorption of nutrients, improved the feed conversion rate, and increased the growth of animals.

4.1.3. Enhancing immunity

Inulin generally enhances immune function in the following ways: 1) It is directly involved in cellular and humoral immune regulation as an immune adjuvant and antigen. For example, inulin stimulates helper T lymphocytes to secrete interleukin-2 and γ-interferon, which can activate white blood cells (Zhang et al., 2014); 2) Phagocytic cells are activated via the proliferation of *Bifidobacterium* in the intestine (Zhang et al., 2016); 3) Inulin is fermented by intestinal flora to produce more SCFA and lactic acid, which reduces the intestinal pH value. The generated H^+ can be exchanged with metal ions to increase the solubility of minerals, such as Ca, Mg, Zn, and Se. The increased absorption of minerals can improve antioxidant status and non-specific immunity (Kelly-Quagliana et al., 2003); 4) Inulin promotes the secretion of glycoproteins from the liver, which can bind bacteria and then activate a series of complements triggering the immune response (Verdonk et al., 2005); 5) Inulin specifically binds the mitogen lectin on the surface of the pathogen, thereby slowing down the absorption of antigen and further increasing the antigen titer (Gallovic et al., 2017).

The mechanism of inulin to exert prebiotic activities in monogastric animals is that it is not digested by enzyme hydrolysis, so it can be successfully utilized by the intestinal probiotics such as *Bifidobacterium* and *Lactobacillus*. During the proliferation of probiotics, on the one hand, it improves the intestinal environment and inhibits the pathogens. On the other hand, it can generate a lot of SCFA to provide substantial energy substrates for the intestinal mucosa cells and immune cells.

4.2. Function and application of inulin in ruminants

Fermentation of inulin improves nitrogen metabolism in the rumen (Umucalilar et al., 2010). The NH_3–N concentration is determined by protein breakdown and NH_3–N utilization of rumen microorganisms (Abe and Kandatsu, 2009). It has been reported

that adding inulin (3% DM) to a cow diet and feeding for 4 wk reduces the rumen NH_3–N concentration by 7.38%, indicating that inulin provides extra energy for the growth of rumen microorganisms and balances the ratio of carbohydrates to nitrogen, which may contribute to the synthesis of microbial protein in the rumen (Umucalilar et al., 2010). Compared to starch, inulin increased butyrate and reduced acetate in the rumen, which may be due to a difference in the microbial species fermenting starch and inulin (Zhao et al., 2014). In the study of Biggs et al. (1998), inulin did not inhibit fibrinase activity, but was adverse to *Fibrobacter succinogenes* and *Ruminococcus flavefaciens* which were the main cellulolytic bacteria in the rumen. This was probably because inulin was degraded to fructose in the rumen, however, *F. succinogenes* and *R. flavefaciens* utilized glucose and cellobiose as growth substrates. Also, inulin can boost the abundances of other rumen cellulolytic bacteria, such as *Pseudomonas* and *Bacteroides ruminicola*. In contrast, protozoa have an advantage in utilizing inulin over bacteria. Inulin can improve the proliferation of *Entodinium* and *Polyplastron multivesiculatum* feeding on plant fiber to accelerate the decomposition of cellulose and to promote digestion in ruminants (Ziolecki et al., 1992).

Few studies of inulin's effects in ruminants have been reported, mainly due to 2 reasons: 1) Rumen microbes have a strong degradation effect on FOS and the addition of inulin will be degraded; 2) Cellulose, hemicellulose, and pectin in the rumen can also produce a lot of FOS, so there is no need to add inulin (Kaur and Gupta, 2002). However, with the increasing understanding of the mechanism of inulin, it was also found to exert a positive effect on the ruminal microflora structures, rumen fermentation performance, immunity, nutrient digestibility and production performance (Umucalilar et al., 2010).

4.3. Bioactive effects

Flavonoids, phenolic acids, and sesquiterpenoids are 3 main bioactive constituents of JA (Table 5), which effectively participate in biological processes such as antioxidant, antitumor, anti-inflammatory, and antibacterial activities (Yuan et al., 2012). The contents of main bioactive substances in JA vary greatly. The total flavonoid content can be as high as 86.4 mg/g DM and as low as 49.4 mg/g DM (Kim et al., 2013). The total phenolic acid content is from 21.6 to 67.3 mg/g DM (Weisz et al., 2009). And, the total terpenoid content can reach 54.9 mg/g DM at maximum, whereas the minimum is only 14.1 mg/g DM (Baba et al., 2005). Variety, growth stage and area, as well as harvest time have a great influence on the content of these bioactive substances (Cardellina, 2015). Additionally, the process conditions for extraction, such as extraction method, reagent, temperature, and time as well as solid-to-liquid ratio, are also affecting factors (Won et al., 2013). In general, the contents of various bioactive substances in the aerial parts of JA at the flowering stage are much greater than those at the bud and tuber expansion stages (Kays and Nottingham, 2007). Besides, extraction with 70% volume fraction of methanol with the solid-to-liquid ratio at 1:30 (g/mL) and at 80 °C for 2 h was reported as the appropriate extraction condition for total flavonoids and phenolic acids (Won et al., 2013). Furthermore, the solvent extraction, silica gel column chromatography, and gel Sephadex LH-20 column chromatography are used to concentrate the terpenoids component and can obtain more than 45% total terpenoids component (Wang, 2015).

4.3.1. Antioxidant property

Flavonoids can scavenge free radicals at the initiation phase in chain reactions or directly capture free radicals (Kim et al., 2013). Heo et al. (2007) reported that when the concentration of flavonoid

Table 5
Bioactive components in the aerial parts of Jerusalem artichoke[1].

Category	Compound
Flavonoid	desacetyleupaserrin, hymenoxin, nevadensin, kaempferol gluconate, kaempferol-3-o- glucoside, kaempferol, rutin, andrographin, nobiletin, silymarin, puerarin, rhamnazin
Phenolic acid	3,4-dicaffeoylquinic acid, 3-feruloyl-quinic acid, chlorogenic acid, 1,5-dicaffeoylquinic acid, catechin, salicylic acid, epigallocatechin gallate, p-coumaroyl-quinic acid
Sesquiterpenoids	17,18-dihydrobudlein A, heliannuols A, D, niveusin B, argophyllin A, B, heliangine, 3-ethoxyniveusin B, 15-hydroxy-3-dehydrodesoxytifruticin, ciliaric acid, angelylgrandifloric acid
Sesquiterpene lactone	desacetyleupaserrin, annuithrin, argophyllin a, heliangine, 3-hydroxy-8b-tigloyl-oxy-1,10-dehydroarigloxin, eupatoliade
Amino acids	tyrosine, isoleucine, valine
Polysaccharide	*Helianthus annuus* polysaccharide, arabinose,
Sterols	Δ7-stigmastenol, Δ7-campestenol
Essential oil	(E)-2-hexen-1-ol, tricyclene, α-thujene, (e)-ocimene, γ-terpinene

[1] Analyzed by our laboratory.

extracts in blood reached 100 μg/mL, the clearance rates of superoxide anion radicals ($O_2 \cdot^-$) and hydroxyl radicals ($\cdot OH^-$) were 66.5% and 69.3%, respectively. In vivo experiments proved that the addition of total flavonoid extracts (45 mg/kg DM) from JA to a sheep diet significantly increased the total antioxidant capacity of serum and liver. In addition, the total superoxide dismutase activity in serum, liver, and spleen, catalase activity, and glutathione peroxidase activity in serum and spleen were also enhanced, but serum and liver malondialdehyde contents were reduced (Wang et al., 2017). The main component of chlorogenic acid belonging to phenolic acids in JA, 3-caffeoylquinic acid, could elevate the scavenging ability of 1,1-diphenyl-2-picrylhydrazyl radical (DPPH radical) and diammonium 2,2′-azino-bis(3-ethylbenzothiazoline-6-sulfonate) after mixing with 3% to 45% flavonoids, such as quercetin, α-tocopherol, and rutin (Kays and Nottingham, 2007; Kapusta et al., 2013). Therefore, the flavonoids and phenolic acids in JA or the synergistic effect of both can exert antioxidant effects by removing various free radicals.

4.3.2. Anti-inflammatory property

Sesquiterpenoids are particularly effective anti-inflammatory substances with a special mechanism to influence inflammatory mediators and pathways (Baba et al., 2005). Furthermore, α-methylene-γ-lactone is considered as an essential anti-inflammatory molecule of sesquiterpenes (Sut et al., 2018). Prostaglandin E_2 (PGE_2) is a pro-inflammatory mediator produced by arachidonic acid catalyzed by cyclooxygenase-2 (COX-2) (Nakanishi and Rosenberg, 2013). Choi et al. (2012) found that santamarin, a sesquiterpene lactone isolated from JA, at 40 μmol/L, could significantly inhibit the expression of COX-2 and PGE_2 in lipopolysaccharide-stimulated leukemia cells in mouse macrophage (RAW 264.7). Inducible nitric oxide synthase in tissues is largely produced during the inflammatory response, which could intensify inflammatory reactions (Clancy et al., 1998). However, the sesquiterpene lactones lychnopholide and ermantholide C isolated from flowers of JA could effectively diminish nitric oxide in mononuclear macrophages in mice (J774.A1) induced by lipopolysaccharide or γ-interferon (Hall et al., 2010).

In addition, the sesquiterpenoids also participate in inflammatory signaling pathways (nuclear factor kappa-B [NF-κB], mitogen-activated protein kinase [MAPK], and signal transducer, and activator of transcription [STAT]) and the transcriptional processes of inflammation-related genes. The binding activity of NF-κB to DNA and NF-κB-related genes can be selectively inhibited by sesquiterpene lactones. The inhibition of inflammatory gene transcription is realized by altering the inhibitor of NF-κB (IκB)/NF-κB complex, as well as interfering with the release of IκB kinase (Lyss et al., 1998). Hye et al. (2015) confirmed that alantolactone, which is a

sesquiterpene extract from *Cichorium intybus* L., could inhibit the phosphorylation of STAT1 induced by tumor necrosis factor-α (TNF-α) and γ-interferon in HaCaT cells, and consequently reduce the production of RANTES (cytokines that regulate T cell expression and secretion) and IL-8. Moreover, the compound, (5S, 7S, 9S, 10S)-(+)-9-hydroxyselina-3,11-dien-12-al (HHX-5), which is a sesquiterpene from JA flowers, could restrain the activation of macrophages and neutrophils in the innate immune system and inhibit adaptive immunity by suppressing the differentiation of initial CD4+ T cells into helper T cell 1 (Th1), Th2, and Th17 cells (Zhu et al., 2016). The mechanism of HHX-5 indicated that it could significantly inhibit the STAT1 signaling pathway in macrophages and the STAT1, STAT4, STAT5, and STAT6 signaling pathways in naive CD4+ T cells (Zhu et al., 2016). In Th cells, the phosphorylation of p38 MAPK and extracellular signal-regulated kinase (ERK) could be reduced by sesquiterpene lactone under polarized conditions, assisting the alleviation of inflammation (Park et al., 2016).

The anti-inflammatory mechanism of sesquiterpenes in JA is mainly through inhibiting the activation of the inflammation-related signaling pathway, such as NF-κB, MAPK, and STAT. Additionally, the sesquiterpenes in JA also has effects in down-regulating the expression of inflammatory factors, such as tumor necrosis factor-α, PGE_2, nitric oxide, IL-1, IL-6, and IL-8.

4.3.3. Antitumor property

The elimination of toxic chemical carcinogens and the inhibition of tumor cell growth could be achieved by flavonoids, terpenoids, and certain specific proteins isolated from the aerial parts of JA (Yuan et al., 2012). The flavonoids worked mainly through the inhibition of cell proliferation, induction of apoptosis, intervention of cell signal transduction, enhancement of tumor suppressor gene activity, and inhibition of oncogene expression (Kanadaswami et al., 2005). Antitumor tests verified that flavonoid extracts in blood (200 μg/mL) could inhibit the growth of human nasopharyngeal carcinoma cells (KB), human hepatoma cells (Hep G-2), and human leukemia cells (K562) (Kanadaswami et al., 2005). Pan et al. (2009) isolated 9 compounds from the aerial parts of JA with cytotoxic effects to MCF-7 human breast cancer cell lines, including 3 diterpenoids, 2 germacrane sesquiterpene lactones, lignans, norisoprenoid, and benzaldehyde derivatives. Of these compounds, germacrane sesquiterpene lactones had the strongest cytotoxicity. The cytotoxic effect of sesquiterpenoids is mainly due to their free conjugated α-methylene-γ-lactone. However, if the structure changes, the cytotoxicity will decrease or be completely inactive (Kupchan et al., 1971). Griffaut et al. (2007) obtained a protein complex in JA leaves by double stress-cutting and drying treatment, which had strong toxic effects on various human tumor cells (e.g., MCF-7 MDA-MB-231 breast cancer cells, Caco2 and DLD1 colon cancer cells, PA1 and

SKOV3 ovarian cancer cells, A549 lung cancer cells, and PC3 prostate cancer cells). The study further showed that the antitumor activity of the protein complex was attributed to an 18-kDa polypeptide that is homologous to superoxide dismutase and a 28-kDa peptide tightly associated with alkaline phosphatase, which is bound to the 18-kDa polypeptide to form the active site of the protein complex.

In summary, the flavonoids, terpenoids, and some protein complexes in JA mainly exert antitumor effects by inhibiting tumor cell proliferation and toxic effects on tumor cells.

4.3.4. Antibacterial property

Phenolic acids are the main source of plant bacteriostatic agents. The sesquiterpenes also had broad-spectrum antibacterial properties, for instance, *proteus, spherical spores Bacillus, E. coli, Klebsiella pneumonia, Staphylococcus aureus*, and *Hemolytic streptococcus* (Dai et al., 2001). The leaves of JA contain a special polypeptide consisting of abundant Pro and Arg with a similar molecular structure of antimicrobial peptides targeting Gram-negative bacteria in mammals (Otvos, 2002). After entering the bacterial cytoplasm, this antimicrobial peptide specifically binds to the bacterial heat shock protein DnaK, which could refold misfolded proteins and inhibit DnaK's activity. Thus, the leaves of JA have a potential to treat Gram-negative bacterial infections in mammals.

In summary, the antibacterial activities of phenolic acid and sesquiterpene in JA are closely related to their chemical structure. The α-methylene-γ-lactone is considered to be an essential group for the antibacterial effect of sesquiterpene. Meanwhile, compounds with strong antibacterial properties among phenolic acid compounds generally exist in the form of esters.

5. Conclusion

Jerusalem artichoke has valuable nutrient contents and various bioactive compounds, so it has wide application prospects in animal production and animal health. The aerial parts of JA as roughage and silage had high nutrient values and satisfactory digestion performance for ruminants. However, further studies and in-depth research of JA are still needed. The research directions and key issues might be on the following 3 aspects: 1) various parts of JA for feeding various ruminants, 2) the ruminal degradation rate of inulin in JA and its appropriate dosage, 3) the mechanism of inulin in JA on rumen metabolism and microflora, and 4) the antioxidant, anti-inflammatory, and tumor cytotoxicity mechanism of the bioactive substances in JA straw, leaves, and flowers. In conclusion, further studies are warranted to characterize the development and utilization of JA as a novel feed resource and as a functional herbal additive in animal production and health.

Conflict of interest

We declare that we have no financial and personal relationships with other people or organizations that can inappropriately influence our work, there is no professional or other personal interest of any nature or kind in any product, service and/or company that could be construed as influencing the content of this paper.

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