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Review

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BIOLOGICAL FUNCTIONS OF LIGNANS IN PLANTS

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Naturally occurring lignans are present in seeds, nuts, cereals, vegetables, and fruits. Lignans play various roles in plants and their multipurpose functions of different organisms including humans is considerable. They are involved in plant defence mechanisms through their antioxidant, antiviral, antibacterial, and antifungal properties. The lignans content may be affected by a variety of factors such as genotype, tissue type, geographic origin, local environmental conditions, nutrition, and plant maturity. Interactive relationships between individual factors are also considered. This review aimed to summarize the biological functions of lignans for plants and empasize the importance of these compounds for the added value of individual genotypes of plant food resources. Understanding the biological functions of lignans in plants can provide solutions to the ever-increasing requirements for the production of functional foods. Flaxseed is the richest source of lignans, and as such is considered the model species for lignans studies. Within our review, one paragraph is focused on the properties and biological functions of flax lignans.

Key words: plants lignans, secoisolariciresinol, lignans functions, lignans content, flax

Lignans are defined as a class of secondary metabolites belonging to the group of phenylpropanoids (phenylpropane derivatives), which are compounds having a tricarbon chain attached to the aromatic nucleus (Teponno *et al.* 2016). They are formed by dimerization of two phenylpropanoid units with a different degree of oxidation and substitution patterns of their aromatic moieties (Markulin *et al.* 2019). Recognition of the importance and functions of lignans is the growing interest to experts. Nineteen core journals have published more than 3,600 publications on lignans, while more than 80% of them appeared since the year 2000, and almost 50% since the year 2010 (Yeung *et al.* 2020). However, it should be emphasized that most of the analysed literature sources focused on the medical and nutritional uses of lignans.

Lignans have a wide range of effects on all organisms (antioxidant, antibacterial, antiviral, fungicidal, insecticidal, estrogenic, antiestrogenic, anticarcinogenic, anticardiovascullar effect), and their occurrence in the plant organism is considerable (Willför *et al.* 2006). The lignans consumed by animals and humans are hydrolyzed and metabolized by the intestinal microflora mainly to enterolignans, enterodiol, and enterolactone. These metabolites, known as mammalian lignans, possess a chemical structure similar to a sex hormone in the oestrogen family and can act as phytoestrogens (Fardet *et al.* 2018; Rodríguez-García *et al.* 2019). The effect of phytoestrogens can positively affect cognitive functions, such as learning, attention, and short-term memory, as well as influence sensorimotor such as fine touch, smell, hearing, and motor activities (Balík

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et al. 2020; Yeung *et al.* 2020). Numerous comprehensive studies provide information on the health effects of lignans and their potential to reduce the risk of diseases development (Touré & Xueming 2010; De Silva & Alcorn 2019; Parikh *et al.* 2019; Rodríguez-García *et al.* 2019).

Demand for healthy foods and nutritional supplements, as a result of the rise in diseases associated with inappropriate lifestyles, will raise awareness of the significant effects of lignans. This trend will significantly support technological progress in the food industry (Global Market Insights, Inc 2020). The value of the global lignan market is expected to exceed $90 million by 2026 (Global Market Insights, Inc 2020). In nowadays, there are efforts to determine the lignan content depending on a particular genotype for bio-fortification breeding purposes and functional foods innovation (Wu *et al.* 2021).

In order to increase the amount of lignan, new varieties of plants species have been bred in recent years.

However, great emphasis should be placed on the fact that certain climatic conditions and cultivation methods, as well as the variety, can influence the composition and the content of different bioactive compounds (Zhou *et al.* 2016).

This review describes the biological functions of lignans in plants and summarizes the factors affecting their content. The study aims to communicate the importance of selecting a specific genotype/variety of plant food resources for the production of functional foods because research confirms the genetic background determines the plant´s lignans content.

PLANT LIGNANS STRUCTURE AND SYNTHESIS

Lignans are traditionally divided into two classes – classic lignans and neolignans (Fang & Hu 2018). The difference between lignan and neolignan lies in the bonding position of their basic monomers, whereas in the case of lignans they are linked by the central carbon C8, in the case of neolignans this bonding is mediated in a different way (Figure 1). The term norlignan refers to a lignan molecule with a missing carbon atom (Kuete 2013).

Lignans are classified into eight groups based on their cyclization pattern, carbon skeleton, and oxygen incorporation as follows: arylnaphthalene (AN), aryltetralin (AT), dibenzocyclooctadiene (DCO), dibenzylbutane (DB), dibenzylbutyrolactol (DBLL), dibenzylbutyrolacton (DBL), furan (FR) and furofuran (FF) (Teponno *et al.* 2016; Markulin *et al.* 2019).

Lignans are synthesized by the shikimate biosynthesis pathway. They originate from cinnamic acid derivatives which are related biochemically to the metabolism of phenylalanine. The basic construction of C6 + C3 results from its initial deamination by phenylalanine ammonium lyase that yields cinnamic acid (Teponno *et al.* 2016). Subsequent hydroxylation with the enzyme P450 leads to the formation of hydroxycinnamic acid (p-coumaric acid) and/or its polyhydroxyl analogues, which can be methylated by O-methyltransferase to form the basic monomeric phenylpropanoid subunits (derivatives cinnamic acid). This class of carboxylic acids is further reduced with an ester of coenzyme A to an intermediate aldehyde, which can be subsequently reduced with the enzyme NADPH to the alcohol. These three categories of compounds – hydroxycinnamic acid derivatives, aldehydes, and alcohols – represent the basic and starting monomer units in the biosynthesis of lignans or neolignans. Dimerizations of these monomers are mediated by laccases, which are multicomponent oxidases, or peroxidases, followed by post-dimerization transformations by methylation and/or hydroxylation processes (Touré *et al.* 2010).

Lignan biosynthesis involves the coupling of two coniferyl alcohols resulting in pinoresinol, mediated by the dirigent protein gene family members (*DIR*s) and with the help of an oxidase (laccase or peroxidase) (Markulin *et al.* 2019). Downstream metabolic processes, leading to conversion of pinoresinol (PINO) to lariciresinol (LARI) and secoisolariciresinol (SECO), are catalysed by the enzyme pinoresinol-lariciresinol reductase (PLR), which controls the crutial step in lignan biosynthesis. Finally, secoisolariciresinol is glycosylated into secoisolariciresinol diglucoside (SDG) under the control of UDP-glycosyltransferase (UGT) (Dalisay *et al.* 2015; Garros *et al.* 2018; Markulin *et al.* 2019) (Figure 2). The expression profile of lignan biosynthetic genes in flax

(*LuDIR*, *LuPLR,* and *LuUGT*) suggested a transcriptional regulation of lignan accumulation (Dalisay *et al.* 2015; Garros *et al.* 2018; Wu *et al.* 2021).

Stereochemistry of lignans differs not only between species, genotypes but also within the plant organs (von Heimendahl *et al.* 2005; Hemmati *et al.* 2010). Variability in amino acid composition of pinoresinol-lariciresinol reductase proteins (PLRs), which catalyses two early steps in lignan biosynthesis, may be responsible for the action of the PLRs concerning to the different enantioselectivity (von Heimendahl *et al.* 2005). Pinoresinol-lariciresinol reductase (*PLR-LU1* and *PLR-LU2*) transcripts were observed in flax seeds participating in the synthesis SS- and RR- secoisolariciresinol, respectively. In flax seeds are present secoisolariciresinol diglucosides (SDG) in enantiomeric mixtures as SS- and RR-SDG. While in leaves and stems only *PLR-LU2* was transcriptionally active accumulating RR enantiomers of lignans (Hemmati *et al.* 2010). Expression patterns of *PLRs* genes behave in a spatio-temporal and organ-specific manner (Markulin *et al.* 2019).

ROLE OF LIGNANS IN PLANTS

It is estimated that there are up to 30,000 variants of lignans, of which only about 6,000 are currently known (Zálešák *et al.* 2019). The furofuran lignans have so far been identified in plants of 53 species, 41 genera, and 27 plant families. Examples of such plant families are *Aracaceae*, *Araliaceae, Fabaceae*, *Linaceae, Piperaceae*, *Rhizophoraceae*, *Rosaceae,* and many others (Xu *et al.* 2019). Lignans together with flavonoids, stilbenes, tannins, and lignin are part of a large group of phenolic derivatives, which have important functions in plants (Heldt & Heldt 2013). Despite their common biochemical basis, they have wide structural variability, and spatio-temporal biological activity (Markulin *et al.* 2019). The goal of biochemists is to create their synthetic substitutes or incorporate them into drugs (Touré *et al.* 2010; Barker 2019).

There is a growing interest in lignan–containing materials in the food industry. The main lignan sources used include oilseeds, cereals, legumes, vegetables, and fruits (Durazzo *et al.* 2018) (Table 1). Among the oilseeds, sesame seeds (*Sesamum indicum* L.) containing sesaminol, which have the highest lignan concentration after flaxseed (*Linum usitatissimum* L.), and cashew nuts (*Anacardium occidentale* L.) are also a relatively rich sources of lignans. In cereals, lignans are most concentrated in the outer layers of grain, whereas are much less abundant in the endosperm. The top lignan–rich crops include rye (*Secale cereale* L.), wheat (*Triticum aestivum* L.), oats (*Avena sativa* L.), triticale (×*Triticosecale*), in contrast, the lowest concentra-

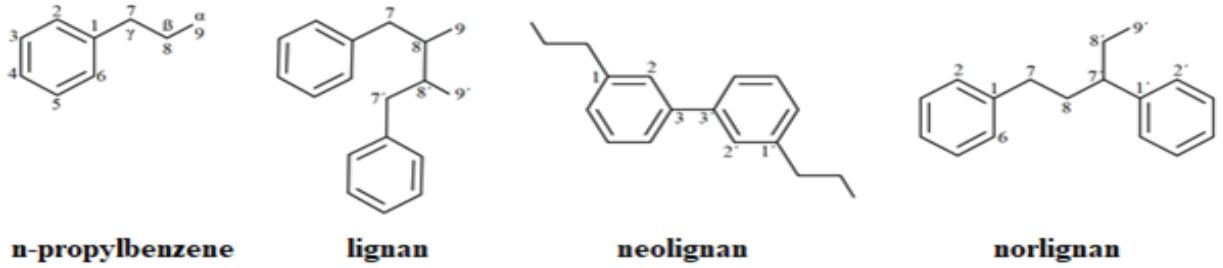


Figure 1. Structure of n–propylbenzene (C6 + C3) monomer, and dimers of lignan, neolignan, and norlignan (adapted from Kuete 2013).

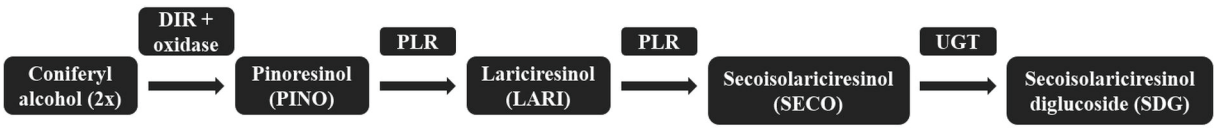


Figure 2. Scheme of the biosynthetic pathway leading to the formation of secoisolariciresinol diglucoside (SDG). DIR – dirigent protein; PLR – pinoresinol-lariciresinol reductase; UGT – UDP-glycosyltransferase; PINO – pinoresinol; LARI – lariciresinol; SECO – secoisolariciresinol; SDG – secoisolariciresinol diglucoside (adapted from Garros *et al.* 2018).

T a b l e 1

Lignan content in selected plant food resources and food products (mg/100 g food)
(adapted from Rodríguez-García *et al.* 2019)

Plant food resources / plant food products	Total lignans (mg/100 g food)
Apricot (*Prunus armeniaca* L.)	11.57
Broccoli (*Brassica oleracea* var. italica (Plenk) Markgr.	98.51
Brussel sprouts (*Brassica oleracea* var. gemmifera (DC.) Markgr.	50.36
Carrot (*Daucus carota* L.)	7.66
Cashew nut (*Anacardium occidentale* L.)	56.33
Cauliflower (*Brassica oleracea* var. botrytis (L.) Markgr.	9.48
Chicory (green) (*Cichorium intybus* L.)	1.17
Cucumber (*Cucumis sativus* L.)	3.80
Extra virgin Olive Oil	1.08
Flaxseed	257.60
Grapefruit (*Citrus paradisi* Macf.)	7.44
Green bean (*Phaseolus vulgaris* L.)	22.67
Green sweet pepper (*Capsicum annum* L.)	12.54
Kale (*Brassica oleracea* var. sabauda (L.) O. E. Schulz)	63.00
Kiwi (*Actinidia deliciosa* C. F. Liang & A. R. Ferguson)	4.17
Melon (*Melo sativus* Sarg.)	4.49
Nectarine (*Prunus persica* var. nucipersica Schneid.)	4.71
Orange (*Citrus sinensis* (L.) Pers.)	2.71
Peach (*Prunus persica* L.)	6.83
Peanut (*Arachis hypogaea* L.)	6.80
Pear (*Pyrus communis* L., emend. Gaertn.)	15.56
Potato (*Solanum tuberosum* L.)	2.89
Red cabbage (*Brassica oleracea* f. rubra (L.) Thell.)	18.10
Rye, whole grain flour	1.46
Sauerkraut	18.30
Sesame seed black oil	1,223.30
Sesame seed oil	1,294.75
Sunflower seed	1.52
Tangerine (*Citrus tangerina*)	5.80
Tomato (*Lycopersicon esculetum* Mill.)	2.15
White cabbage (*Brassica oleracea* f. alba DC.)	21.51
Yellow sweet pepper (*Capsicum annum* L.)	8.21
Zucchini (*Cucurbita pepo* var. pepo L.)	7.02

Note: The table shows resources with a total lignan content exceeding 1 mg/100 g food.

tions can be detected in brown rice (*Oryza sativa* L.) (Fardet 2010).

Because lignan is found in many common foods, it is taken daily by humans. There are several national databases on the content of lignans in foods helping to determine the relationship between a lignan-rich diet and its health benefits (Durazzo *et al.* 2018). According to Milder *et al.* (2005), the Dutch population takes most lignans from beverages, which corresponds to 37%, followed by vegetables (24%), seeds (14%), bakery products, and lignans from fruit in both cases 10% falls below.

Lignans have been identified in different parts of plant organisms as flowers, seeds, leaves, roots, fruits, and wooden parts, playing various roles in plants, but primarily they act as defence substances (Willför *et al.* 2006; Garros *et al.* 2018). For example, pinoresinol is formed when the plant is wounded, and malognol inhibits the growth of fungi and bacteria (Heldt & Heldt 2013; Kyselka *et al.* 2017; Markulin *et al.* 2019). Some lignans (e.g. sesamin) are also involved in the regulation of plant growth (DellaGreca *et al.* 2013; Yamauchi *et al.* 2015). Considering the various patterns of localization

T a b l e 2

Functions of lignans in plants

Plant source	Function	Reference
Resistance against diseases		
Cotton (*Gossypium hirsutum* L.)	Defence response against *Fusarium oxysporum*	Dowd *et al.* 2004
Tissue extracts of sesame	Antifungal activity	Syed *et al.* 2015
Flax (*Linum usitatissimum* L.)	Defence response against *Fusarium oxysporum*	Preisner *et al.* 2014
Poplar (*Populus alba* L.)	No effect on colonization with mycorrhiza	Danielsen *et al.* 2013
Poplar – infection with fungal pathogens	Induced the synthesis of cinnamyl alcohol dehydrogenase, which diverts the substrate from lignans to monolignols and lignin	Bagniewska-Zadworna *et al.* 2014
Flax cell culture elicited with fungal pathogens	Did not increase lignan levels in the cells	Hano *et al.* 2006
Dimorphic yeasts and zygomycetous, ascomycetous and basidiomycetous fungi including plant pathogens, but except for dimorphic yeasts	Antimicrobial activity	Andargie *et al.* 2021
Resistance against herbivores		
Purified lignans of sesame	Might contribute to the protection of seeds against herbivores – insecticidal and antifeedant activities	Harmatha and Dinan 2003
Furofuran lignans from himalayan shrub lopseed (*Phryma leptostachya* L.)	Demonstrate insecticidal activity	Li *et al.* 2019
Fesame lignans	Antifeedant activity of sesamin	Srivastava *et al.* 2001
Pinoresinol ingested by caterpillars	Protected the larvae from insectivorous ants	Schroeder *et al.* 2006
Methyl jasmonate induct lignan biosynthetic pathway	Methyl jasmonate – phytohormone activating plant defence against insects – observed *in vitro*	Chen *et al.* 2015; Wang *et al.* 2019
Protection from radiation damage		
Plants exposed to continuous light	Stimulated the expression of the sesamin synthase gene, and the accumulation of sesamin in leaves	Hata *et al.* 2012
Developmental control in seeds		
Sesame seeds – sesamin and sesamin-binding protein steroleosin B	Caused various developmental defects when concomitantly produced in genetically engineered *A. thaliana* (L.) plants	Tera *et al.* 2019

and biochemical properties of lignans, their role in plants can only be hypothesized, while taking into account allelopathic roles as well (Markulin *et al.* 2019). Some authors question the protective functions of lignans because most of the studies have been performed *in vitro*, and therefore these results cannot be considered unambiguous (Xu *et al.* 2019). War *et al.* (2012) stated, that protective biological functions cannot be applied to lignans despite the fact the lignans are derived from phenylpropanoids, which usually participate in plant resistance. Other authors (Suzuki *et al.* 2002; Hemmati *et al.* 2010) consider the protective role of lignans against UV damage unlikely due to their low content in the leaves and absence in other plant parts. Still, the published results are not conclusive and emphasize the importance of the need for further investigation on the biological functions of lignans in plants (Table 2). Despite the recent review by Andargie *et al.* (2021) for sesame, information on the functions and significance of the lignans for plants remains severely limited.

The integrated omics approach has revealed the spatio-temporal distribution and accumulation of lignans (secoisolariciresinol diglucoside – SDG and SDG hydroxymethylglutaryl ester) (Dalisay *et al.* 2015). Lignans were localized in early seed coat development stages (at 6 and 7 days after pollination), while during seed coat maturation they were converted into phenolics of higher molecular weights. Undetectable values of the diglucosides or their precursors in undeveloped or aborted seeds suggested a rapid conversion of these metabolites and uneven SDG distribution during flax seed and capsule development (Dalisay *et al.* 2015).

Hence the stereochemistry of lignan biosynthesis is regulated organ-specifically and has also been confirmed in flax by current omics technologies (Dalisay *et al.* 2015).

Dirigent (DIR) proteins have been found to mediate lignan and lignin biosynthesis in plants under stress, suggesting their role in adaptive plant responses (Paniagua *et al.* 2017). Expression patterns analyses of selected DIRs genes in flax pointed out the participation of specific DIRs in (-)-pinoresinol formation in seed-coats, and (+)-pinoresinol in vegetative organs and/or specific responses to hormone or fungi elicitor stress (Corbin *et al.* 2018).

Increased synthesis of polyphenols was recorded under abiotic stress conditions such as drought, extreme temperatures, salinity, heavy metal, and UV radiations. Similarly to other polyphenols (Sharma *et al.* 2019), the key feature of their role in plants is their antioxidant activity during defence responses (Ghotbzadeh Kerman *et al*. 2019). The level of lignans in sesame (*Sesamum indicum* L.) changed under drought stress in genotype-specific manner. Higher levels of polyphenols such as sesamin and/or sesamolin were observed in drought-tolerant genotypes (Ghotbzadeh Kermani *et al.* 2019).

T a b l e 3

An overview of the analysed factors influencing the lignan content in flax

Factor	Impact rate	References
Genotype	major influence	Garros *et al.* 2018
Economic types of flax	significant	Krajčová *et al.* 2009
Geographic origin	not significant	Garros *et al.* 2018
Location of cultivation	not significant	Garros *et al.* 2018
Nutrition	not significant	Krajčová et al. 2009
Cultivation year	no influence	Krajčová *et al.* 2009
Genotype × location	significant	Garros *et al.* 2018
Genotype × year	significant	Garros *et al.* 2018
Content of alpha linolenic acid in linseed	is taken into account	Bjelková *et al.* 2017

Note: Opinions are given in relation to the genotypes tested.

Upon exposure to toxic cadmium, relatively higher amounts of lignans accumulated in the metal-tolerant genotype of oilseed rape (*Brassica napus* L.) compared with the sensitive counterparts (Mwamba *et al.* 2020).

Environmental stress conditions are usually connected with increased levels of stress hormones in plants. Exogenously applied stress hormones have been suggested to enhance lignan biosynthesis (Nadeem *et al.* 2018). Indeed, moderate concentrations of salicylic acid (50 μM) significantly influenced the biosynthesis of lignans and neolignans in flax cell culture (Nadeem *et al.* 2018). Such elicitation of secondary metabolites biosynthesis is a promising biotechnological approach for the production of pharmacologically valuable polyphenols, including biological active lignans.

LIGNANS IN FLAX

The economic importance of flax (*L. usitatissimum* L.) is constantly growing and that is why it is referred to as the „market crop of the future" (Jhalla & Hall 2010) or as a „multi-component system" (De Silva & Alcorn 2019), containing many of bioactive substances. In the last decade, the interest in growing and using flax has been significantly reconsidered, not only in terms of the importance of omega-3 fatty acids for human nutrition but also other health-promoting secondary metabolites such as phytoestrogens lignans or soluble mucilaginous fibre (Oomah 2001). The antioxidant properties of flax lignans offer great potential for their use in food (such as natural antioxidants for oil stability or as food stabilizers) and cosmetics industries, as well as nutraceuticals (Oomah 2001; Sainvitu *et al.* 2012).

Flaxseed is one of the richest sources of lignans, followed by cereals and legumes. It contains 800 times more lignans and norlignans than other medicinal plants (9 – 30 mg/g) (Chhillar *et al.* 2020; Ganguly *et al.* 2021). Secoisolariciresinol diglucoside (SDG), matairesinol (MAT), secoisolariciresinol (SECO) and lariciresinol diglucoside (LDG) are the most abundant lignans produced by flax (Khan *et al.* 2020). They represent more than 95% of the total lignan amount and after ingestion are metabolized in the digestive tract to mammalian lignans (Anjum *et al.* 2020).

Detailed and comprehensive studies focused on lignans in flowering aerial parts of *Linum* species (Schmidt *et al.* 2010) and in seeds of *Linum* species (Schmidt *et al.* 2012) are available. Based on the lignan´s profile, 41 *Linum* species were divided into two groups, accumulating as major lignans groups AT (aryltetralin) or ADN/AN (aryldihydronaphthalene/arylnaphthalene). The latter group also includes sections *Linum* (Schmidt *et al.* 2010). The content of lignans in flaxseed significantly correlates with antioxidant activity (Kasote 2013; Zeitoun *et al.* 2014; Kyselka *et al.* 2017). The major flax lignan compounds, secoisolariciresinol (SECO), and its diglucoside (SDG) prove their antioxidant activity as well as antiviral, antibacterial, and antifungal properties (Kasote 2013; Zeitoun *et al.* 2014; Kyselka *et al.* 2017; Wu *et al.* 2021). Some types of lignans as pinoresinol, isolariciresinol, matairesinol, hydroxymatairesinol, and lariciresinol were detected in a mucilage layer of linseeds (Kyselka *et al.* 2017). The research of lignans in flax, as a model species of technological and economic importance, is considerable and involves studying stereochemistry (Sicilia *et al.* 2003), analyses of chemodivesity, composition variability, spatiotemporal formation, and localisation in different plant parts (Schmidt *et al.* 2010, 2012; Dalisay *et al.* 2015), the kinetics of lignin formation during seed development (Ramsay *et al.* 2017), detection in specific matrices like seed mucilage (Kyselka *et al.* 2017).

Synthesis of flax lignans *de novo* was observed after the infestation of plants by pathogens in several studies (Zeitoun *et al.* 2014; Oros & Kállai 2019), denoting lignans as phytoalexins and attributing them a role in defence against biotic stress. Secoisolariciresinol diglucoside (SDG) extracts isolated from the hull, endosperm, and flour fractions of Indian flaxseed cultivars revealed antibacterial properties against different bacterial species including *Pseudomonas aeruginosa*, *Staphylococcus aureus*, *Bacillus subtilis*, *Agrobacterium tumefaciens*, *Bacillus cereus*, and *Escherichia coli* (Rajesha *et al.* 2010). The maximum SDG and phenolic contents were found in hull fractions of tested genotypes and the maximum activity was shown against *E. coli*, while minimum inhibitory activity against *B. subtilis.* Lignans in combination with phenolic acid from crude linseed extract exhibit almost 50%

inhibitory effect on the growth of Gram-negative and Gram-positive bacteria, yeast, and mould associated with food industry and safety (Kyselka *et al.* 2017). The most sensitive strains have been recognized *Candida albicans* and *Staphylococcus aureus*.

FACTORS INFLUENCING THE LIGNANS CONTENT

The content of lignans in plant tissues is affected by genomic, physiological, biochemical, and environmental factors. There are a few studies that have identified the extent to which certain factors affect the content of secoisolariciresinol (Table 3). Krajčová *et al.* (2009) analysed the relationship between the type of fertilisers and the levels of SECO (secoisolariciresinol) and MAT (matairesinol) in nine cultivars of oil linseeds and one cultivar of fibre flax. Levels of SECO in linseed cultivars ranged from 2,312.1 to 4,886.0 mg/kg or from 2,381.8 to 6,993.5 mg/kg depending on the tested fertiliser, but the difference between them was not significant. The authors also analysed the concentration of SECO in fibre flax cultivar where it ranged from 1,569.3 to 2,658.3 mg/kg or from 1,812.2 to 3,100.9 mg/kg depending on the year. Although the aim of the research was not to compare the SECO concentration between oil and fibre types of flax, an almost a threefold difference was observed in favor of oil types of flax. In contrast, Wu *et al.* (2021) reported on a non-significant difference in SECO concentration among different economic types of flax (oil, fibre, and intermediate) pointing out that the economic type of flax is not a key factor in the accumulation of lignans. Regarding these findings, it is necessary to note that in the first case the storage organs of flax (seeds) were analysed, while in the second case the flax sprout 8-days after germination. Interestingly, the seed coat colour may interfere with the different antioxidant levels and the content of lignans in the sesame seeds (*Sesamum indicum* L.) due to the action of different abiotic stress factors (Ghotbzadeh Kermani *et al.* 2019). Light-coloured sesame seeds contained higher levels of polyphenols sesamin and sesamolin than dark-coloured seeds. In terms of nutritional parameters, interesting results were obtained by analysing the SECO content in 29 linseed genotypes cultivated in the Czech Republic, using the certified methodology of the team Bjelková *et al.* (2017). The measured values ranged between 1,124.19 – 6,248 mg/kg (average 3,700 mg/kg). Lignan SECO was found in the highest proportion in the variety Agram (medium content of alpha-linolenic acid), which represents a novelty in the range of linseed genotypes. The results showed a higher SECO content in Czech varieties and also in varieties with a lower content of alpha-linolenic acid (omega 3). The lowest content was detected in the Polish variety Bukoz, followed by the varieties Prairie Blue and Bowler.

CONCLUSION AND FUTURE PERSPECTIVES

Plant lignans are substances of immense importance and potential, both for the plant organism itself and human nutrition and health. The scientific community pays great attention to understanding the structures, synthesis, and metabolism of lignans, as well as their effects on the human body and in particular their preventive effect. Our aim was to point out the diversity of lignan´s biological functions in the plants. However, there is a need to investigate the potential of lignans in the context of genotype specificity as the major factor affecting the lignan content. Such knowledge can be valuable information for food supplement manufacturers to consider a specific plant genotype for appropriate nutritional parameters. Equally important is the characterization of tissue-specific lignan variability. Both approaches may help us to identify the appropriate plant genetic background suitable for the production of functional food products or nutritional supplements as well as point out the added value of plant food resources.

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REFERENCES

Andargie, M., Vinas, M., Rathgeb, A., Möller, E., and Karlovsky, P. (2021). Lignans of sesame (*Sesamum indicum* L.): A Comprehensive Review. *Molecules, 26*(4), 883. DOI: 10.3390/molecules26040883.

Anjum, S., Komal, A., Drouet, S., Kausar, H., Hano, C., and Abbasi, B.H. (2020). Feasible production of lignans and neolignans in root-derived *in vitro* cultures of flax (*Linum usitatissimum* L.). *Plants*, *9*(4), 409. DOI:10.3390/plants9040409.

Bagniewska-Zadworna, A., Barakat, A., Łakomy, P., Smolíński, D.J., and Zadworny, M. (2014). Lignin and lignans in plant defence: Insight from expression profiling of cinnamyl alcohol dehydrogenase genes during development and following fungal infection in Populus. *Plant Science*, *229,* 111 – 121. DOI:10.1016/j.plantsci.2014.08.015.

Balík, J., Híc, P., Tříska, J., Vrchotová, N., Smetana, P., Smutek, L., Rohlik, B.A., and Houška, M. (2021). Beer and beer-based beverage contain lignans. *Journal of Food Science and Technol*ogy, *58*(2), 581 – 585. DOI:10.1007/s13197-020-04570-8.

Barker, D. (2019). Lignans. *Molecules, 24*(7). DOI:10.3390/molecules24071424.

Bjelková, M., Filip, V., Kyselka, J., Ševčík, R., and Větrovcová, M. (2017). *Výběr a charakteristika lněného semene jako vstupní suroviny [Selection and characteristics of flaxseed as an input raw material]*. Agritec Plant Research Ldt. Šumperk, Czech Republic. ISBN 978-80-87360-57-6.

Chen, R., Li, Q., Tan, H., Chen, J., Xiao, Y., Ma, R., Gao, S., Zerbe, P., Chen, W., and Zhang, L. (2015). Gene-to-metabolite network for biosynthesis of lignans in MeJA-elicited Isatis indigotica hairy root cultures. *Frontiers in Plant Science, 6,* 952. DOI:10.3389/fpls.2015.00952.

Chhillar, H., Chopra, P., and Ashfaq, M. (2020). Lignans from linseed (*Linum usitatissimum L.*) and its allied species: Retrospect, introspect and prospect. *Critical Reviews in Food Science and Nutrition.* DOI: 10.1080/10408398.2020.1784840.

Corbin, C., Drouet, S., Markulin, L., Auguin, D., Lainé, É., Davin, L.B., Cort, J.R., Lewis, N.G., and Hano, C. (2018). A genome-wide analysis of the flax (*Linum usitatissimum* L.) dirigent protein family: from gene identification and evolution to differential regulation. *Plant Molecular Biology, 97*(1 – 2), 73 – 101. DOI:10.1007/s11103-018-0725-x.

Dalisay, D.S., Kim, K.W., Lee, C.S., Yang, H., Rübel, O., Bowen, B.P., Davin, L.B., and Lewis, N.G. (2015). Dirigent protein-mediated lignan and cyanogenic glucoside formation in flax seed: integrated omics and MALDI mass spectrometry imaging. *Journal of Natural Products, 78*(6), 1231 – 1242. DOI:10.1021/acs.jnatprod.5b00023.

Danielsen, L., Lohaus, G., Sirrenberg, A., Karlovsky, P., Bastien, C., Pilate, G., and Polle, A. (2013). Ectomycorrhizal colonization and diversity in relation to tree biomass and nutrition in a plantation of transgenic poplars with modified lignin biosynthesis. *PLoS ONE*, *8,* e59207. DOI:10.1371/journal.pone.0059207.

De Silva, S.F. and Alcorn, J. (2019). Flaxseed lignans as important dietary polyphenols for cancer prevention and treatment: Chemistry, pharmacokinetics, and molecular targets. *Pharmaceuticals*, *12*(2), 68. DOI:10.3390/ph12020068.

DellaGreca, M., Zuppolini, S., and Zarrelli, A. (2013). Isolation of lignans as seed germination and plant growth inhibitors from Mediterranean plants and chemical synthesis of some analogues. *Phytochemistry Reviews, 12,* 717 – 731. DOI:10.1007/s11101-013-9311-7.

Dowd, C., Wilson, I.W., and McFadden, H. (2004). Gene expression profile changes in cotton root and hypocotyl tissues in response to infection with Fusarium oxysporum f. sp. vasinfectum. *Molecular Plant-Microbe Interactions, 17,* 654 – 667. DOI:10.1094/MPMI.2004.17.6.654.

Durazzo, A., Lucarini, M., Camilli, E., Marconi, S., Gabrielli, P., Lisciani, S., Gambelli, L., Aguzzi, A., Novellino, E., Santini, A., Turrini, A., and Marletta, L. (2018). Dietary lignans: Definition, description and research trends in databases development. *Molecules*, *23*(12), 3251. DOI:10.3390/molecules23123251.

Fang, X. and Hu, X. (2018). Advances in the synthesis of lignan natural products. *Molecules, 23*(12). DOI:10.3390/molecules23123385.

Fardet, A. (2010). New hypotheses for the health-protective mechanisms of whole-grain cereals: What is beyond fibre? *Nutrition Research Reviews*, *23,* 65 – 134. DOI:10.1017/S0954422410000041.

Ganguly, S., Panjagari, N.R., and Raman, R.K. (2021). Flaxseed (*Linum usitatissimum*). In: Tanwar, B., Goyal, A. (Eds.) *Oilseeds: Health Attributes and Food Applications.* Singapore: Springer. DOI:10.1007/978-981-15-4194-0_10.

Garros, L., Drouet, S., Corbin, C., Decourtil, C., Fidel, T., Lebas de Lacour, J., Leclerc, E.A., Renouard, S., Tungmunnithum, D., Doussot, J., Abassi, B.H., Maunit, B., Lainé, É., Fliniaux, O., Mesnard, F., and Hano, C. (2018). Insight into the influence of cultivar type, cultivation year, and site on the lignans and related phenolic profiles, and the health-promoting antioxidant potential of flax (*Linum usitatissimum* L.) seeds. *Molecules, 123*(10), 2636. DOI:10.3390/molecules23102636.

Ghotbzadeh Kermani, S., Saeidi, G., Sabzalian, M.R., and Gianinetti, A. (2019). Drought stress influenced sesamin and sesamolin content and polyphenolic components in sesame (*Sesamum indicum* L.) populations with contrasting seed coat colors. *Food Chemistry, 289,* 360 – 368. DOI: 10.1016/j.foodchem.2019.03.004.

Global Market Insights, Inc (2020). Lignans Market revenue to hit $90 million by 2026. Dostupné na: <http://www.globenewswire.com/news-release/2020/03/25/2006051/0/en/Lignans-Market-revenue-to-hit-90-million-by-2026-Says-Global-Market-Insights-Inc.html>

Hano, C., Addi, M., Bensaddek, L., Crônier, D., Baltora-Rosset, S., Doussot, J., Maury, S., Mesnard, F., Chabbert, B., Hawkins, S., and et al. (2006). Differential accumulation of monolignol-derived compounds in elicited flax (*Linum usitatissimum*) cell suspension cultures. *Planta, 223,* 975 – 989. DOI:10.1007/s00425-005-0156-1.

Harmatha, J. and Dinan, L. (2003). Biological activities of lignans and stilbenoids associated with plant-insect chemical interactions. *Phytochemistry Reviews, 2,* 321 – 330. DOI: 10.1023/B:PHYT.0000045494.98645.a3.

Hata, N., Hayashi, Y., Okazawa, A., Ono, E., Satake, H., and Kobayashi, A. (2012). Effect of photoperiod on growth of the plants, and sesamin content and CYP81Q1 gene expression in the leaves of sesame (*Sesamum indicum* L.). *Environmental and Experimental Botany, 75,* 212 – 219. DOI: 10.1016/j.envexpbot.2011.07.004.

Heldt, H.W. and Heldt, F. (2013). *Plant Biochemistry*. Elsevier Academic Press: USA, 3rd edition, 2005, 630 p. ISBN 0-12-088391-033.

Hemmati, S., von Heimendahl, C.B., Klaes, M., Alfermann, A.W., Schmidt, T.J., and Fuss, E. (2010). Pinoresinol-lariciresinol reductases with opposite enantiospecificity determine the enantiomeric composition of lignans in the different organs of *Linum usitatissimum* L. *Planta medica*, *76*(9), 928 – 34. DOI:10.1055/s-0030-1250036.

Jhala, A.J. and Hall, L.M. (2010). Flax (*Linum usitatissimum* L.): current uses and future applications. *Australian Journal of Basic and Applied Sciences, 4*(9), 4304 – 4312.

Kasote, D.M. (2013). Flaxseed phenolics as natural antioxidants. *International Food Research Journal*, *20*(1), 27 – 34.

Khan, I., Khan, M.A., Shehzad, M.A., Ali, A., Mohammad, S., Ali, H., Alyemeni, M.N., and Ahmad, P. (2020). Micropropagation and production of health promoting lignans in *Linum usitatissimum*. *Plants*, *9*(6), 728. DOI:10.3390/plants9060728.

Kuete, V. (2013). Medicinal plant research in Africa. *Pharmacology and Chemistry.* > eBook ISBN: 9780124059368.

Krajčová, A., Schulzová, V., Hajšlová, J., and Bjelková, M. (2009). Lignans in flaxseed. *Czech Journal of Food Sciences*, *27,* S252 – S255. DOI:10.17221/1062-CJFS.

Kyselka, J., Rabiej, D., Dragoun, M., Kreps, F., Barčová, Z., Němečková, I., Smolková, J., Bjelková, M., Szydlowska-Czerniak, A., Schmidt, Š., Šarman, L., and Filip, V. (2017). Antioxidant and antimicrobial activity of linseed lignans and phenolic acids. *European Food Research and Technology, 243,* 1633 – 1644. DOI:10.1007/s00217-017-2871-9.

Li, Y., Wei, J., Fang, J., Lv, W., Ji, Y., Aioub, A.A.A., Zhang, J., and Hu, Z. (2019). Insecticidal activity of four lignans isolated from *Phryma leptostachya. Molecules, 24*(10), 1976. DOI:10.3390/molecules24101976.

Markulin, L., Corbin, C., Renouard, S., Drouet, S., Gutierrez, L., Mateljak, I., Auguin, D., Hano, C., Fuss, E., and Lainé, E. (2019). Pinoresinol-lariciresinol reductases, key to the lignan synthesis in plants. *Planta*, *249*(6), 1695 – 1714. DOI:10.1007/s00425-019-03137-y.

Milder, I.E., Arts, I.C., van de Putte, B., Venema, D.P., and Hollman, P.C. (2005). Lignan contents of Dutch plant foods: a database including lariciresinol, pinoresinol, secoisolariciresinol and matairesinol. *British Journal of Nutrition*, *93*(3), 393 – 402. DOI:10.1079/bjn20051371.

Mwamba, T.M., Islam, F., Ali, B., Lwalaba, J.L.W., Gill, R.A., Zhang, F., Farooq, M.A., Ali, S., Ulhassan, Z., Huang, Q., Zhou, W., and Wang, J. (2020). Comparative metabolomic responses of low- and high-cadmium accumulating genotypes reveal the cadmium adaptive mechanism in *Brassica napus. Chemosphere*, DOI:10.1016/j.chemosphere.2020.126308.

Nadeem, M., Ahmad, W., Zahir, A., Hano, C., and Abbasi, B.H. (2018). Salicylic acid-enhanced biosynthesis of pharmacologically important lignans and neo lignans in cell suspension culture of *Linum ussitatsimum* L. *Engineering in Life Sciences, 19*(3), 168–174. DOI:10.1002/elsc.201800095.

Oomah, B.D. (2001). Flaxseed as a functional food source. *Journal of the Science of Food and Agriculture, 81*(9), 889 – 894. DOI:10.1002/jsfa.898.

Oros, G. and Kállai, Z. (2019). Phytoanticipins: The Constitutive Defense Compounds as Potential Botanical Fungicides. In Jogaiah, S., Abdelrahman M. (Eds), *Bioactive Molecules in Plant Defense*. Springer, Cham. DOI:10.1007/978-3-030-27165-7_11.

Paniagua, C., Bilkova, A., Jackson, P., Dabravolski, S., Riber, W., Didi, V., Houser, J., Gigli-Bisceglia, N., Wimmerova, M., Budínská, E., Hamann, T., and Hejatko, J. (2017). Dirigent proteins in plants: modulating cell wall metabolism during abiotic and biotic stress exposure. *Journal of Experimental Botany 68*(13), 3287 – 3301. DOI:10.1093/jxb/erx141. PMID: 28472349.

Parikh, M., Maddaford, T.G., Austria, J.A., Aliani, M., Netticadan, T., and Pierce, G.N. (2019). Dietary flaxseed as a strategy for improving human health. *Nutrients*, *11*(5), 1171. DOI:10.3390/nu11051171.

Preisner, M., Kulma, A., Zebrowski, J., Dymińska, L., Hanuza, J., Arendt, M., Starzycki, M., and Szopa, J. (2014). Manipulating cinnamyl alcohol dehydrogenase (CAD) expression in flax affects fibre composition and properties. *BMC Plant Biology, 14,* 50.

Rajesha, J., Rao, A.R., Madhusudhan, B., and Karunakumar, M. (2010). Antibacterial properties of secoisolariciresinol diglucoside isolated from Indien flaxseed cultivars. *Current Trends in Biotechnology and Pharmacy*, *4*(1), 551 – 560. DOI:10.4014/jmb.1607.07036.

Ramsay, A., Fliniaux, O., Quéro, A., Molinié, R., Demailly, H., Hano, C., Paetz, C., Roscher, A., Grand, E., Kovensky, J., Schneider, B., and Mesnard, F. (2017). Kinetics of the incorporation of the main phenolic compounds into the lignan macromolecule during flaxseed development. *Food Chemistry, 217,* 1 – 8. DOI:10.1016/j.foodchem.2016.08.039.

Rodríguez-García, C., Sánchez-Quesada, C., Toledo, E., Delgado-Rodríguez, M., and Gaforio, J.J. (2019). Naturally lignan-rich foods: A dietary tool for health promotion? *Molecules*, *24*(5), 917. DOI:10.3390/molecules24050917.

Sainvitu, P., Nott, K., Gaëtan, R., Blecker, Ch., Jérôme, Ch., Wathelet, J.P., Paquot, M., and Deleu, M. (2012). Structure, properties and obtention routes of flaxseed lignan secoisolariciresinol: A review. *Biotechnologie, Agronomie, Société et Environnement*, *16,* 115 – 124.

Schmidt, T.J., Hemmati, S., Klaes, M., Konuklugil, B., Mohagheghzadeh, A., Ionkova, I., Fuss, E., and Wilhelm Alfermann, A. (2010). Lignans in flowering aerial parts of Linum species--chemodiversity in the light of systematics and phylogeny. *Phytochemistry*, *71*(14 – 15), 1714 – 28. DOI: 10.1016/j.phytochem.2010.06.015.

Schmidt, T.J., Klaes, M. and Sendker, J. (2012). Lignans in seeds of Linum species. *Phytochemistry*, *82,* 89 – 99. DOI: 10.1016/j.phytochem.2012.07.004.

Schroeder, F.C., del Campo, M.L., Grant, J.B., Weibel, D.B., Smedley, S.R., Bolton, K.L., Meinwald, J., and Eisner, T. (2006). Pinoresinol: A lignol of plant origin serving for defense in a caterpillar. *Proceedings of the National Academy of Sciences, 103,* 15497 – 15501. DOI:10.1073/pnas.0605921103.

Sharma, A., Shahzad, B., Rehman, A., Bhardwaj, R., Landi, M., and Zheng, B. (2019). Response of phenylpropanoid pathway and the role of polyphenols in plants under abiotic stress. *Molecules*, *24*(13), 2452. DOI:10.3390/molecules24132452.

Sicilia, T., Niemeyer, H.B., Honig, D.M., and Metzler, M. (2003). Identification and stereochemical characterization of lignans in flaxseed and pumpkin seeds. *Journal of Agricultural and Food Chemistry*, *51*(5), 1181 – 8. DOI: 10.1021/jf0207979.

Srivastava, S., Gupta, M.M., Prajapati, V., Tripathi, A.K., and Kumar, S. (2001). Sesamin a potent antifeedant principle from Piper mullesua. *Phytotherapy Research, 15,* 70 – 72. DOI:10.1002/1099-1573(200102)15:1<70:aid-ptr671>3.0.co;2-n.

Suzuki, S., Umezawa, T., and Shimada, M. (2002). Stereochemical diversity in lignan biosynthesis of *Arctium lappa* L. *Bioscience Biotechnology and Biochemistry*, *66*(6), 1262 – 9. DOI:10.1271/bbb.66.1262. PMID: 12162547.

Syed, R.N., Laurentin, H., Splivallo, R., and Karlovsky, P. (2015). Antifungal properties of extracts of sesame (*Ses-*

amum indicum). *International Journal of Agriculture and Biology, 17,* 575 – 581. DOI:10.17957/IJAB/17.3.14.612.

Teponno, R., Kusari, S., and Spiteller, M. (2016). Recent advances in research on lignans and neolignans. *Journal Natural Product Reports, 33*(9), 1044 – 1092. DOI:10.1039/C6NP00021E>.

Tera, M., Koyama, T., Murata, J., Furukawa, A., Mori, S., Azuma, T., Watanabe, T., Hori, K., Okazawa, A., Kabe, Y., Suematsu, M., Satake, H., Ono, E. and Horikawa, M. (2019). Identification of a binding protein for sesamin and characterization of its roles in plant growth. *Scientific Reports,* 9, 8631. DOI:10.1038/s41598-020-64237-4.

Touré, A. and Xueming, X. (2010). Flaxseed lignans: Source, biosynthesis, metabolism, antioxidant activity, bio-active components, and health benefits. *Food Science and Food Safety*, *9,* 261 – 269. DOI:10.1111/j.1541-4337.2009.00105.x.

von Heimendahl, C.B., Schäfer, K.M., Eklund, P., Sjöholm, R., Schmidt, T.J., and Fuss, E. (2005). Pinoresinol-lariciresinol reductases with different stereospecificity from *Linum album* and *Linum usitatissimum*. *Phytochemistry, 66*(11), 1254 – 63. DOI:10.1016/j.phytochem.2005.04.026. PMID: 15949826.

Wang, J., Wu, D., Wang, Y., and Xie, D. (2019). Jasmonate action in plant defense against insects. *Journal of Experimental Botany, 70,* 3391 – 3400. DOI:10.1093/jxb/erz174.

War, A.R., Paulraj, M.G., Ahmad, T., Buhroo, A.A., Hussain, B., Ignacimuthu, S., and Sharma, H.C. (2012). Mechanisms of plant defense against insect herbivores. *Plant Signaling & Behavior, 7,* 1306 – 1320. DOI:10.4161/psb.21663.

Willför, S.M., Smeds, A.I., and Holmboma, B.R. (2006). Chromatographic analysis of lignans. *Journal of Chromatography A, 1112*(1 – 2), 64 – 77. DOI:10.1016/j.chroma.2005.11.054.

Wu, Y., Wang, H., Wang, Y., Brennan, Ch.S., Brennan, M.A., Qiu, C., and Guo, X. (2021). Comparison of lignans and phenolic acids in different varieties of germinated flaxseed (*Linum usitatissimum* L.). *International Journal of Food Science & technology*, *56*(1), 196 – 204. DOI:10.1111/ijfs.14619.

Xu, Y., Vinas, M., Alsarrag, A., Su, L., Pfohl, K., Rohlfs, M., Schäfer, W., Chen, W., and Karlovsky, P. (2019). Bis-naphthopyrone pigments protect filamentous ascomycetes from a wide range of predators. *Nature Communications, 10,* 3579. DOI:10.1038/s41467-019-11377-5.

Yamauchi, S., Ichikawa, H., Nishiwaki, H., and Shuto, Y. (2015). Evaluation of plant growth regulatory activity of furofuran lignan bearing a 7,90:70,9-diepoxy structure using optically pure (+)- and (-)-enantiomers. *Journal of Agriculture and Food Chemistry, 63,* 5224 – 5228. DOI:10.1021/acs.jafc.5b01099.

Yeung, A.W.K., Tzvetkov, N.T., Balacheva, A.A., Georgieva, M.G., Gan, R.Y., Jozwik, A., Pyzel, B., Horbańczuk, J.O., Novellino, E., Durazzo, A., Lucarini, M., Camilli, E., Souto, E.B., Atanasov, A.G., and Santini, A. (2020). Lignans: Quantitative analysis of the research literature. *Frontiers in Pharmacology, 11,* 37. DOI:10.3389/fphar.2020.00037.

Zálešák, F., Bon, D., and Pospíšil, J. (2019). Lignans and neolignans: Plant secondary metabolites as a reservoir of biologically active substances. *Pharmacological Research, 146,* 104284. DOI:10.1016/j.phrs.2019.104284.

Zeitoun, A.M., Preisner, M., Kulma, A., Dymińska, L., Hanuza, J., Starzycki, M., and Szopa, J. (2014). Does biopolymers composition in seeds contribute to the flax resistance against the Fusarium infection? *Biotechnology Progress, 30*(5), 992 – 1004. DOI:10.1002/btpr.1965.

Zhou, Y., Zheng, J., Li, Y., Xu, D-P., Li, S., Chen, Y-M., and Li, H-B. (2016). Natural polyphenols for prevention and treatment of cancer. *Nutrients*, *8*(8), 515. DOI:10.3390/nu8080515.

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