Comprehensive REVIEWS in Food Science and Food Safety

Polyphenols in Common Beans (*Phaseolus vulgaris* L.): Chemistry, Analysis, and Factors Affecting Composition

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Abstract: Common bean (*Phaseolus vulgaris* L.) is one of the most important grain legumes worldwide. Polyphenols are the predominant bioactive components with multifold bioactivities in diverse common bean cultivars. Phenolic acids, flavonoids, and proanthocyanidins are the main polyphenols in common beans, and colorful common beans are overall rich in polyphenols, mainly in their pigmented seed coats. In addition, factors of influence, such as genotype, environmental conditions, storage, and processing methods, play a critical role in the content and composition of common bean polyphenols. Besides, analytical methods, including extraction, separation, and identification, are of importance for precise and comparable evaluation of polyphenols in common beans. Therefore, in order to provide a comprehensive and updated understanding of polyphenols in common beans, this review first summarizes the content and different compositions of polyphenols in common beans, and next discusses the factors affecting these compositions, followed by introducing the analytical methods for common bean polyphenols, and finally highlights the antioxidant activity of polyphenols in common beans. Considering the recent surge in interest in the use of grain legumes, we hope this review will further stimulate work in this field by providing a blueprint for further analytical studies to better utilize common bean polyphenols in food products to improve human nutrition.

Keywords: common bean, processing methods, analytic methods, antioxidant activity, phenolic composition

Introduction

Common beans (*Phaseolus vulgaris* L.), also known as navy, pinto, red kidney, or French beans, are a valuable food source for humans around the world. They are regarded as an important constituent of healthy diets not merely because of their high nutritional value (rich in protein and low in fat) but also owing to their functional properties. The main functional components of common beans are carbohydrates, vitamins, phytate, lectins, soluble fiber, and phenolics. Phenolics, which include phenolic acids, flavonoids, and proanthocyanidins, are particularly notable because of their potent antioxidant properties (García-Lafuente et al., 2014). For example, small red beans (*Phaseolus vulgaris* L.) showed the highest antioxidant activity out of 100 common foods (Wu et al., 2004). Epidemiological investigations have indicated that the consumption of legumes with high phenolic content and high antioxidant value was associated with reduced risk of many chronic conditions such as obesity, diabetes, heart diseases, and even certain types of cancer (Curran, 2012). Moreover, common bean extracts rich in polyphenols were reported to show anti-inflammatory, antioxidant, antimutagenic, chemopreventive, and antibacterial effects (Aparicio-Fernández et al., 2006; Frassinetti, Gabriele, Caltavuturo, Longo, & Pucci, 2015; Gan et al., 2016; García-Lafuente et al., 2014). Therefore, as a dietary component, common beans have considerable health benefits.

Scientific studies of the phenolic content, composition, and health benefits of common beans have increased considerably in the past few decades. In these studies, total phenolic content (TPC) and antioxidant activities are generally reported, but they may be obtained by different and not directly comparable methods. Variation in phenolic composition and antioxidant activities among common bean cultivars and their processed products have also been widely studied (for example, Aquino-Bolaños et al., 2016; Luthria & Pastor-Corrales, 2006; Oomah, Cardador-Martínez, & Loarca-Piña, 2005; Ranilla, Genovese, & Lajolo, 2007; Rocha-Guzmán, González-Laredo, Ibarra-Pérez, Nava-Berúmen, & Gallegos-Infante, 2007). Growing location (environment) and genotype, and genotype × environment interaction, may all strongly influence the phytochemical composition of common beans, and much of the variation discussed is closely related to genetics and growing locations (Barampama & Simard, 1993; Beninger, Hosfield, and Bassett, 1999; Beninger & Hosfield, 1999b; de Mejía et al., 2003; Dinelli et al., 2006; Islam, Rengifo, Redden, Basford, & Beebe, 2003; Valdés, Medeiros Coelho, Michelluti, & Cardoso García Tramonte, 2011). In addition, quite a number of studies have also been conducted

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doi: 10.1111/1541-4337.12391

to identify and quantify phenolic compounds in common beans. Numerous groups of phenolic compounds have been isolated and identified in common beans, including phenolic acids, flavonoids, anthocyanins, and proanthocyanidins.

Since the demand for phenolics is steadily increasing, it is worthwhile to review the TPC, total flavonoid content (TFC), total proanthocyanidins content (TPAC), and composition of phenolic compounds in common beans. Furthermore, considerable research efforts have been devoted to finding more specific and efficient phenolics with minimum side effects and high health benefits. Then, these phenolics may be applied in the food and pharmaceutical fields. Therefore, based on Web of Science, we searched for English articles on common beans from 1990 to 2017. In this review, we summarize the TPC, TFC, TPAC, and main polyphenols in common beans, summarize the factors influencing phenolic content and composition, including environmental conditions, genotype, storage, germination, and thermal processing, briefly describe current methods used for the extraction, separation, and identification of common bean phenolics, and finally highlight the antioxidant activities of common beans.

Polyphenols in Common Beans

Total phenolic content

Phenolics, which have at least one phenol unit with one or more hydroxyl substituents, are a type of secondary metabolites in plants (Akyol, Riciputi, Capanoglu, Caboni, & Verardo, 2016; Gan, Li, Gunaratne, Sui, & Corke, 2017). Phenolics are broadly classified as phenolic acids, flavonoids, proanthocyanidins, stilbenes, and coumarins (Nayak, Liu, & Tang, 2015). Their presence gives common bean seeds diverse colors. Phenolics are found in both the cotyledons and seed coats of common beans, but most are concentrated in the seed coats (Aquino-Bolaños et al., 2016). The TPC of common beans has been extensively reported and the data are scattered across many research articles. We have compiled this scattered information and summarized it (Table 1), showing that the TPC of common beans has been determined in the range of not detectable (ND) to 4871 mg gallic acid equivalents per 100 g dry weight (mg GAE/100 g DW). The remarkable position of pinto kidney bean should be emphasized because its TPC in seed coats had the highest level (4871 mg GAE/100 g DW) among diverse common bean cultivars (Gan et al., 2017).

Polyphenol composition

In the past few decades, many studies have investigated the phenolic composition of various common bean cultivars. Here, we summarize the main phenolic compounds identified in common beans (Figure 1), including phenolic acids, flavonoids, proanthocyanidins, and coumarins.

Phenolic acids

According to the chemical structure, phenolic acids in plants can be divided into hydroxycinnamic acids and hydroxybenzoic acids. Sixteen hydroxycinnamic acids and 12 hydroxybenzoic acids have been identified in common beans (Figure 1). Caffeic, *p*-coumaric, sinapic, and ferulic acids are the most common hydroxycinnamic acids in common beans. In addition, gallic, *p*-hydroxybenzoic, protocatechuic, vanillic, and syringic acids are the most frequently occurring hydroxybenzoic acids in common beans (Table 2). Hydroxycinnamic acids frequently occur in foods as esters with quinic acid or sugars, while hydroxybenzoic acids are mainly present in foods as glycosides. In the plant kingdom, phenolic acids mainly exist in free or bound forms in plant cells. Recently, free and bound phenolic acids in regular- and non-darkening cranberry beans (*Phaseolus vulgaris* L.) were studied, and three hydroxycinnamic acids (*p*-coumaric, ferulic, and sinapic acid) and 1 hydroxybenzoic acid (*p*-hydroxybenzoic acid) were identified (Chen et al., 2015b). Lopéz et al. (2013) investigated the phenolic composition in dark beans (*Phaseolus vulgaris* L.) and identified 22 phenolic compounds in either free or conjugated forms, the majority of which were phenolic acids consisting of protocatechuic, feruloyl aldaric, *trans*-ferulic, *p*-coumaryl aldaric, sinapyl aldaric, and sinapic acids. They also reported that feruloyl aldaric acid was the predominant phenolic acid at a level of 46.2 μg/g and that ferulic acid derivatives accounted for the highest percentage of TPC in raw and boiled beans (19% and 24%, respectively). Duenas et al. (2016) identified seven hydroxycinnamic compounds and five hydroxybenzoic compounds in dark beans (*Phaseolus vulgaris* L.), most of which were bound phenolic acids, while only a few were free phenolic acids. Therefore, the total bound phenolics in common beans are at a comparable level to that of free phenolics, which means that the content of phenolics in common beans may be significantly underestimated if only soluble phenolic content is considered (Chan, Gan, & Corke, 2016). In addition, a complete assessment of all forms of phenolics helps to better understand and explain the overall health benefits of consuming common beans.

Flavonoids

Flavonoids are the most abundant secondary metabolites in the plant kingdom and their presence influences the flavor and color of common beans. The TFC of common bean seeds and seed coats have been widely reported. Pinto bean seed coats were recorded to have the highest TFC among pigmented bean seed coats (4477 mg CE/100 g DW), followed by small speckled kidney bean (oval) coats (3529 mg CE/100 g DW), and big speckled kidney bean seed coats (3513 mg CE/100 g DW) (Gan et al., 2016).

Flavonoids have six subclasses, including flavonols, flavones, isoflavonoids, flavanols, flavanones, and anthocyanins. Normally, they accumulate in the vacuoles of plant tissues as conjugates in glycosylated or esterified forms, but occasionally they can be found as aglycones (Nayak et al., 2015).

Twenty-two flavonols have been identified in common bean cultivars. Flavonols, like kaempferol, quercetin, myricetin, and their derivatives, are widely identified in common bean cultivars (Table 2). Duenas et al. (2016) concluded that kaempferol glycosides and quercetin glycosides accounted for approximately 6% and 26% of total phenolic compounds in raw and germinated dark common beans, respectively.

It is surprising that only two flavones (apigenin-7-O-glucoside and luteolin-7-O-glucoside) have been detected in common beans (Figure 1), an issue which may need further investigation. In contrast, isoflavonoids like genistein, daidzein, glycitein, formononetin, and their derivatives are widely found in various common beans such as dark beans (Lopéz et al., 2013), zolfino landraces (Romani et al., 2004), wild and cultivated Mexican common beans (*Phaseolus vulgaris* L.; Díaz-Batalla, Widholm, Fahey, Castaño-Tostado, & Paredes-López, 2006), and others (Dinelli, Aloisio, Bonetti, Marotti, & Cifuentes, 2007).

Flavanols, including catechin, epicatechin, epigallocatechin, and epicatechin gallate, are the most abundant flavonoids detected in common beans with the range of ND to 611 mg/g DW (Gan et al., 2016; Ombra et al., 2016; Ranilla, Genovese, & Lajolo, 2009)

Table 1–Total phenolic, total flavonoid, and total proanthocyanidin content of common beans (all *Phaseolus vulgaris* L.).

Bean sample	Extracts	Content	Unit	References
TPC				
Green bean	80% Acetone	≈0.80	mg GAE/g DW	(Jiratanan & Liu, 2004)
Storage-induced hard-to-cook bean	Water	2.34–4.66	mg GAE/g DW	(Martín-Cabrejas et al., 1997)
Fresh dry bean	Water	2.66–4.14	mg GAE/g DW	
Maverick pinto bean	Acidified methanol +10 N NaOH + 12 N HCl	3.49	mg GAE/g DW	(Ross et al., 2009)
Redhawk dark red kidney bean		3.45	mg GAE/g DW	
Cdc jet black bean		3.34	mg GAE/g DW	
Kidney bean	80% Chilled acetone	≈3.90	mg GAE/g DW	(Aguilera et al., 2014)
	4 mol/L NaOH	≈0.46	mg GAE/g DW	
Common bean	50% Methanol	2.36	mg GAE/g DW	(Akillioglu & Karakaya, 2010)
Pinto bean	50% Methanol	3.74	mg GAE/g DW	
Dry bean	Water	5.48–5.62	mg CAE/g DW	(Nergiz & Gökgöz, 2007)
Black bean sprout	80% Methanol	≈0.90	mg GAE/g DW	(Guajardo-Flores et al., 2013)
Black bean cotyledon	80% Methanol	≈2.20	mg GAE/g DW	
Black bean coat	80% Methanol	≈30.0	mg GAE/g DW	
Navy bean	Water	1.76	mg GAE/g DW	(Sutivisedsak et al., 2010)
	50% Methanol	8.34	mg GAE/g DW	
Pinto bean	Water	15.4	mg GAE/g DW	
	50% Methanol	52.9	mg GAE/g DW	
Small bean	Water	20.4	mg GAE/g DW	
	50% Methanol	10.3	mg GAE/g DW	
Black bean	Water	14.7	mg GAE/g DW	
	50% Methanol	63.8	mg GAE/g DW	
Great northern bean	Water	1.61	mg GAE/g DW	
	50% Methanol	56.5	mg GAE/g DW	
Pink bean	Water	18.0	mg GAE/g DW	
	50% Methanol	70.6	mg GAE/g DW	
Light red kidney bean	Water	12.5	mg GAE/g DW	
	50% Methanol	56.21	mg GAE/g DW	
Dark red kidney bean	Water	12.4	mg GAE/g DW	
	50% Methanol	60.8	mg GAE/g DW	
Phaseolus vulgaris L.	Methanol	8.80	mg GAE/g DW	(Hernández-Saavedra et al., 2013)
Pinto bean	70% Acetone with 0.5% acetic acid	≈6.80	mg GAE/g DW	(Xu & Chang, 2011)
Black bean	70% Acetone with 0.5% acetic acid	≈7.40	mg GAE/g DW	
Bean	Methanol	4.57–5.26	mg GAE/g DW	(Treviño-Mejía et al., 2016)
Bean	2 mol/L NaOH	1.58–4.38	mg GAE/g DW	
Regular darkening cranberry bean	70% Methanol with 1% HCl	2.82–4.15	mg GAE/g DW	(Chen et al., 2015b; Coutin et al., 2017)
Non-darkening cranberry bean	70% Methanol with 1% HCl	0.67–0.81	mg GAE/g DW	
Common bean whole seed	Acetone	0.14–1.29	mg GAE/g DW	(Ombra et al., 2016)
Common bean seed coat	Acetone	0.13–0.69	mg GAE/g DW	
Black bean	Methanol (0.5% HCl)	0.85	mg GAE/g DW	(Sancho et al., 2015)
Small red bean	Methanol (0.5% HCl)	≈1.23	mg GAE/g DW	
Regular darkening cranberry bean	70% Ethanol with 1% Acetic acid	≈2.60	mg GAE/g DW	(Chen et al., 2015a)
Non-darkening cranberry bean	70% Methanol with 1% acetic acid	≈0.60	mg GAE/g DW	
White kidney bean	80% Methanol	4.63	mg GAE/g DW	(García-Lafuente et al., 2014)
Round purple bean	80% Methanol	13.4	mg GAE/g DW	
Common bean	Water	≈3.50–5.00	mg GAE/g DW	(Valdés et al., 2011)
Common bean	60% Methanol with 0.3% HCl	6.66–32.0	mg GAE/g DW	(Doria, Campion, Sparvoli, Tava, & Nielsen, 2012)
Common bean	40% Ethanol with 1% 1 mol/L HCl	11.7–14.7	mg GAE/g DW	(Ariza-Nieto, Blair, Welch, & Glahn, 2007)
Black bean	Water	1.20	mg GAE/g DW	(Hernández-Salazar et al., 2010)
Phaseolus vulgaris L. dry bean	70% Ethanol (pH = 2)	1.17–4.40	mg GAE/g DW	(Heimler et al., 2005)
Turkish white bean	80% Methanol	0.33–0.63	mg GAE/g DW	(Orak, Karamać, Orak, & Amarowicz, 2016)
Red kidney bean seed coat	80% Methanol	33.9	mg GAE/g DW	(Gan et al., 2016)
Big speckled kidney bean seed coat	80% Methanol	43.4	mg GAE/g DW	
Small speckled kidney bean (oval) seed coat	80% Methanol	43.1	mg GAE/g DW	
Violet red kidney bean seed coat	80% Methanol	30.0	mg GAE/g DW	
Brown string bean seed coat	80% Methanol	5.18	mg GAE/g DW	
Pinto bean seed coat	80% Methanol	48.7	mg GAE/g DW	
TFC				
Phaseolus vulgaris L. dry bean	70% Ethanol (pH 2)	0.24–1.43	mg CE/g DW	(Heimler et al., 2005)
Red kidney bean seed coat	80% Methanol	26.4	mg CE/g DW	(Gan et al., 2016)

(*Continued*)

Table 1–Continued.

Bean sample	Extracts	Content	Unit	References
TPC				
Big speckled kidney bean seed coat	80% Methanol	35.1	mg CE/g DW	
Small speckled kidney bean (oval) seed coat	80% Methanol	35.3	mg CE/g DW	
Violet red kidney bean seed coat	80% Methanol	26.0	mg CE/g DW	
Brown string bean seed coat	80% Methanol	2.66	mg CE/g DW	
Pinto bean seed coat	80% Methanol	44.8	mg CE/g DW	
Phaseolus vulgaris L. seed coat	70% Methanol and 5% acetic acid	ND–7.65	mg CE/g FW	(Ranilla et al., 2007)
Common bean	80% Ethanol	0.41–1.02	mg RE/g DW	(Oomah et al., 2005)
Common bean seed coat	70% Methanol and 5% acetic acid	5.90–21.5	mg CE/g DW	(Aquino-Bolaños et al., 2016)
Common bean whole flour	70% Methanol and 5% acetic acid	0.10–0.78	mg CE/g DW	
Common bean	70% Methanol with 0.5% HCl	0.01–0.21	mg C3GE/g DW	(Díaz, Caldas, & Blair, 2010)
Phaseolus vulgaris L.	Methanol	0.50	mg C3GE/g DW	(Hernández-Saavedra et al., 2013)
Common bean	80% Acetone	0.29	mg QE/g DW	(Starzyńska-Janiszewska et al., 2015)
Black Jamapa bean flour	Methanol	0.69	mg C3GE/g DW	(Aparicio-Fernández et al., 2005)
Two years stored black Jamapa bean flour	Methanol	0.17	mg C3GE/g DW	
Black Jamapa bean seed coat	Methanol	7.60	mg C3GE/g DW	
Two years stored black Jamapa bean seed coat	Methanol	1.87	mg C3GE/g DW	
Common bean	50% Methanol	0.14	mg CE/g DW	(Akillioglu & Karakaya, 2010)
Pinto bean	50% Methanol	1.27	mg CE/g DW	
Green bean	4 mol/L NaOH	≈6.00	mg CE/g DW	(Jiratanan & Liu, 2004)
	80% Acetone	≈0.52	mg CE/g DW	
TPAC				
Pinto bean	Water	≈28.0–158	mg CE/g DW	(Beninger et al., 2005)
Dry bean	Water	0.57–0.72	mg TAE/g DW	(Nergiz & Gökgöz, 2007)
Kidney bean	Water	5.37	mg CE/g DW	
Black Jamapa bean flour	Methanol	13.8	mg CE/g DW	(Aparicio-Fernández et al., 2005)
Black Jamapa bean seed coat	Methanol	222	mg CE/g DW	
Fresh common bean	Methanol with 0.0027 mol/L HCl	0.90	mg CE/g FW	(Valdez-González et al., 2017)
Hardened common bean	Methanol with 0.0027 mol/L HCl	0.60	mg CE/g DW	
Common bean	80% Acetone	3.05	mg CE/g DW	(Starzyńska-Janiszewska et al., 2015)
Phaseolus vulgaris L.	Methanol	4.60	mg CE/g DW	(Hernández-Saavedra et al., 2013)
Common bean	70% Acetone with 0.1% ascorbic acid	10.7–30.9	mg CE/g DW	(Díaz et al., 2010)
Peruano	Water	2.00	mg CE/g FW	(Coelho et al., 2007)
Paraiso	Water	23.0	mg CE/g FW	
Common bean seed	80% Acetone	ND	mg CE/g DW	(Madhujith et al., 2004)
Common bean seed coat	80% Acetone	0.01– 0.03	mg CE/g DW	
Common bean with red seed coat	Water	4.25	mg CE/g DW	(Jyothi & Sumathi, 1995)
	0.005 mol/L NaOH	1.25	mg CE/g DW	
	0.01 mol/L NaOH	0.50	mg CE/g DW	
	0.025 mol/L Na_2CO_3	1.00	mg CE/g DW	
	0.05 mol/L $NaHCO_3$	1.25	mg CE/g DW	
	0.1 mol/L $NaHCO_3$	0.50	mg CE/g DW	
Bean	Methanol	4.67–6.62	mg CE/g DW	(Treviño-Mejía et al., 2016)
Regular darkening cranberry bean	70% Methanol with 1% HCl	1.63–2.89	mg PAC/g DW	(Chen et al., 2015a; Coutin et al., 2017)
Non-darkening cranberry bean	70% Methanol with 1% HCl	0.02–0.05	mg PAC/g DW	
Black bean	Methanol with 0.5% HCl	760	mg CE/g DW	(Sancho et al., 2015)
Small red bean	Methanol with 0.5% HCl	540	mg CE/g DW	
Regular darkening cranberry bean	65% Acetone with 1% acetic acid	≈2.20	mg PAC/g DW	(Chen et al., 2015a)
Non-darkening cranberry bean	65% Acetone with 1% acetic acid	≈0.04	mg PAC/g DW	
Common bean	Water	0.01- 0.02	mg CE/g DW	(Valdés et al., 2011)
Black bean	Water	54.6	mg GAE/g DW	(Hernández-Salazar et al., 2010)

TPC, total phenolic content; TFC, total flavonoid content; TPCA, total proanthocyanidin content; GAE, gallic acid equivalent; CE, catechin equivalent; DW, dry weight; ND, not determined; FW, fresh weight; C3GE, cyanin 3-glucoside equivalent; RE, rutin equivalent; QE, quercetin equivalent; PAC, proanthocyanidin; TAE, tannic acid equivalent.

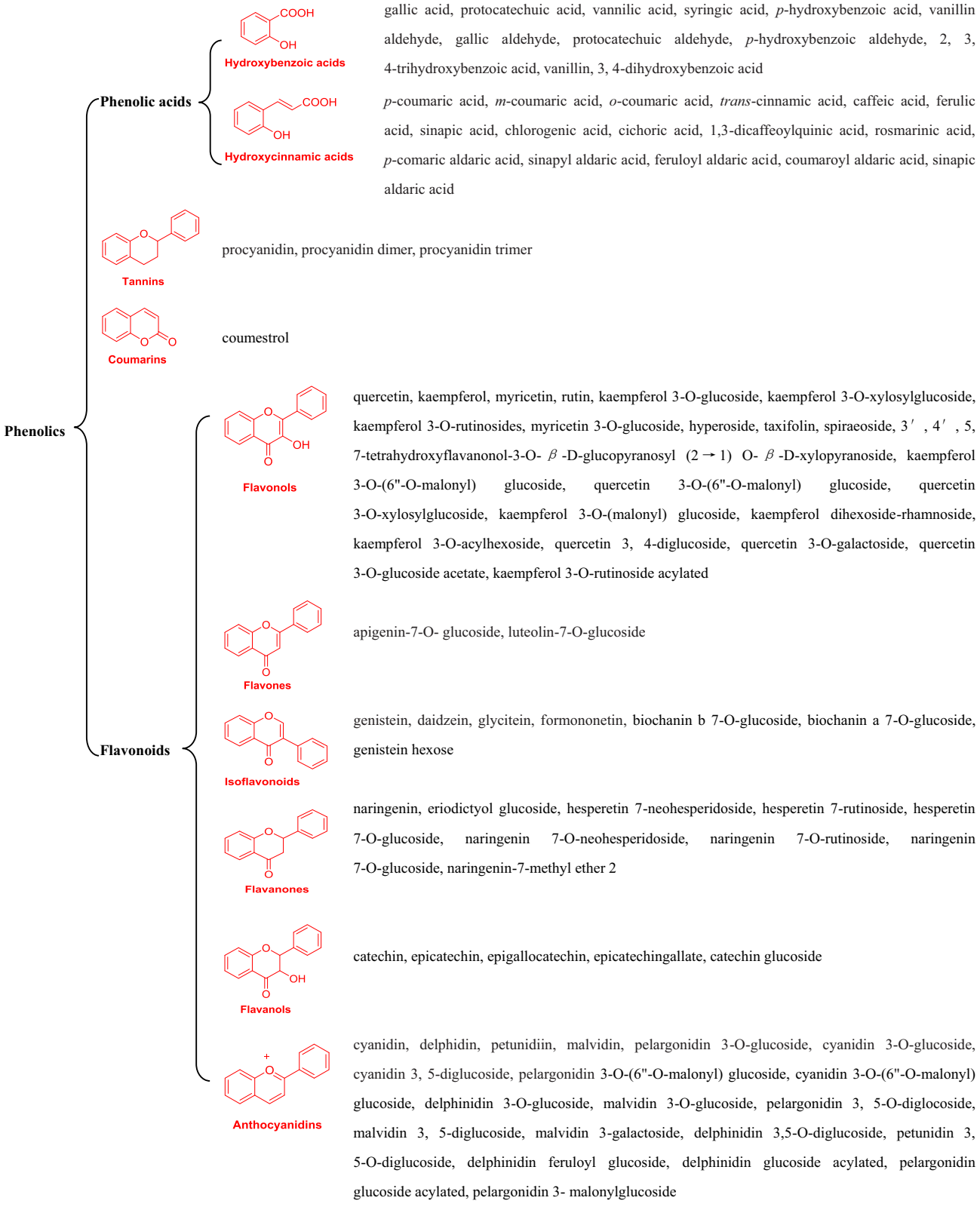

Figure 1–Main common bean phenolics and chemical structures for major compound classes.

Table 2–Flavonoids and phenolic acids in common beans (*Phaseolus vulgaris* L.).

Bean sample	Major compounds	Reference
Dark bean	Hesperetin 7-neohesperidoside, hesperetin 7-rutinoside, hesperetin 7-O-glucoside, hesperetin derivatives, naringenin 7-O-neohesperidoside, naringenin 7-O-rutinoside, naringenin 7-O-glucoside, naringenin-7-methyl ether 2, naringenin, quercetin 3-O-Rutinoside, quercetin 3-O-galactoside, quercetin 3-O-glucoside, quercetin 3-O-Glucoside acetate, quercetin, kaempferol 3-O-glucoside, kaempferol 3-O-rutinoside acylated, kaempferol, myricetin 3-glucoside, myricetin derivatives, myricetin, apigenin 7-O-glucoside, biochanin b 7-O-glucoside, biochanin a 7-O-glucoside, daidzein derivatives, genistein hexose, genistein derivatives, delphinidin 3-O-glucoside, cyanidin 3-O-glucoside, pelargonidin 3, 5-diglucoside, pelargonidin 3-O-glucoside, delphinidin glucoside acylated, pelargonidin glucoside acylated, pelargonidin 3-malonylglucoside, petunidin feruloyl glucose, petunidin derivatives, malvidin derivatives, galic acid, protocatechuic acid, ferulyl aldaric acid, *trans* ferulic acid, *p*-coumaryl aldaric acid, *trans p*-coumaric acid, sinapyl aldaric acid, sinapic acid	(Lopéz et al., 2013)
Phaseolus vulgaris L.	Kaempferol	(Perazzini et al., 2008)
Brazilian common bean germplasm	Daidzein, genistein, kaempferol, myricetin, quercetin	(de Lima et al., 2014)
Alubia bean	*p*-Coumaric acid derivatives, ferulic acid derivatives, kaempferol 3-*O*-xylosyl-glucoside, delphinidin 3-*O*-glucosyl-glucoside, petunidin 3-O-(6"-acetyl glucoside)	(Lin et al., 2008)
Black bean	*p*-Coumaric acid derivatives, ferulic acid derivatives, sinapic acid, ferulic acid, delphinidin 3-O-glucoside, petunidin 3-O-glucoside, malvidin 3-O-glucoside	
Cranberry bean	*p*-Coumaric acid derivatives, ferulic acid derivatives	
Great northern bean	*p*-Coumaric acid derivatives, ferulic acid derivatives, sinapic acid, ferulic acid	
Pinto bean	Kaempferol, kaempferol 3-O-glucoside, quercetin 3-O-(6"-O-malonyl) glucoside, kaempferol 3-O-(malonyl)glucoside, *p*-coumaric acid derivatives, ferulic acid derivatives, sinapic acid, ferulic acid	
Red Mexican bean	Kaempferol 3-O-xylosylglucoside, quercetin 3-O-(6"-O-malonyl) glucoside, myricetin, kaempferol 3-O-(6"-O-malonyl) glucoside, kaempferol, *p*-coumaric acid derivatives, ferulic acid derivatives, sinapic acid, ferulic acid	
Light red kidney bean	*p*-Coumaric acid derivatives, ferulic acid derivatives, sinapic acid, ferulic acid, quercetin 3-*O*-glucoside, quercetin 3-O-rutinoside, quercetin 3-O-(6"-O-malonyl) glucoside, kaempferol 3-O-glucoside, quercetin, kaempferol, quercetin 3-O-xylosylglucoside, kaempferol 3-O-xylosylglucoside,	
Navy bean	*p*-Coumaric acid derivatives, ferulic acid derivatives, sinapic acid, ferulic acid	
Dark red kidney bean	*p*-Coumaric acid derivatives, ferulic acid derivatives, sinapic acid, ferulic acid, quercetin diglycosides, kaempferol diglycosides, quercetin, kaempferol	
Pink kidney bean	Quercetin diglycosides, kaempferol diglycosides, *p*-coumaric acid derivatives, ferulic acid derivatives, sinapic acid, ferulic acid, quercetin 3-O-xylosylglucoside, kaempferol 3-O-xylosylglucoside, quercetin, kaempferol	
Small red bean	Kaempferol 3-*O*-glucoside, pelargonidin 3-*O*-glucoside	
Common bean (verdone)	Daidzein, glycitein, genistein, kaempferol	(Dinelli et al., 2007)
Common bean (zolfino)	Daidzein, glycitein, genistein, kaempferol	
Common bean (lingua difuoco)	Daidzein, glycitein, genistein, kaempferol	
Wild and cultivated Mexican common bean	Quercetin, kaempferol, daidzein, genistein, coumestrol, *p*-hydroxybenzoic acid, vanillic acid, *p*-coumaric acid, ferulic acid	(Díaz-Batalla et al., 2006)
Black-ed bean	Myricetin, quercetin, kaempferol, delphinidin, petunidin, malvidin	(Hungria, Joseph, & Phillips, 1991)
Montcalm dark red kidney bean	3′, 4′, 5, 7-Tetrahydroxyflavonol 3-O-β-D-glucopyranosyl (2→1) O-β-D-xylopyranoside, quercetin 3-O-β-D-glucopyranoside, kaempferol 3-O-β-D-glucopyranoside	(Beninger & Hosfield, 1999b)
Italian bean	Kaempferol 3-O-glucoside, kaempferol 3-O-xylosylglucoside	(Dinelli et al., 2006)
Cranberry bean	Catechin, kaempferol, pelargonidin-3-O-glucoside, cyanidin-3-O-glucoside, cyanidin, ferulic acid, *p*-coumaric acid, sinapic acid, *p*-hydroxybenzoicacid	(Chen et al., 2015a)
Common bean	Quercetin, genistein	(Doria et al., 2012)
Green french bean	Kaempferol 3-O-glucoside, kaempferol 3-O-rutinosides, quercetin 3-O-glucoside, quercetin 3-O-rutinosides	(Hempel & Böhm, 1996)
Sarconi bean	Kaempferol, kaempferol 3-O-glucoside, kaempferol 3-O-glucosylxylose, kaempferol 3-O-(6"-O-malonyl) glucoside, quercetin, cyanidin 3, 5-diglucoside, cyanidin 3-O-glucoside, pelargonidin 3-O-glucoside, cyanidin 3-O-(6"-malonyl) glucoside, pelargonidin 3-O-(6"-malonyl) glucoside	(Romani, Vignolini, Falvino, & Heimler, 2013)
Dry edible bean	Caffeic acid, *p*-coumaric acid, ferulic acid, sinapic acid	(Luthria & Pastor-Corrales, 2006)
New Manteca-type dry bean	Kaempferol 3-O-glucoside, kaempferol 3-O-glucosylxylose	(Beninger et al., 1998)
Red bean	Cyanidin 3-O-glucoside, pelargonidin 3-O-glucoside	(Tsuda, Osawa, Ohshima, & Kawakishi, 1994)
Black bean	Delphinidin 3-O-glucoside	
Dry bean	Kaempferol 3-O-glucoside	(Beninger & Hosfield, 1999a)
Black turtle bean	Delphinidin 3-O-glucoside, malvidin 3-O-glucoside, pelargonidin 3-O-glucoside, petunidin, malvidin	(Yoshida et al., 1996)
Red kidney bean	Delphinidin 3-O-glucoside, pelargonidin 3-O-glucoside, cyanidin 3-O-(6"-malonyl) glucoside, cyanidin 3, 5-diglucoside	(Choung et al., 2003)
Black kidney bean	Delphinidin 3-O-glucoside, petunidin 3-O-glucoside	
Wild and weedy Mexican common bean	Quercetin, kaempferol, coumestrol, daidzein, ferulic acid derivatives, *p*-coumaric acid, sinapic acid, *p*-hydroxybenzoic acid, vanillic acid, caffeic acid, vanillin aldehyde	(Guevara-Lara et al., 2007)

(*Continued*)

Table 2–Continued.

Bean sample	Major compounds	Reference
Common bean	Myricetin 3-O-glucoside, quercetin 3-O-glucoside, quercetin 3-O-(6″-*β*-O-malonyl) glucoside, kaempferol 3-O-glucoside, myricetin, kaempferol 3-O-(6″-O-malonyl) glucoside, quercetin, kaempferol, quercetin 3-O-xylosylglucoside, quercetin 3-O-rutinoside, kaempferol 3-O-xylosylglucoside, kaempferol 3-O- (malonyl) glucoside, delphinidin 3-O-glucoside, pelargonidin 3, 5-O-diglucoside, petunidin 3-O-glucoside, malvidin 3-O-glucoside, cyanidin 3-O-glucoside, pelargonidin 3-O-glucoside, cyanidin 3-O-(6″-malonyl) glucoside, pelargonidin 3-O-(6″-malonyl) glucoside, delphinidin, petunidin, malvidin, cyanidin, pelargonidin, *p*-coumaric acid derivatives, ferulic acid derivatives, *p*-coumaric acid, sinapic acid, ferulic acid, caffeic acid, vanillin aldehyde, syringic acid	(Lin et al., 2008)
Dark bean	Kaempferol dihexoside-rhamnoside, kaempferol 3-O-acylhexoside, sinapic acid, *p*-hydroxybenzoic acid, gallic aldehyde, protocatechuic acid, protocatechuic aldehyde, *p*-hydroxybenzoic aldehyde, *trans*-feruloyl aldaric acid, sinapoyl aldaric acid, *trans*-*p*-coumaric acid, *trans*-ferulic acid	(Duenas et al., 2016)
Common bean	Catechin, epicatechin, hyperoside, epigallocatechin, spiraeoside, formononetin, taxifolin, genistein, kampherol, dadzein, quercetin, quercetin 3, 4 diglucoside, naringenin, miricetin, gallic acid, cafaric acid, chlorogenic acid, cichoric acid, coumaric acid, vanillic acid, 1, 3 dicaffeoylquinic acid, rosmarinic acid	(Ombra et al., 2016)
Regular darkening cranberry bean	Catechin, epicatechin, kaempferol, cyanidin-3-O-glucoside, pelargonidin-3-O-glucoside, cyanidin, pelargonidin, protocatechuic acid, *p*-hydroxybenzoic acid, *p*-coumaric acid, ferulic acid, sinapic acid, *p*-hydroxybenzoic acid, procyanidin B-type dimer, procyanidin C-type trimer, propelargonidin dimer	(Chen et al., 2015a,b,c)
Non-darkening cranberry bean	Kaempferol, *p*-coumaric acid, ferulic acid	
Pinto saltillo	Kaempferol xyloglucoside, kaempferol 3-O-glucoside, kaempferol, naringenin derivate, *p*-coumaric aldaric acid isomer	(Moreno-Jiménez et al., 2015)
Pinto durango	Kaempferol 3-O-glucoside, kaempferol isomer, eriodictyol glucoside, *p*-coumaric aldaric acid isomer, sinapyl aldaric acid	
Black bean 8025	Myricetin-3-O-glucoside, kaempferol-3-O-glucoside, kaempferol gallic acid, *p*-coumaric aldaric acid isomer, sinapyl aldaric acid, ferulic acid	
Bayo victoria	Eriodictyol glucoside, quercetin 3-O-glucopyranoside, kaempferol xyloglucoside protocatechuic acid	
White kidney bean	Naringenin derivatives, hesperitin derivatives, feruroyl aldaric acid, coumaroyl aldaric acid, coumaroyl aldaric acid, sinapic aldaric acid, sinapic derivatives, sinapic acid, ferulic acid	(García-Lafuente et al., 2014)
Round purple bean	Quercetin glucoside, quercetin malonil glucoside, catechin glucoside, catechin, cyanidin glucoside, pelargonidin glucoside, coumaroyl aldaric acid, feruroyl aldaric acid, sinapic aldaric acid	
Pinto bean	Kaempferol-3-O-acetylglucoside, kaempferol-3-O-glucoside, gallic acid, protocatechuic acid, 2, 3, 4-trihydroxybenzoic acid, protocatechu aldehyde, *p*-hydroxybenzoic acid, vanillic acid, vanillin, chlorogenic acid, *p*-coumaric acid, syring aldehyde, *m*-coumaric acid, ferullic acid, sinapic acid, gallic acid, protocatechuic acid, *trans*-cinnamic acid, *o*-coumaric acid	(Xu & Chang, 2009)
Black bean	(+)-Catechin, (+)-epicatechin, epicatechin gallate, kaempferol-3-O-glucoside, myricetin delphinidin-3-O-glucose, malvidin-3, 5-diglucose, petunidin-3-O-glucose, malvidin-3-O-galactoside, malvidin-3-O-glucose, caffeic acid, gallic acid, protocatechuic acid, 2, 3, 4-trihydroxybenzoic acid, protocatechu aldehyde, *p*-hydroxybenzoic acid, vanillic acid, vanillin, chlorogenic acid, *p*-coumaric acid, syringaldehyde, m-coumaric acid, ferullic acid, sinapic acid, *o*-coumaric acid	
White bean	(+)-Catechin, *p*-coumaric acid, hydroxybenzoic acid, ferulic acid, caffeic acid	(Laparra, Glahn, & Miller, 2008)
Red bean	kaempferol, astragalin, (+)-catechin, *p*-coumaric acid, hydroxybenzoic acid, ferulic acid, caffeic acid	
Phaseolus vulgaris L.	Kaempferol 3-O-glucoside, kaempferol 3-O-xylosylglucoside, quercetin 3-O-xylosylglucoside, quercetin 3-O-glucoside, delphinidin 3-O-glucoside, petunidin 3-O-glucoside, malvidin 3-O-glucoside	(Beninger & Hosfield, 2003)
Zolfino landraces	Kaempferol 3-O-xylosylglucoside, kaempferol 3-O-glucoside, daidzein, kaempferol 3-O-acetylglucoside, genistein, quercetin 3-O-glucoside, kaempferol 3-acetylglucoside delphinidin 3, 5-O-diglucoside, petunidin 3, 5-O-diglucoside, delphinidin 3-O-glucoside, petunidin 3-O-glucoside, malvidin 3-O-glucoside, petunidin 3-O-rhamnoside, delphinidin feruloylglucoside	(Romani et al., 2004)
Red and black bean seed coat	Delphinidin 3-O-glucoside, petunidin 3-O-glucoside, cyanidin-3-O-glucoside	(Tsuda, Shiga, Ohshima, Kawakishi, & Osawa, 1996)
Ui 911 black bean	Delphinidin 3-O-glucoside, petunidin 3-O-glucoside, malvidin 3-O-glucoside	(Takeoka et al., 1997)
Black bean seed coat	Myricetin 3-O-glucoside, quercetin 3-O-glucoside, kaempferol 3-O-glucoside, catechin, myricetin, quercetin, kaempferol 3, 4-dihydroxybenzoic acid	(Hart et al., 2015)
Black bean seed coat	Myricetin 3-O-glucoside, quercetin 3-O-glucoside, kaempferol 3-O-glucoside	(Chavez-Santoscoy et al., 2014)
Aged pinto bean	Kaempferol, kaempferol 3-O-glucoside, kaempferol 3-O-glucosylxylose, kaempferol 3-O-acetylglucoside	(Beninger et al., 2005)

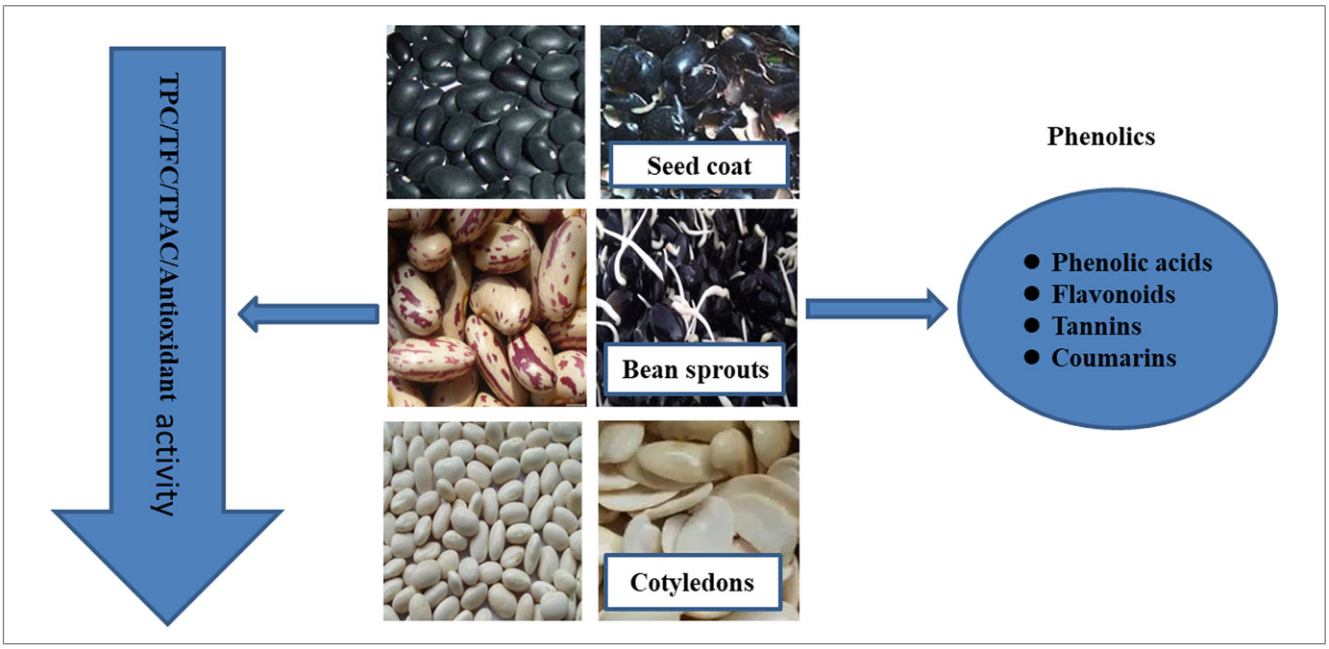

Figure 2–Trends in common bean polyphenols in different matrices. Generally, dark beans contain more polyphenols and exhibit higher antioxidant activity than lighter colored beans; seed coats contain more polyphenols and exhibit more antioxidant activity than cotyledons.

Nine flavanones have been identified in common bean cultivars, seven of which were obtained from dark common beans (Lopéz et al., 2013). Naringenin and hesperetin glucosides are the main flavanones detected in common beans. Eriodictyol glucoside is mainly found in Pinto durango (*Phaseolus vulgaris* L.) and Bayo victoria (*Phaseolus vulgaris* L.).

In addition, anthocyanins are an important type of flavonoids in pigmented common beans. Mostly, anthocyanins occur as glycosides in nature. Twenty anthocyanins have been identified from common beans, the most common of which are the glycosides of delphinidin, petunidin, malvidin, and cyanidin. Pelargonidin glycosides such as pelargonidin 3-O-glucoside, pelargonium 3-O-(6"-malonyl) glucoside, and pelargonidin 3, 5-O-diglucoside, are also found in common beans (Lopéz et al., 2013).

Proanthocyanidins

Apart from phenolic acids and flavonoids, proanthocyanidins have also been widely detected in common beans (Table 1). Proanthocyanidins mainly distribute in the common bean seed coats and are the main component of polyphenols in common beans. Black bean seed coats and small red bean seed coats were recorded to possess the highest level of proanthocyanidins (760 mg CE/g and 540 mg CE/g, respectively) (Sancho, Pavan, & Pastore, 2015) among common bean cultivars (Table 1). Our group has determined the TPAC of pigmented bean coats and discovered that four kidney bean seed coats were rich in proanthocyanidins with the range of 46.7 to 79.9 mg CE/g DW and small speckled kidney bean seed coats had the highest content (Gan et al., 2016).

Compared to phenolic acids and flavonoids, studies on the identification of proanthocyanidins in common beans are relatively scarce. Mostly, the identified proanthocyanidins are procyanidin dimers and trimers. López et al. (2013) identified procyanidin dimers and trimers in dark beans with a total content of 1006 μg/g, which was the highest concentration of non-anthocyanin compounds in raw dark beans. García-Lafuente et al. (2014) identified procyanidin dimers and trimers in round purple beans (*Phaseolus vulgaris* L.) with contents of 6336 and 130 μg/g, respectively. Chen et al. (2015a) identified procyanidin B_1 dimer, procyanidin C_1 trimer, and proanthocyanidin in cranberry beans with contents of 7.04 to 56.9, 12.8 to 33.9, and 15.0 to 35.3 μg/g, respectively.

Coumarins

Coumarins are a type of phenolic derivatives widely found in plants. These compounds can be used for anticoagulation and antithrombotic treatment of cardiovascular diseases (Li, Yao, & Li, 2017). Like proanthocyanidins, there is relatively little comprehensive research on the coumarin profiles in beans. Only coumestrol was identified in germinated Mexican common beans (*Phaseolus vulgaris* L.) at a level of 2.40 to 35.6 mg/g DW (Díaz-Batalla et al., 2006).

In conclusion, common bean polyphenols in different matrices exhibit difference in TPC, TFC, TPAC, and phenolic compounds. The general trends of common bean polyphenols have been summarized in Figure 2.

Factors Influencing Phenolic Content and Composition

The TPC, TFC, TPAC, and composition of common beans are influenced by several factors, such as environmental conditions, genotype, storage, and processing methods. Generally, processing methods have the greatest influence in altering the genetically determined phenolic content and composition (Nayak et al., 2015). The effect of processing methods on the polyphenols has been summarized in Figure 3. The following sections briefly describe the factors that affect the TPC, TFC, TPAC, and composition of common beans.

Environmental conditions and genotypes

In the last decade, many studies have been conducted to investigate the effect of environmental conditions (location of experimental production) (de Mejía et al., 2003; Dinelli et al., 2006; Islam et al., 2003) and genotype (Beninger et al., 1999a; Beninger

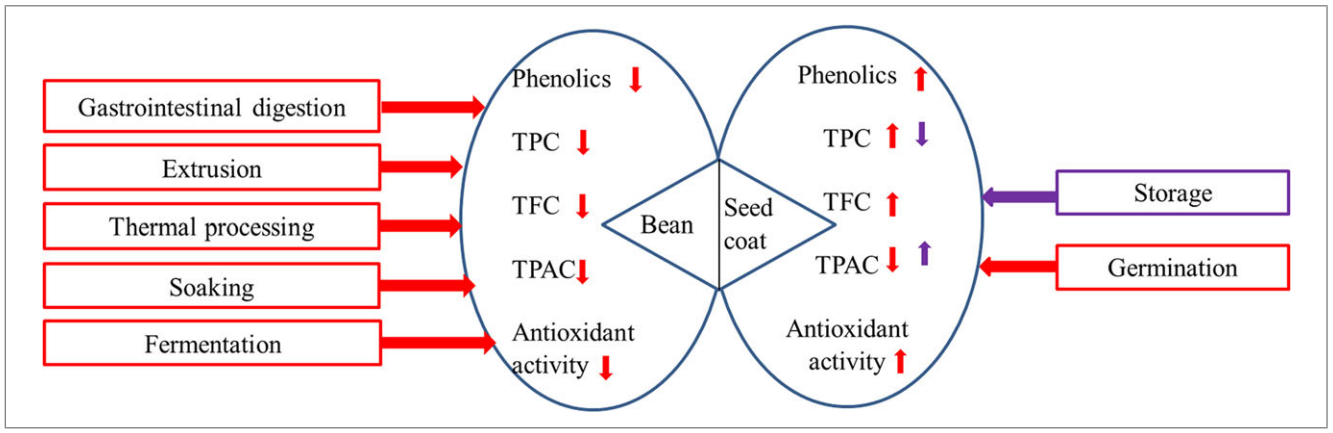

Figure 3–General trends of different processing methods on polyphenols in common beans.

& Hosfield, 1999b; Valdés et al., 2011) on the polyphenols of common beans. Islam et al. (2003) reported that the TPC of common beans in Middle American gene pool was the highest, and that of the Andean gene pool was the lowest. These experiments also showed that both the location and genotype play an important role in the TPC of common beans. Espinosa-Alonso, Lygin, Widholm, Valverde, and Paredes-Lopéz (2006) also investigated the effect of genotype and location on the TPC of common beans and concluded that genotype had more effect on the TPC of common beans than the location.

Some studies have undertaken work to identify the flavonoid compounds in common beans and determined their contributions to seed coat color. Beninger, Hosfield, and Bassett (1999) analyzed the phytochemicals of three dry bean (*Phaseolus vulgaris* L.) genotypes differing in seed-coat color, mineral brown (*P C D J G B v*), yellow brown (*P C D J G b v*), and pale greenish yellow (*P C D J g b v*) and found that astragalin existed in similar concentrations in pale greenish yellow and mineral brown genotypes but was significantly lower in yellow brown. This means that the G and B color genes may control the amount of astragalin present. In the same year, Beninger and Hosfield (1999b) isolated another 2 flavonol glycosides (3′, 4′, 5, 7-tetrahydroxyflavonol 3-O-β-D-glucopyranosyl (2→1) O-β-D-xylo-pyranoside and quercetin 3-O-β-D-glucopyranoside) from dark red kidney beans (*Phaseolus vulgaris* L.) and concluded that the change of the *Rk* allele to rk^d might allow the synthesis of flavonol glycosides in the presence of c^u.

The influence of environmental conditions and genotype on proanthocyanidins has also been widely investigated. Barampama and Simard (1993) reported that proanthocyanidins were highly influenced by both environmental conditions and genetic factors. However, de Mejía et al. (2003) concluded that the TPAC of common beans was mainly influenced by genetic factors but not environmental conditions. Even though the conclusions drawn from these studies are slightly different, they both show that environmental conditions and genetic factors have an influence on the polyphenols of common beans.

Storage

Longtime storage can alter the color, texture, flavor, cooking time, TPC, and TPAC of beans (*Phaseolus vulgaris* L.) (Coelho, de Mattos Bellato, Santos, Ortega, & Tsai, 2007). Martín-Cabrejas, Esteban, Pérez, Maina, and Waldron (1997) pointed out that long-term storage could lower TPC while increasing TPAC. The results of Mariotto-Cezar, Coelho, Christ, Schoeninger, and de Almeida (2013) were consistent with this finding and showed that the TPAC increased with storage time and reached the highest concentration at 180 days. Beninger et al. (2005) reported that the TPC of different pinto bean genotypes varied during storage, and the kaempferol content of CDC Pentium cultivar seed coats was reduced by almost half, whereas the kaempferol content of 1533-15 cultivar seed coats did not change significantly. This phenomenon might be attributed to hard-to-cook defect (Coelho et al., 2007; Jombo, Minnaar, & Taylor, 2017; Martín-Cabrejas et al., 1997). Several theories have been proposed to explain the hard-to-cook phenomenon, including phytase–phytate–pectin theory, lignification theory, protein and starch interactions, and a multiple mechanism theory, but the "phytase–phytate–pectin" theory is the most widely accepted (Jombo et al., 2017). According to the "phytase–phytate–pectin" theory, water-soluble pectin permits water uptake by legume seeds. Both phytate and the carboxyl groups of soluble pectin can crosslink with calcium or magnesium ions, but phytate chelates preferentially with the above mentioned divalent cations. If the phytate is crosslinked with calcium or magnesium ions, legume seeds appear to be easy-to-cook. However, phytate may be hydrolyzed by phytase during storage so that the chelating potential of phytate vanishes, and then the calcium or magnesium ions will crosslink with the carboxyl groups of soluble pectin to form insoluble calcium and magnesium pectates, which are not dissolved readily when heated, thus restricting cell separation, inhibiting water uptake, and resulting in hard-to-cook defect (Figure 4). Paradoxically, other studies concluded that the TPAC of common beans dropped significantly after storage (Aparicio-Fernández, Manzo-Bonilla, & Loarca-Piña, 2005; Coelho et al., 2007), which might be attributed to the difference of cultivars. Beninger et al. (2005) reported a more specific conclusion that the high-molecular-weight procyanidins decreased after storage, while that of low-molecular-weight procyanidins increased. More information about the effect of storage on phenolic contents is summarized in Table 3.

Germination

The influence of germination on the TPC of edible seeds has been comprehensively summarized by our group (Gan et al., 2017). Contradictory findings have been published regarding the effects of germination on common bean cultivars (Table 3). For example, a study found that TPC in black bean sprouts decreased dramatically after germination (Guajardo-Flores, Serna-Saldívar,

Table 3–The effects of processing on common bean TPC, TFC, and TPAC (*Phaseolus vulgaris* L.).

Processing methods	Bean sample	Content		Unit	References
		Before processing	After processing		
TPC					
In vitro Gastrointestinal digestion	Black bean	≈0.85	≈0.20	mg GAE/g DW	(Sancho et al., 2015)
	Regular darkening cranberry bean	≈2.60	≈0.21	mg GAE/g DW	(Chen et al., 2015b)
	Non-darkening cranberry bean	≈0.60	≈0.06	mg GAE/g DW	
	Small red bean	≈1.23	≈0.60	mg GAE/g DW	(Sancho et al., 2015)
Extrusion	Kidney bean	0.44	0.22	mg GAE/g DW	(Marzo, Alonso, Urdaneta, Arricibita, & Ibanez, 2002)
	Kidney bean	2.07	1.12	mg TAE/g DW	(Alonso et al., 2000)
Pressure cooking	Common bean	≈44.0–96.0	≈12.0–27.0	mg CE/g DW	(Rocha-Guzmán et al., 2007)
	Dry bean	5.48–5.62	1.56–1.66	mg CAE/g DW	(Nergiz & Gökgöz, 2007)
	Pinto bean	≈6.80	≈2.00	mg GAE/g DW	(Xu & Chang, 2011)
	Black bean	≈7.40	≈2.00	mg GAE/g DW	
Traditional cooking	Common bean	2.36	8.58–11.8	mg GAE/g DW	(Akillioglu & Karakaya, 2010)
	Common bean	≈3.50–5.00	≈2.20–2.40	mg GAE/g DW	(Valdés et al., 2011)
	Regular darkening cranberry bean	≈2.60	≈2.40	mg GAE/g DW	(Chen et al., 2015b)
	Non-darkening cranberry bean	≈0.60	≈0.40	mg GAE/g DW	
	Common bean	135–1292	126–688	mg GAE/g DW	(Ombra et al., 2016)
	Pinto bean	3.74	10.9–16.1	mg GAE/g DW	(Akillioglu & Karakaya, 2010)
	Common bean	3.91–5.61	1.32–1.36	mg TAE/g DW	(Starzyńska-Janiszewska et al., 2015)
	Common beans	8.80	3.00	mg GAE/g DW	(Hernández-Saavedra et al., 2013)
	Var. Raba	1.06	0.55- 0.94	mg CAE/g DW	(Piecyk, Wolosiak, Druzynska, & Worobiej, 2012)
	Var. Warta	0.94	0.43–0.77	mg CAE/g DW	
	Pinto bean	≈6.80	≈1.70	mg GAE/g DW	(Xu & Chang, 2011)
	Black bean	≈7.40	≈2.00	mg GAE/g DW	
	Black bean	7.90	2.09–2.49	mg GAE/g DW	(Xu & Chang, 2008)
Soaking +cooking	Common bean	≈3.50–5.00	≈2.10–2.50	mg GAE/g DW	(Valdés et al., 2011)
	Dry bean	5.48–5.62	1.21–1.32	mg CAE/g DW	(Nergiz & Gökgöz, 2007)
	Kidney bean	1.73	1.71–2.74	mg CAE/g DW	(Haileslassie, Henry, & Tyler, 2016)
Soaking in hot/cold water +cooking with/without $NaHCO_3$	Common bean	2.36	7.91–11.8	mg GAE/g DW	(Akillioglu & Karakaya, 2010)
	Pinto bean	3.74	12.4–16.1	mg GAE/g DW	
Soaking	Common bean	≈3.50–5.00	≈13.7–16.2	mg GAE/g DW	(Valdés et al., 2011)
	Black bean	7.90	4.63–7.19	mg GAE/g DW	(Xu & Chang, 2008)
	Kidney bean	2.07	1.64	mg TAE g DW	(Alonso et al., 2000)
	Red gram	3.16	2.53	mg GAE/g DW	(Khandelwal, Udipi, & Ghugre, 2010)
	Green gram	5.13	3.43	mg GAE/g DW	
	Bengal gram	2.75	2.21	mg GAE/g DW	
Steaming	Pinto bean	≈6.80	≈2.50	mg GAE/g DW	(Xu & Chang, 2011)
	Black bean	≈7.40	≈3.00	mg GAE/g DW	
	Black bean	7.90	2.46–2.93	mg GAE/g DW	(Xu & Chang, 2008)
Pressure steaming	Pinto bean	≈6.80	≈2.50	mg GAE/g DW	(Xu & Chang, 2011)
	Black bean	≈7.40	≈2.80	mg GAE/g DW	
Thermal processing	Green bean	≈0.8	≈0.5–0.58	mg GAE/g DW	(Jiratanan & Liu, 2004)
Germination (24h dark)	Kidney bean	≈3.90	≈4.00–4.50	mg GAE/g DW	(Aguilera et al., 2014)
Germination (12 h light/12 h dark)	Kidney bean	≈3.90	≈1.30 –1.70	mg GAE/g DW	
Germination	Black bean	≈4.00	6.74	mg GAE/g FW	(Xue et al., 2016)
	Black bean sprout	≈0.90	≈0.30–0.50	mg GAE/g DW	(Guajardo-Flores et al., 2013)
	Black bean cotyledon	≈2.20	≈0.30–2.10	mg GAE/g DW	
	Black bean seed coat	≈30.0	≈27.0–61.0	mg GAE/g DW	
	Kidney bean	2.07	0.97–1.40	mg TAE/g DW	(Alonso et al., 2000)
fermentation	Dark common bean	3.91 – 5.61	1.39–1.76	mg TAE/g DW	(Starzyńska-Janiszewska et al., 2015)
TFC					
Thermal processing	Green bean	≈0.50	≈0.19–0.22	mg CE/g DW	(Jiratanan & Liu, 2004)
	Phaseolus vulgaris L.	0.50	0.20	mg C3GE/g DW	(Hernández-Saavedra et al., 2013)

(*Continued*)

Table 3–Continued.

Processing methods	Bean sample	Content		Unit	References
		Before processing	After processing		
	Common bean	0.29	0.27	mg QE/g DW	(Starzyńska-Janiszewska et al., 2015)
Soaking in hot/cold water +cooking with/without $NaHCO_3$	Common bean	0.14	0.02–0.75	mg CE/g DW	(Akillioglu & Karakaya, 2010)
	Pinto bean	1.27	1.75–2.74	mg CE/g DW	
Tempe-type fermentation	Common bean	0.29	0.35	mg QE/kg DW	(Starzyńska-Janiszewska et al., 2015)
Germination	Black bean	≈2.80	4.25	mg RE/g FW	(Xue et al., 2016)
TPAC					
After-darkening process	Pinto bean	≈28.0–158	≈40.0–130	mg CE/g DW	(Beninger et al., 2005)
Roasting	White kidney bean	67.1	61.3	mg CE/g DW	(Khattab & Arntfield, 2009)
	Red kidney bean	26.7	5.61	mg CE/g DW	
Thermal processing	Red kidney bean	26.7	7.54	mg CE/g DW	
Cooking	Dark common bean	3.05	0.43	mg CE/kg DW	(Starzyńska-Janiszewska et al., 2015)
	Kidney bean	5.37	3.55	mg CE/g DW	(Shimelis & Rakshit, 2007)
	Common bean	3.05	0.43	mg CE/kg DW	(Starzyńska-Janiszewska et al., 2015)
	Phaseolus vulgaris L.	4.06	0.30	mg CE/g DW	(Hernández-Saavedra et al., 2013)
	White kidney bean	67.1	21.1	mg CE/g DW	(Khattab & Arntfield, 2009)
	Red kidney bean	21.7	0.19	mg CE/g DW	
Water soaking + cooking	Kidney bean	5.37	1.61	mg CE/g DW	(Shimelis & Rakshit, 2007)
Sodium bicarbonate soaking + cooking	Kidney bean	5.37	1.71	mg CE/g DW	
Autoclaving	Kidney bean	5.37	1.51	mg CE/g DW	
	White kidney bean	67.1	19.5	mg CE/g DW	(Khattab & Arntfield, 2009)
	Red kidney bean	26.7	1.32	mg CE/g DW	
Soaking (H_2O) + autoclaving	Kidney bean	5.37	1.35	mg CE/g DW	(Shimelis & Rakshit, 2007)
Soaking ($NaHCO_3$) + autoclaving	Kidney bean	5.37	1.34	mg CE/g DW	
Sprouting for 24–96h + autoclaving	Kidney bean	5.37	0.19–ND	mg CE/g DW	
Soaking	Kidney bean	3.59	2.72	mg CE/g DW	(Alonso et al., 2000)
Soaking (12 h in plain water)	Kidney bean	5.37	4.03	mg CE/g DW	(Shimelis & Rakshit, 2007)
Sodium bicarbonate soaking (12 h)	Kidney bean	5.37	3.92	mg CE/g DW	
Extrusion	Kidney bean	1.12	0.28	mg CE/kg DW	(Marzo et al., 2002)
	Kidney bean	3.59	0.58	mg CE/g DW	(Alonso et al., 2000)
Fermentation	Fresh common bean	0.90	0.70	mg CE/g FW	(Valdez-González et al., 2017)
	Hardened common bean	0.60	0.80	mg CE/g DW	
	White kidney bean	67.1	33.5	mg CE/g DW	(Khattab & Arntfield, 2009)
	Red kidney bean	26.7	4.22	mg CE/g DW	
	Dark common bean	3.05	1.03	mg CE/g DW	(Starzyńska-Janiszewska et al., 2015)
In vitro gastrointestinal digestion	Black bean	760	60.4	mg CE/g DW	(Sancho et al., 2015)
	Regular darkening cranberry bean	≈2.20	≈1.40	mg PAC/g DW	(Chen et al., 2015b)
	Small red bean	540	50.3	mg CE/g DW	(Sancho et al., 2015)
Germination	Kidney bean	3.59	1.02–2.03	mg CE/g DW	(Alonso et al., 2000)
	Green gram	6.60	5.90	mg CE/g DW	(Ghavidel & Prakash, 2007)
	Green gram	4.50	1.17–2.59	mg CE/g DW	(Hemalatha, Platel, & Srinivasan, 2007)
	Kidney bean	5.37	3.66–1.28	mg CE/g DW	(Khattab & Arntfield, 2009)
Storage	Dry bean	ND–0.48	0.49 – 1.56	mg CE/g DW	(Martín-Cabrejas et al., 1997)
	Pinto bean of 1533-15	≈28.0	≈40.0	mg CE/g DW	(Beninger et al., 2005)
	Pinto bean of CDC pintium	≈128	≈158	mg CE/g DW	

TPC, total phenolic content; TFC, total flavonoid content; TPCA, total proanthocyanidin content; GAE, gallic acid equivalent; CE, catechin equivalent; DW, dry weight; ND, not determined; FW, fresh weight; C3GE, cyanin 3-glucoside equivalent; RE, rutin equivalent; QE, quercetin equivalent; PAC, proanthocyanidin; TAE, tannic acid equivalent.

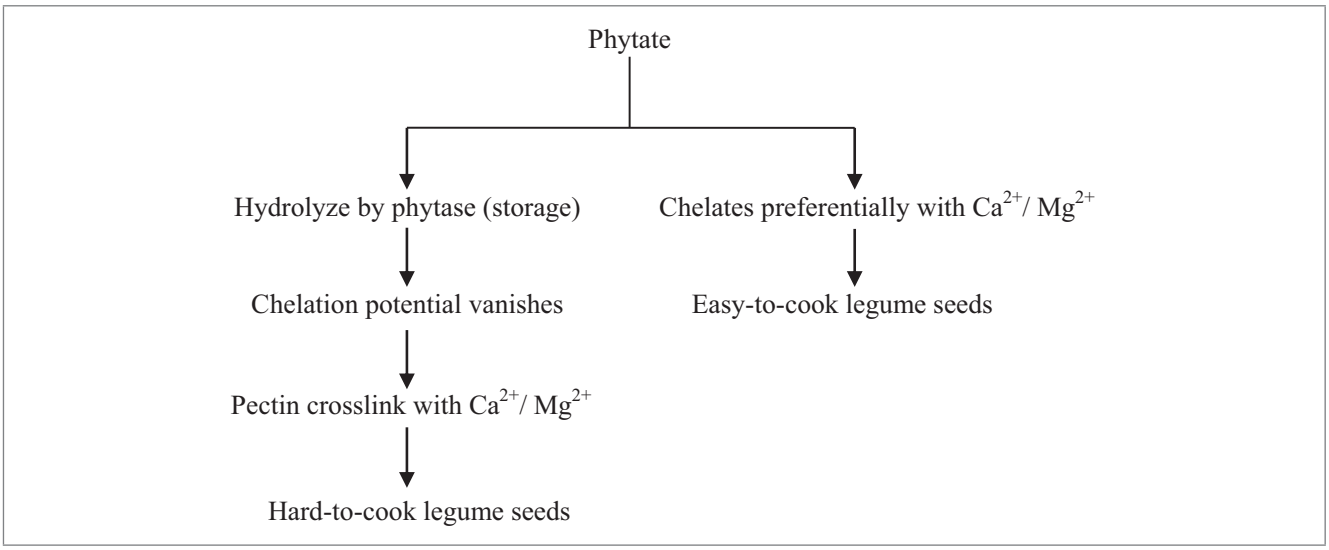

Figure 4–The proposed 'phytase–phytate–pectin' mechanism. Both phytate and the pectin can crosslink with calcium or magnesium ions, but phytate chelates preferentially with these divalent cations. If the phytate is crosslinked with calcium or magnesium ions, legume seeds appear to be easy-to-cook. However, phytate may be hydrolyzed by phytase during storage so that the chelating potential of phytate vanishes, and then the calcium or magnesium ions can crosslink with pectin to form insoluble calcium and magnesium pectates, which are not dissolved readily when heated, thus restricting cell separation, inhibiting water uptake, and resulting in hard-to-cook defect (Galiotou-Panayotou et al., 2008; Jombo et al., 2017).

& Gutiérrez-Uribe, 2013). However, recently, Xue et al. (2016) found that germination can cause the accumulation of polyphenols in black bean sprouts, and bean sprouts have about 1.54 times more TPC than raw beans after sprouting for 6 days. This contradiction may be partly attributed to the way of calculating methods. The former only calculated the TPC of the sprouts without considering the TPC of seed coats, while the latter calculated the TPC of the whole beans.

Compared to TPC, there are fewer reports about the effect of germination on the TFC of common beans. Xue et al. (2016) showed that the TFC of black beans increased with the increase of germination time and reached the highest value on the 5th day.

Generally, germination can cause significant but varying degrees of TPAC reduction (Table 3). Alonso, Aguirre, and Marzo (2000) reported that the TPAC of kidney bean (*Phaseolus vulgaris* L.) decreased significantly after germination. Similar results were obtained by Ghavidel and Prakash (2007) and Hemalatha, Platel, and Srinivasan (2007), who reported that the TPAC of green gram (*Phaseolus aureus*) sprouts was much lower than that in the raw beans.

On the other hand, germination has a significant impact on the phenolic composition of common beans. For instance, five hydroxybenzoic compounds (gallic aldehyde, protocatechuic acid, protocatechuic aldehyde, *p*-hydroxybenzoic acid, and *p*-hydroxybenzoic aldehyde) were detected in the insoluble fractions of raw dark beans (*Phaseolus vulgaris* L.). However, no hydroxybenzoic compounds were detected in the insoluble fraction of the germinated beans. The same situation was observed in hydroxycinnamic compounds (*trans*-feruloyl aldaric acid and sinapoyl aldaric acid), which were detected in the insoluble fraction of raw dark beans but not in the insoluble fraction of germinated beans. The total content of hydroxybenzoic compounds in raw beans was much higher than that in germinated beans. By contrast, the total content of hydroxycinnamic compounds in raw beans was less than that in germinated beans (Duenas et al., 2016).

Based on the above discussion, germination shows a significant effect on the TPC, TFC, TPAC, and phenolic composition of common beans.

Thermal processing

Based on the majority of the articles reviewed, thermal processing has a significant effect on the phenolic content of common beans (Table 3). Xu and Chang (2009) reported that thermal processing methods caused a significant decrease in the TPC of both pinto and black beans. The similar conclusion was obtained in other studies. Hernández-Saavedra et al. (2013) concluded that the TPC of common beans decreased significantly after cooking, and Valdés et al. (2011) also reported that there was a loss of TPC in all cooked beans, while simple phenolics were only slightly decreased. However, Akillioglu and Karakaya (2010) found that common beans and pinto beans soaking in hot/cold water and cooking with/without $NaHCO_3$ had a significant increase in TPC, indicating that these methods may retain phenolic compounds during thermal processing.

In addition, contradictory findings have also appeared in the literature regarding the effect of thermal processing on the TFC of common beans. Jiratanan and Liu (2004) reported that thermal processing led to a significant reduction in the TFC of green beans (*Phaseolus vulgaris* L.). However, Akillioglu and Karakaya (2010) found that the TFC of beans (*Phaseolus vulgaris* L.) that were soaked in hot/cold water and cooked with/without $NaHCO_3$ increased. This explains to a certain extent that soaking and cooking with $NaHCO_3$ can largely retain the flavonoids in common beans.

Furthermore, Table 3 shows that thermal processing such as cooking, roasting, and autoclaving can significantly reduce the TPAC of common beans. For example, Helbig, do Oliveira, Queiroz, and Reis (2003) reported that nearly 90% proanthocyanidins in common beans were lost after cooking. This finding was further confirmed by other studies in Table 3.

Some studies have also been conducted to further investigate how the phenolic compositions in common beans are affected

by thermal processing. Chen et al. (2015b) reported that cooking significantly increased the release of bound ferulic, sinapic acids, and flavanols. These results were consistent with a previous study, which reported that specific phenolic compounds, such as flavonols and free phenolic acids, were increased during thermal treatment (Ranilla et al., 2009). However, Xu and Chang (2009) reported that thermal processing methods significantly decreased the level of individual phenolic acids, anthocyanins, flavan-3-ols, and flavonols. This disagreement may be attributed to the common bean varieties.

In conclusion, genotype, environment conditions, storage conditions, and thermal processing methods all strongly affect the phenolic compounds in common beans. In addition, other processing interventions, including *in vitro* gastrointestinal digestion, extrusion, soaking, and fermentation, also have effects on common bean polyphenols and antioxidant activity, which have been summarized in Figure 3.

Extraction, Separation, and Identification Methods

Extraction

Extraction procedure plays an important role in the recovery of polyphenols. Common bean polyphenols have been extracted from different matrices, including whole raw beans, seed coats, cotyledons, germinated common beans, fermented common beans, and thermally processed common beans. Generally, polyphenol extraction is a typical liquid–solid extraction procedure consisting of grinding, defatting, solvent extraction, centrifugation, filtration, evaporation, and drying (Figure 5). Extraction solvent is a key factor governing the efficiency of polyphenol extraction. Methanol/water/acid systems are most commonly employed for the extraction of phenolic acids, while acetone/water/acid systems are predominantly used for the extraction of proanthocyanins (Table 1). The concentration of methanol or acetone used to extract polyphenols in common beans commonly ranges from 50 to 80%. Several studies also use pure water or methanol as the extraction solvent. However, the above mentioned solvents are only suitable for the extraction of soluble phenolics. Bound phenolics need to be hydrolyzed with 2 mol/L NaOH and 12 mol/L HCl before further extraction (Aguilera et al., 2014; Ross, Beta, & Arntfield, 2009; Treviño-Mejía, Luna-Vital, Gaytán-Martínez, Mendoza, & Loarca-Piña, 2016). In addition, numerous studies have reported that the optimization of processing parameters plays a vital role in obtaining maximal polyphenols (Ghafoor, Choi, Jeon, & Jo, 2009; Jovanovic et al., 2017; Mourtzinos et al., 2016; Paleologou, Vasiliou, Grigorakis, & Makris, 2016; Wong, Li, Li, Razmovski-Naumovski, & Chan, 2017; Zhang & Wang, 2016). However, few studies have systematically optimized the extraction conditions of common bean polyphenols. Owing to the lack of more data about the optimal extraction condition of common bean polyphenols, further studies are necessary to focus on this point.

In addition, extracting from isolated seed coats versus the whole beans using the same solvents makes a great difference in the outcome of analysis. Aquino-Bolaños et al. (2016) extracted flavonoids from the seed coats and whole seeds of Mexican common bean landraces using 70% methanol containing 5% acetic acid, and found that TFC in seed coats was much higher than that in the whole seeds. Similar conclusion was also obtained by Aparicio-Fernández, Yousef, Loarca-Piña, de Mejía, and Lila (2005) who extracted flavonoids from the whole seeds and seed coats of black Jamapa beans using 100% methanol, finding that TFC in seed coats was much higher than that in whole seeds. Besides, they also found that TPAC in seed coats was significantly higher than that in whole seeds. This trend also appears in other common bean varieties. Madhujith, Naczk, and Shahidi (2004) extracted proanthocyanidins with 80% acetone from the seed coat and whole seeds of 4 bean varieties with different seed coat colors (white, red, brown, and black), and also found that TPAC in seed coat was higher than that in whole seeds. In all studies, the seed coats are reported to contain higher levels of TFC and TPAC than whole seeds. However, there has been a disagreement concerning the TPC in seed coats and whole seeds. Madhujith et al. (2004) reported that TPC in seed coats was higher than that in whole seeds, while Ombral et al. (2016) reported that TPC in whole seeds was higher than that in seed coats of 11 common beans with different colors. This inconsistancy may be due to different extraction conditions or common bean cultivers, and further studies are needed to clarify the potential reasons.

Separation

To obtain polyphenol-rich extracts, it is necessary to purify the sample by removing impurities with column chromatography (Nemitz et al., 2015). Different types of adsorbents, such as silica gel, macroporous resins, Sephadex LH-20, HW-F40 Toyopearl resin polymer, and silica gel type 60 have been used to purify common bean polyphenols.

Due to the polar nature of phenolics presented in common beans, HPLC has become the most commonly used analytical technique for the separation of these compounds. Almost all the chosen columns for phenolics were reverse phase type, with C_{18} as stationary phase, a 2 to 4.6 mm internal diameter, and a particle size between 3 and 10 μm (Beninger et al., 2005; Hu et al., 2006; Lin, Harnly, Pastor-Corrales, & Luthria, 2008). Apart from stationary phase, the mobile phase is usually made up of methanol or acetonitrile mixed isocratically or in a gradient with water. Usually, 0.1 to 10% acetic acid or formic acid is added to the solvents. For the separation of polyphenols, it is preferred that extraction solvents are mixtures of water/acetonitrile/acetic acid or water/methanol/acetic acid.

Identification

The most commonly used technology to characterize phenolic structure is mass spectrometry coupled to HPLC, such as ESI–MS. Lin et al. (2008) analyzed 24 common bean phenolic profiles via HPLC–DAD–ESI/MS. Kaempferol and astragalin were identified in red and pinto bean seed coats using HPLC–ESI/MS (Hu et al., 2006). HPLC-ESI/MS has also been applied to analyze the polyphenols in other common bean cultivars such as black Jamapa bean (*Phaseolus vulgaris* L.) (Aparicio-Fernández et al., 2005), Zolfino landraces (*Phaseolus vulgaris* L.) (Romani et al., 2004), cranberry beans (*Phaseolus vulgaris* L.) (Chen et al., 2015c), black beans (*Phaseolus vulgaris* L.) (Hart, Tako, Kochian, & Glahn, 2015), dark beans (*Phaseolus vulgaris* L.) (Duenas et al., 2016), white and red common beans (*Phaseolus vulgaris* L.) (García-Lafuente et al., 2014), processed common beans (Moreno-Jiménez et al., 2015), and 4 landraces (12 samples) of common beans (*Phaseolus vulgaris* L.) (Heimler, Vignolini, Dini, & Romani, 2005). In addition, de Lima et al. (2014) characterized isoflavonoids in Brazilian common bean germplasm (*Phaseolus vulgaris* L.) via LC–ESI-QTOF–MS. The phytochemical characterization of green bean (*Phaseolus vulgaris* L.) was also conducted by LC–ESI-TOF–MS. (Abu-Reidah, Arráez-Román, Lozano-Sánchez, Segura-Carretero, & Fernández-Gutiérrez, 2013). Furthermore, Tako et al. (2015) used UPLC–ESI–MS to characterize the phenolic

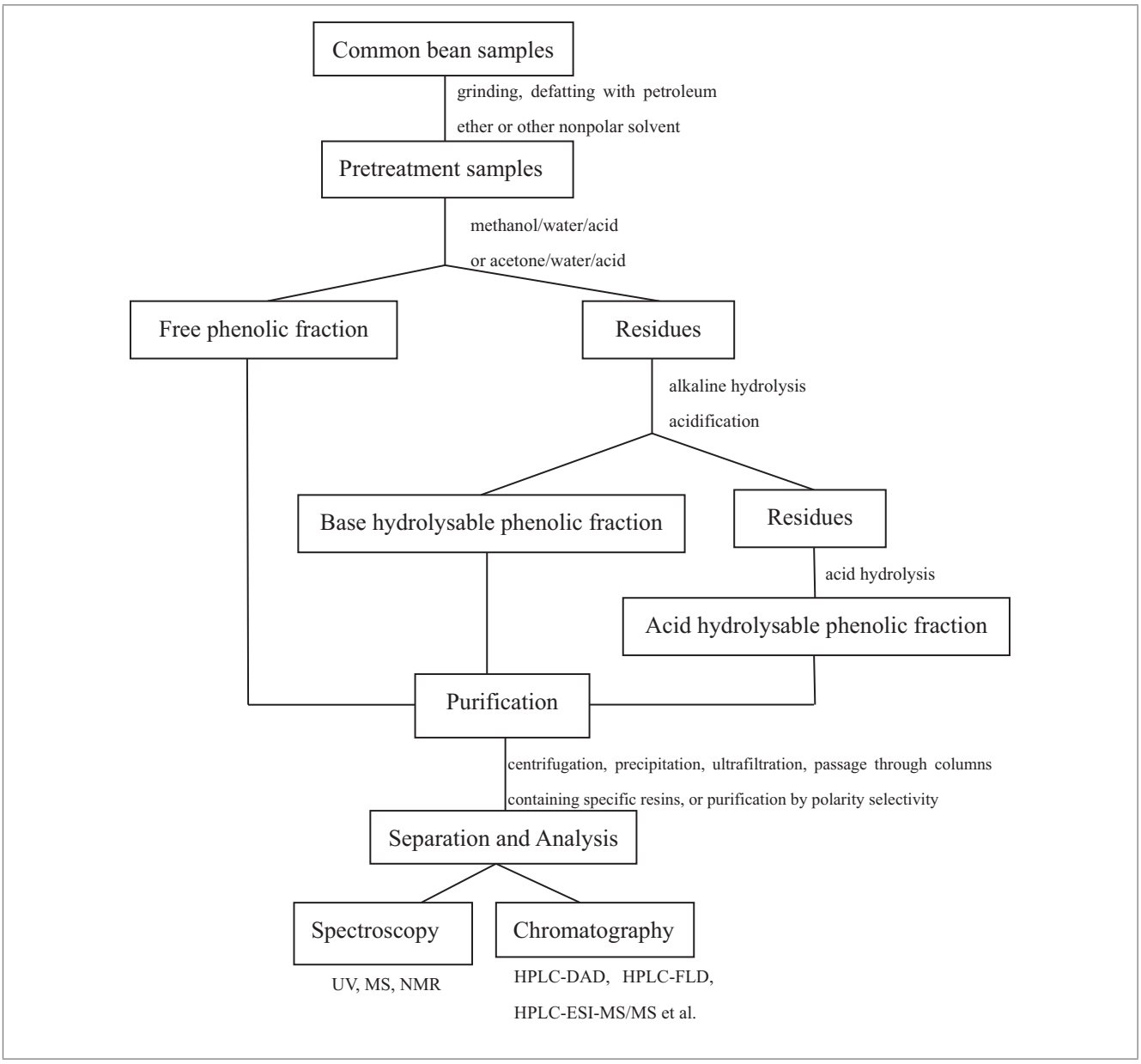

Figure 5–General steps of extraction, purification, separation, and identification common beans phenolics.

compounds in cream seeded carioca bean seed (*Phaseolus vulgaris* L.) coat extracts.

Nuclear magnetic resonance (NMR) is also widely used for the identification of phenolic compounds in common beans. Beninger and Hosfield (2003) used ^{1}H and ^{13}C NMR spectroscopy to identify flavonoids and to characterize the flavonoid composition of three dry bean (*Phaseolus vulgaris* L.) genotypes. They used the same methodology to characterize the flavonol glycosides from Montcalm dark red kidney bean (*Phaseolus vulgaris* L.), and the seed coat of a new Manteca-type dry bean (*Phaseolus vulgaris* L.) (Beninger, Hosfield, & Nair, 1998). In addition, Yoshida et al. (1996) also used ^{1}H and ^{13}C NMR to analyze the structure of anthocyanins from the colored seed coat of *Phaseolus* legumes. Most of the time, it is combined with MS. For instance, Beninger et al. (2005) identified kaempferol, kaempferol 3-O-glucoside, and kaempferol 3-O-glucosylxylose in pinto bean (*Phaseolus vulgaris* L.) using NMR and ESI–MS; Takeoka et al. (1997) also used NMR and ESI–MS to characterize black bean (*Phaseolus vulgaris* L.) anthocyanins; Choung, Choi, An, Chu, and Cho (2003) characterized the anthocyanin profile of Korean cultivated kidney bean (*Phaseolus vulgaris* L.) by UV-Vis, LC/ES–MS, and ^{1}H and ^{13}C NMR.

Antioxidant Activity

Numerous studies have demonstrated that common bean polyphenols exhibited manifold effects related to human health, such as anti-mutagenic, antimicrobial, anti-diabetic, and anti-inflammatory activities (Figure 6). These are strongly related to the antioxidant characteristics of the polyphenols. Therefore, we herein highlight the antioxidant effect in more detail. However, detailed review of the health benefits of polyphenols is beyond the scope of this review.

Table 4–Antioxidant activity of common bean extracts (all *Phaseolus vulgaris* L.).

Bean sample	Extracts	Antioxidant assay	Antioxidant effect	Unit	Reference
Dry bean	80% Ethanol	TEAC	0.40–1.30	μmol TE/g DW	(Oomah et al., 2005)
Dry bean	Methanol	ARA	14.5–47.9	μmol TE/g DW	(Cardador-Martínez, Loarca-Piña, & Oomah, 2002)
	Methanol	TEAC	1.20–3.10	μmol TE/g DW	
Green bean	80% Acetone	TOSC	≈38.0	μmol VCE/g DW	(Jiratanan & Liu, 2004)
Kidney bean	80% Chilled acetone	ORAC	14.8–24.0	μmol TE/g DW	(Aguilera et al., 2014)
Common bean	85% Methanol with 10% acetic acid	FRAP	2.81–14.6	μmol/g DW	(Redan, Vinson, & Coco Jr 2013)
	2.4 mol/L NaOH	FRAP	381–603	μmol/g DW	
Ft Nobre bean	70% Methanol	DPPH	5.80	μmol TE/g DW	(Ranilla et al., 2009)
Jalo precoce bean	70% Methanol	DPPH	6.40	μmol TE/g DW	
Black bean sprout	80% Methanol	ORAC	27.0	μmol TE/g DW	(Guajardo-Flores et al., 2013)
Black bean cotyledon	80% Methanol	ORAC	98.0	μmol TE/g DW	
Black bean seed coat	80% Methanol	ORAC	120	μmol TE/g DW	
Common bean	80% Acetone	ABTS	39.6	μmol TE/g DW	(Starzyńska-Janiszewska et al., 2015)
	80% Acetone	OH	2.51	IC_{50} (mg/mL)	
	80% Acetone	DPPH	8.04	μmol TE/g DW	
	80% Acetone	RP	23.0	$RP_{0.5}$ (mg/mL)	
Cranberry bean	80% Acetone	DPPH	0.80–10.7	μmol TE/g DW	(Chen et al., 2015c)
	80% Acetone	FRAP	0.40–7.00	μmol/g DW	
	80% Acetone	ORAC	1.00–33.0	μmol TE/g DW	
Turkish white bean	80% Methanol	ABTS	3.50–5.17	μmol TE/g DW	(Orak et al., 2016)
	80% Methanol	FRAP	7.99–11.2	μmol Fe^{2+}/g DW	
Red kidney bean seed coat	80% Methanol	FRAP	260	mmol Fe^{2+}/g DW	(Gan et al., 2016)
	80% Methanol	ABTS	237	mmol TE/g DW	
Big speckled kidney bean seed coat	80% Methanol	FRAP	346	mmol Fe^{2+}/g DW	
	80% Methanol	ABTS	288	mmol TE/g DW	
Small speckled kidney bean (oval) seed coat	80% Methanol	FRAP	365	mmol Fe^{2+}/g DW	
	80% Methanol	ABTS	282	mmol TE/g DW	
Violet red kidney bean seed coat	80% Methanol	FRAP	281	mmol Fe^{2+}/g DW	
	80% Methanol	ABTS	212	mmol TE/g DW	
Brown string bean seed coat	80% Methanol	FRAP	43.7	mmol Fe^{2+}/g DW	
	80% Methanol	ABTS	37.0	mmol TE/g DW	
Black bean	Water	TEAC	13.2	μmol TE/g DW	(Hernández-Salazar et al., 2010)
Phaseolus vulgaris L. seed coat	70% Ethanol	DPPH	1.05–518	mmol TE/g FW	(Ranilla et al., 2007)
Phaseolus vulgaris L. cotyledon	70% Ethanol	DPPH	0.88–2.67	mmol TE/g FW	
Sarconi bean	70% Ethanol	DPPH	2.78–16.9	EC_{50} (g/mg)	(Romani et al., 2013)
Common bean	Water	DPPH	0.05–0.09	EC_{50} (g/mg)	(Valdés et al., 2011)
White kidney bean	80% Methanol	DPPH	109	$1/EC_{50}$ (mg/g)	(García-Lafuente et al., 2014)
	80% Methanol	ORAC	171	μmol TE/g	
Round purple bean	80% Methanol	DPPH	218	$1/EC_{50}$ (mg/g)	
	80% Methanol	ORAC	304	μmol TE/g	
Common bean	70% Acetone	OH	≈2400–4700	IC_{50} (μg/mL)	(Moreno-Jiménez et al., 2015)
	80% Methanol	LPI	≈200–1800	IC_{50} (μg/mL)	
Regular darkening cranberry bean	70% Methanol with 1% acetic acid	ORAC	≈142	μmol TE/g DW	(Chen et al., 2015b)
Non-darkening cranberry bean	70% Methanol with 1% acetic acid	ORAC	≈50.0	μmol TE/g DW	
Common bean	Water	DPPH	1.57–55.2	EC_{50} (mg/mL)	(Ombra et al., 2016)
Common bean seed coat	70% Acetone with 0.5% acetic acid	DPPH	133–1022	μmol TE/g DW	(Aquino-Bolaños et al., 2016)
Common bean whole flour	70% Acetone with 0.5% acetic acid	DPPH	7.10–32.4	μmol TE/g DW	
Black bean	Methanol	ABTS	170	μmol TE/g DW	(Sancho et al., 2015)
	Methanol	ORAC	1241	μmol TE/g DW	
Small red bean	Methanol	ABTS	211	μmol TE/g DW	
	Methanol	ORAC	1079	μmol TE/g DW	

Abbreviations, TOSC, total oxyradical scavenging capacity; VCE, vitamin C equivalent; TEAC, Trolox equivalent antioxidant activity; ARA, Antiradical activity; TE, Trolox equivalent; ABTS, 2, 2′-azino-bis(3-ethylbenzothiazoline-6-sulfonic acid) free radical scavenging assay; DPPH, 1, 1-diphenyl-2-picrylhydrazyl free radical scavenging assay; FRAP, ferric reducing antioxidant potential assay; ORAC, oxygen radical absorbance capacity; LPI, lipid peroxidation inhibition; OH, hydroxyl free radical scavenging assay.

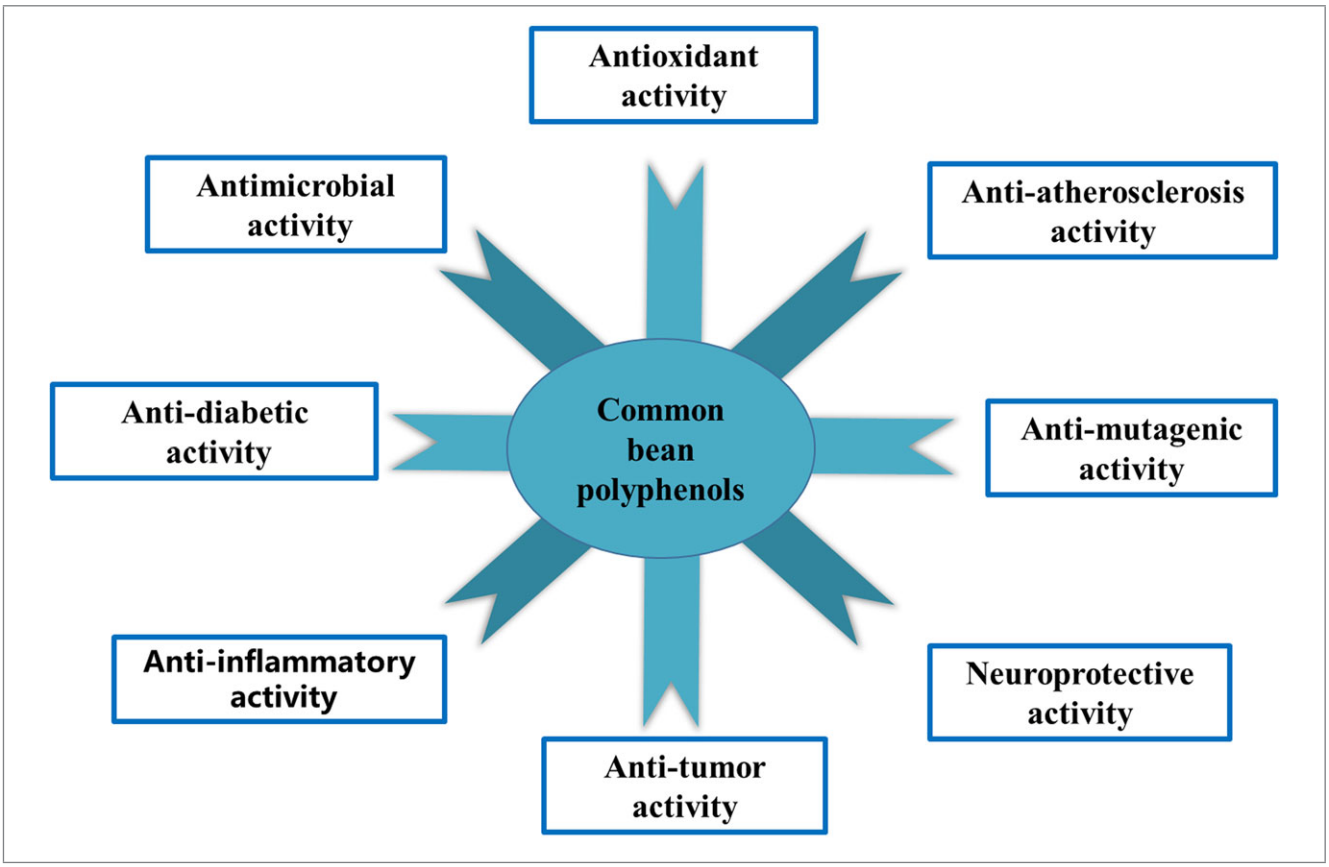

Figure 6–Health benefits of common bean polyphenols.

Oxidative stress is thought to be a biochemical imbalance caused by overproduction of reactive oxygen species or a reduction in the antioxidant systems. It is a negative effect produced by free radicals in the body and is considered an important factor leading to the aging and complications of many chronic conditions, such as Alzheimer's disease, diabetes, and various types of cancer. Among the characteristics of polyphenols, their antioxidant activity and high potential for resistance to oxidative stress are emphasized (Nakatani & Kikuzaki, 1995). Table 4 summarizes the available antioxidant activity data of common beans measured by different *in vitro* assays, including oxygen radical absorbance capacity (ORAC), ferric reducing antioxidant potential assay (FRAP), 1, 1-diphenyl-2-picrylhydrazyl free radical scavenging assay (DPPH), hydroxyl free radical scavenging assay (OH), 2, 2′-azino-bis(3-ethylbenzothiazoline-6-sulfonic acid) free radical scavenging assay (ABTS), total oxyradical scavenging capacity (TOSC), and Trolox equivalent antioxidant activity assay (TEAC). Basically, most common bean cultivars possess antioxidant activity, and colored ones show superior antioxidant activity compared to white beans. For example, Ombra et al. (2016) used the DPPH method to compare the antioxidant activity of colored and white common beans, and found that the antioxidant activity of colored ones was higher than that of non-pigmented common beans. Similar conclusion was also obtained by Madhujith and Shahidi (2005), who evaluated the antioxidant activity of four common bean varieties (white kidney, red pinto, Swedish brown, and black kidney beans) using TEAC assay, and deduced that compared with white beans, colored beans had excellent antioxidant activity. In addition, Table 4 shows that most of the polyphenols are concentrated in the seed coats of common beans, especially for the colored common beans. Ranilla et al. (2007) found that the antioxidant activity of common bean seed coat was higher than that of its cotyledon. This finding was further confirmed by other studies (for example, Aquino-Bolaños et al., 2016; Guajardo-Flores et al., 2013). More importantly, several studies have concluded that the antioxidant activity of common beans was positively correlated with the TPC of common beans (Anton, Ross, Beta, Fulcher, & Arntfield, 2008; Elizabeth et al., 2007; Ranilla et al., 2007). Another noteworthy point is that according to FRAP and ABTS methods, the antioxidant activity of most pigmented bean coats is higher than most common fruits and vegetables (Gan et al., 2016). Furthermore, not only the *in vitro* studies but animal studies have also confirmed that common beans possess antioxidant activity, as measured in various biochemical parameters such as thiobarbituric acid reactive substances, hydroperoxides, glutathione, glutathione reductase, glutathione S-transferase, glutathione peroxidase, and catalase (Ganesan & Xu, 2017). Xu and Chang (2011) reported that raw pinto and black beans (*Phaseolus vulgaris* L.) exhibited cellular antioxidant activities in dose-dependent manners.

On the other hand, the antioxidant activity of common beans is significantly affected by processing methods such as thermal processing, fermentation, and germination. Table 5 shows the effect of processing methods on the antioxidant activity of common beans. Generally, thermal processing methods, such as cooking and steaming, cause a significant decrease in antioxidant activity (Table 5). For instance, Starzyńska-Janiszewska, Stodolak, and Wikiera (2015) reported that soaking and cooking significantly reduced the free radical scavenging activity and reducing power of

Table 5–Effect of processing methods on common bean antioxidant activities (all *Phaseolus vulgaris* L.).

				Antioxidant activity			
Processing methods	Bean sample	Soluble/bound extract	Analytic methods	Before processing	After processing	Unit	References
Thermal processing							
	Pinto Saltillo	Soluble	OH	≈2300	≈2600	IC_{50} (μg/mL)	(Moreno-Jiménez et al., 2015)
		Soluble	OH	≈2700	≈2750	IC_{50} (μg/mL)	
	Negro 8025	Soluble	OH	≈4600	≈2600	IC_{50} (μg/mL)	
		Soluble	LPI	≈200	≈700	IC_{50} (μg/mL)	
	Bayo Victoria	Soluble	OH	≈2850	≈2800	IC_{50} (μg/mL)	
		Soluble	LPI	≈600	≈900	IC_{50} (μg/mL)	
	Pinto Saltillo	Soluble	LPI	≈1800	≈2400	IC_{50} (μg/mL)	
		Soluble	LPI	≈600	≈950	IC_{50} (μg/mL)	
	Pinto bean	Soluble	DPPH	≈18.0	≈6.00–9.00	μmol TE/g DW	(Xu & Chang, 2009)
		Soluble	FRAP	≈6.00	≈1.50–2.80	μmol Fe^{2+}/g DW	
		Soluble	ORAC	≈58.0	≈18.0–30.0	μmol TE/g DW	
	Black bean	Soluble	DPPH	≈19.0	≈10.0–14.0	μmol TE/g DW	
		Soluble	FRAP	≈9.80	≈2.8–4.50	μmol Fe^{2+}/g DW	
		Soluble	ORAC	≈70.0	≈12.0–38.0	μmol TE/g DW	
	Green bean	Total	TOSC	≈38.0	≈32.0	μmol VC/g DW	(Jiratanan & Liu, 2004)
	Ft nobre bean	Soluble	DPPH	5.80	1.90–7.30	μmol TE/g DW	(Ranilla et al., 2009)
	Jalo precoce bean	Soluble	DPPH	6.40	2.50–11.9	μmol TE/g DW	
	Common bean	Soluble	ABTS	39.6	10.9	μmol TE/g DW	(Starzyńska-Janiszewska et al., 2015)
		Soluble	DPPH	8.04	2.11	μmol TE/g DW	
		Soluble	RP	23.0	63.5	$RP_{0.5}$ (mg/mL)	
		Soluble	OH	2.51	16.8	IC_{50} (mg/mL)	
	Common bean	Soluble	DPPH	0.05–0.09	0.07–0.24	EC_{50} (g/mg)	(Valdés et al., 2011)
	Regular darkening cranberry bean	Soluble	ORAC	≈142	≈128	μmol TE/g DW	(Chen et al., 2015b)
	Non-darkening cranberry bean	Soluble	ORAC	≈50.0	≈40.0	μmol TE/g DW	
	Common bean	Soluble	DPPH	1.57–55.2	3.82–66.6	EC_{50} (mg/mL)	(Ombra et al., 2016)
	Black bean	Soluble	DPPH	19.0	10.7–15.6	μmol TE/g DW	(Xu & Chang, 2008)
		Soluble	ORAC	92.7	10.8–64.6	μmol TE/g DW	
	Pinto bean	Total	FRAP	572	378	μmol CE/g DW	(Redan, Vinson, & Coco, 2013)
	Navy bean	Total	FRAP	508	442	μmol CE/g DW	
	Black bean	Total	FRAP	476	404	μmol CE/g DW	
	Light red kidney bean	Total	FRAP	592	442	μmol CE/g DW	
	Dark red kidney bean	Total	FRAP	603	352	μmol CE/g DW	
	Garbanzo bean	Total	FRAP	479	408	μmol CE/g DW	
	Great northern bean	Total	FRAP	489	371	μmol CE/g DW	
	Red bean	Total	FRAP	463	431	μmol CE/g DW	
	Blackeye bean	Total	FRAP	381	387	μmol CE/g DW	
Soaking + cooking							
	Common bean	Soluble	DPPH	0.05–0.09	0.035–0.04	EC_{50} (g/mg)	(Valdés et al., 2011)
	Kidney bean	Soluble	TEAC	4.50	3.20–9.50	mmol TE/g DW	(Haileslassie et al., 2016)
	Green bean	Soluble	TOSC	≈38.0	≈30.0–33.0	μmol VCE/g DW	(Jiratanan & Liu, 2004)
	Common bean	Soluble	FRAP	2.81–14.6	1.59–7.96	μmol/g DW	(Redan et al., 2013)
		Bound	FRAP	381–603	352–442	μmol/g DW	
	Common bean	Soluble	OH	≈2.40–4.70	≈2.05–2.80	IC_{50} (mg/mL)	(Moreno-Jiménez et al., 2015)
		Soluble	LPI	≈200–1800	≈80.0–3300	IC_{50} (μg/mL)	
	Black bean	Soluble	DPPH	19.0	12.1–13.6	μmol TE/g DW	(Xu & Chang, 2008)
	Black bean	Soluble	ORAC	92.7	50.3–77.2	μmol TE/g DW	
Soaking							
	Common bean	Soluble	DPPH	0.05–0.09	0.14–0.22	EC_{50} (g/mg)	(Valdés et al., 2011)
	Black bean	Soluble	DPPH	19.0	17.4–17.8	μmol TE/g DW	(Xu & Chang, 2008)
	Black bean	Soluble	ORAC	92.7	66.3–77.9	μmol TE/g DW	
Germination							
	Black bean sprout	Soluble	ORAC	27.0	10.0	μmol TE/g DW	(Guajardo-Flores et al., 2013)
	Black bean cotyledon	Soluble	ORAC	98.0	10.0	μmol TE/g DW	
	Black bean seed coat	Soluble	ORAC	120	590	μmol TE/g DW	
	Kidney bean	Soluble	ORAC	≈24.0	≈12.0–46.0	μmol TE/g DW	(Aguilera et al., 2014)
	Common bean	Soluble	ABTS	39.6	14.4	μmol TE/g DW	(Starzyńska-Janiszewska et al., 2015)
		Soluble	OH	2.51	9.30	IC_{50} (mg/mL)	
		Soluble	DPPH	8.04	3.08	μmol TE/g DW	
		Soluble	RP	23.0	55.2	$RP_{0.5}$ (mg/mL)	

Abbreviations, TOSC, total oxyradical scavenging capacity; VCE, vitamin C equivalent; TEAC, Trolox equivalent antioxidant activity; TE, Trolox equivalent; ABTS, 2, 2′-azino-bis(3-ethylbenzothiazoline-6-sulfonic acid) free radical scavenging assay; DPPH, 1, 1-diphenyl-2-picrylhydrazyl free radical scavenging assay; OH, hydroxyl radical absorbance capacity; ORAC, oxygen radical absorbance capacity; LPI, lipid peroxidation inhibition; OH, hydroxyl free radical scavenging assay; FRAP, ferric reducing antioxidant potential assay; RP, reducing power.

common beans. Chen et al. (2015b) also found similar phenomena and explained that the decline in antioxidant activity was related to the decrease in the content of phenolics and flavonoids. However, still several other studies have reported a fluctuation or an increase of antioxidant activity in cooked common beans. For example, Ranilla et al. (2009) reported that there was a fluctuation in antioxidant activity of thermal processed common beans, mainly associated with the bean cultivar and whether they retained soaking water during thermal processing. In addition, some researchers found that thermal processing promoted the release of bound phenolics and then caused an increase in antioxidant activity (Moreno-Jiménez et al., 2015; Rocha-Guzmán, Herzog, et al., 2007; Valdés et al., 2011). On the other hand, germination can significantly increase the antioxidant activity of common beans. Several studies concluded that germination led to increased antioxidant activity due to the increased TPC in germinated beans (Aguilera et al., 2014; Xu & Chang, 2011; Xue et al., 2016), and in order to highlight this phenomenon, our group gave a comprehensive review about antioxidant activity of germinated edible seeds and sprouts (Gan et al., 2017). However, Guajardo-Flores et al. (2013) found that germination resulted in reduced antioxidant activity of black bean sprouts and cotyledons but increased antioxidant activity of black bean seed coats. Other processing methods such as Nano-Gro, an organic biostimulant, and fermentation are also applied to improve the antioxidant activity of common beans. Kocira, Kocira, Zlotek, Kornas, and Swieca (2015) applied Nano-Gro to increase the antioxidant activity of common beans. They also reported that fermentation increased the antioxidant activity of common beans compared with cooked beans. Overall, processing methods have a significant effect on the antioxidant activity of common beans.

Perspectives and Conclusions

Common bean (*Phaseolus vulgaris* L.) is one of the most important pulses because of its nutritional value and beneficial effects. In this review, the content, composition, distribution, and related factors influencing polyphenols in common beans as well as their antioxidant activity are systemically summarized and discussed. However, the following aspects still need further research to make up gaps in knowledge.

For the extraction of polyphenols, the extraction solvent plays an important role in the extraction efficiency. Although acetone/water or methanol/water mixtures are most commonly used for the simultaneous extraction of polar and nonpolar polyphenols, there is no precise recommendation for extracting a particular sample with a specific solvent or solvent mixture. Mathematical modeling such as the artificial neural networks and response surface methodology, an ideal candidate for predicting the interactions between the target compound and solvent, has been successfully applied in the selection of a particular solvent for higher extraction yield of polyphenols in many plants. However, to date, no available study has applied these modeling methods to optimize the extraction conditions of common bean polyphenols. Therefore, further studies can apply these methods to minimize the effort required to select solvents for common bean polyphenols in different varieties.

In addition, the research on the chemical composition of common beans provides a solid theoretical basis for the development and utilization of common beans. To further develop these beans, it is necessary to find more bioactive compounds and investigate their health benefits or their biologically active metabolites. Thus, future research can focus on the extraction and purification of new active compounds from common beans, and clinical studies are also needed to verify the therapeutic benefits of common beans rich in polyphenols.

Besides, thermal processing can adversely affect polyphenols thereby reducing the antioxidant activity of processed common beans. However, in several studies, antioxidant activity increased after processing, which may be due to the inherent nature of some common bean cultivars. Thus, special attention should be paid to such common bean varieties because of their intrinsic textures and other parameters after thermal processing.

It is obvious that the antioxidant activity of common beans is mainly attributed to the complex mixture of phytochemicals rather than a single antioxidant in beans. Measuring the antioxidant activity of common beans based solely on the presence of any single antioxidant is biased because phytochemical complexes can exhibit synergistic effects. Therefore, the synergistic effect of common bean polyphenols and other bioactive compounds deserves further study.

Acknowledgments

This study was financially supported by the Shanghai Agricultural Science and Technology Key Program (18391900600), Shanghai Basic and Key Program (18JC1410800), the National Key R&D Program of China (2017YFC1600100), Shanghai Pujiang Talent Plan (18PJ1404600), and Shanghai Jiao Tong University Young Scholar Starting Funding.

Author Contributions

R.Y.G. and H.C. conceived the idea, Q.Q.Y. and R.Y.G. constructed the manuscript, R.Y.G., Y.Y.G., D.Z., and H.C. edited and revised the manuscript.

Conflict of Interest

The authors declare no conflict of interest.

Abbreviations

TPC	Total phenolic content
TFC	Total flavonoid content
TPAC	Total proanthocyanidin content
ORAC	Oxygen radical absorbance capacity
FRAP	Ferric reducing antioxidant potential
DPPH	1,1-Diphenyl-2-picrylhydrazyl
OH	Hydroxyl free radical
ABTS	2, 2′-Azino-bis (3-ethylbenzothiazoline-6-sulfonic acid)
TOSC	Oxyradical scavenging capacity
TEAC	Trolox equivalent antioxidant activity assay
GAE	Gallic acid equivalent
CE	Catechin equivalent

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