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The Brassicas – An Undervalued Nutritional and Health Beneficial Plant Family

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Introduction

Plants in the family Brassicaceae are among the oldest cultivated plants known to man. Evidence has been unearthed that indicates that a brassica (cruciferous) vegetable was widely cultivated as early as 10,000 years ago[1]. We have come a long way since then with plants in the Brassicaceae family cultivated for a wide range of uses: biofuel, edible oil, human food and animal feed .

Many of these Brassicaceae crops are staples of Scottish agriculture and traditionally had a strong foothold in the Scottish diet. Amongst these are broccoli, cauliflower, cabbage, kale and Brussel sprouts, which are all part of the *Brassica oleracea* species but rest in different sub-groups[2] as well as turnip (*B. rapa*), swede, both reviewed in an previous FHIS report,[3] and oilseed rape (both *B. napus*) .

Over the last 50 years, with the advent of food trade globalisation and increased personal travel, people have been exposed to other members of the Brassica family. These included kohlrabi (*B. oleracea*), chinese cabbage (*B. rapa*), indian/brown mustard (*B. juncea*), white mustard (*Sinapis alba or B. hirta*), black mustard (*B. nigra*), horseradish (*Armoracia rusticana*), radish (*Raphanus sativus*), watercress (*Nasturtium officinale*) and wasabi (*Wasabi japonica)*. Indeed, the development and sophistication of the western palette has been accompanied by an explosion in demand, and subsequent production of, what were previously more minor cruciferous vegetables, with rocket lettuce (*Eruca sativa*) a classic example.

The development of these as staple and occasional, or supplementary, food crops depends on their nutritional and organolpetic properties. These cruciferous vegetables have unique tastes and aromas but also come with both significant nutritional and health beneficial values. This short review highlights the nutritional and health benefits in the above crops and how, from a Scottish perspective, we may capitalise on this to improve our national health and stimulate economic development.

Cruciferous Vegetables as a source of nutrition

The nutritional content of some common cruciferous vegetables is highlighted in Tables 1 and 2. It is clear, even from a cursory scan, that cruciferous vegetables can make significant contributions to daily nutritional requirements.

With respect to the macro-nutrient components the cruciferous vegetables are, with the exception of the oil crops, not major sources of nutritional energy. However, as part of a normal diet a standard portion (100g) can contribute, on average, around 5-6 % of ones Recommended Dietary Allowance (RDA) for energy. Similarly, and depending on the crop, they can represent significant sources of protein with, for example, broccoli and kale potentially contributing 6-8% of the RDA (Table 1). Studies into the free and protein derived amino acid content in cruciferous foods have shown that in some cases, for example kale and broccoli[4,5], the amino acid complement and content compared very favourable against the ideal nutritional standard protein as outlined by the Food and Agriculture Organisation, the World Health Organisation and the United Nations University[73]. It should be borne in mind that as with any crop the absolute level of free and protein-derived amino acid content and composition can vary considerably with cultivar season and environment with, for example, Lee et al[6] reporting a four-fold variation in broccoli methionine content depending on the fertilizer treatment.

The cruciferous vegetables also contain an appreciable level of dietary fibre (Table 1) which can represent as much as 25-35% of the dry matter in the crops[7,8].

Interestingly, and again with the exception of the oilseed crops, the total fat levels tend to be relatively low and contain negligible amounts of either of the detrimental saturated or *trans* fats. However there are appreciable levels of the polyunsaturated fatty acids (PUFAs), linoleic and α-linolenic acids. The PUFAs have been reported as beneficial in reducing the risk of incidence and progression of chronic disease[9] type II diabetes by improving insulin sensitivity[10] and coronary heart disease (CHD)[11,12]. Indeed, in oilseed brassicas, the PUFAs, linoleic and linolenic acid, make up a major part of the oil content[13]. Furthermore, oleic acid, (a monounsaturated fatty acid; MUFA) is present at an approximately 2-3-fold greater level than PUFAs in rapeseed oil and this component has been implicated in reducing the risk of CHD, inflammation etc [14,15]. The beneficial oil composition of rapeseed oil has been favourably compared with olive oil, which has been the focus of multiple clinical studies into its health benefits[16,17,18,19,75,76]. Indeed there is now an effort in the northern hemisphere to promote rapeseed oil as a viable (or even better) alternative to olive oil[20].

The cruciferous vegetables are also a good source of many vitamins (Table 2) with particularly high levels of Vitamin A and K, in the green fleshed ones: broccoli, Brussel sprouts and kale. In fact, the inclusion of a modest level of kale in the diet can significantly deliver on the RDA for many of the essential vitamins. These vegetables are also good sources of vitamin C. This fact is probably unknown to the public, who see generally see fruit as the major source of vitamin C, and it represents a simple message that could be promoted more positively. In fact, the comparative study by Lee and Kader[21] and the data from the Fineli food compositional database[22] show that cruciferous vegetables were significantly better sources of vitamin C than fruits such as apple, banana, raspberry and, in some cases such as broccoli, orange.

Minerals are essential components for a healthy life with deficiencies leading to several conditions such as anaemia (iron), rickets (calcium [and vitamin D]). influenza (selenium)[23], mortality, poor immune function, and cognitive decline[24] and immune function (zinc)[25]. Many of these minerals are obtained from diverse sources in a balanced diet but for minerals like zinc, where normally the bulk is derived from meat, the cruciferous vegetables can represent a key source of nutrition. This consumption will also be accompanied by appreciable intakes of phosphorus, calcium and magnesium. It is worth noting that for vegetarians and vegans the cruciferous vegetables may represent a rich source of nutrition and should be considered as staples in such dietary or lifestyle choices.

In general then the cruciferous vegetables including the oilseeds have accrued a significant health halo based on their nutritional content alone[26] and the evidence-based case for their inclusion in our diet, and in particular the Scottish diet, is sound.

Health benefits beyond nutrition

Glucosinolates

The most researched aspect of the Brassicacea with respect to human health centre around the group of compounds called the glucosinolates (Figure 1). These sulphur containing compounds are found in all cruciferous vegetables to varying degrees and the chemistries and relative proportions vary from crop to crop. In general these compounds have been attributed to exert beneficial health effects[27] but they can also exhibit toxicological effects[28]. However, epidemiological studies have shown that consumption of vegetables containing glucosinolates and their catabolites (metabolism-derived breakdown products) is linked to reduced incidence of some cancers[29,30,31] and these natural chemicals have been specifically implicated as putative dietary prevention routes for several cancers such as colon[32,33], lung[34] (London et al, 2000), and potentially breast[35] and prostate cancers[36] .

The current paradigm suggests that at low doses these compounds generate redox stress that, in turn, stimulates increased expression of the body's own protective antioxidant and detoxication proteins whereas detrimental effects, such as cell cycle arrest and apoptosis, can occur at high doses. Recently, the glucosinolate glucoraphanin, present in all the cruciferous vegetables grown and eaten in Scotland, has been a focus of research due to the anticancer efficacy of its in vivo metabolite, the isothiocyanate sulforaphane (4-methylsulphinylbutyl)[29,77]. Sulforaphane, isolated from broccoli cultivars with high levels in seeds and sprouts, has been shown to have an inhibitory effect on tumour growth in prostate [36,37], breast[38] and colon cancers[39].

Indoles

Less well researched than the glucosinolates are the class of compounds called the indoles (Figure 2). These compounds are generally thought to be synthesised in response to (or to prevent) pathogen attack. However, studies have shown that some of the crucifer indoles exhibit anti-cancer abilities, albeit in model systems, and may have potential as dietary chemopreventative agents[40].

Polyphenols

Polyphenolics compounds are ubiquitous in the plant kingdom and they perform a variety of functions in the plant, generally centred on responses to pathogen attach and UV protection. However, these compounds, ubiquitous in all the crops and their associated products that we eat including the cruciferous ones, have been the focus of intense research interest with respect to human health benefits[41,42].

Within the Brassicaceae family there is a wide range of polyphenols, such as lignans, flavonoids and simple phenolics, all of which have many studies associated with their beneficial impact on human health either in intervention or model system studies.

With respect to total polyphenol content, *B. rapa* and *B. oleracea* contain relatively elevated levels; broccoli (822 ± 89 μg/g), cauliflower (278 ± 15 μg/g), and white cabbage (153 ± 21 μg/g) on a fresh weight basis. More specifically, broccoli has hydroxycinnamic acids as the abundant polyphenolic species[26]. The sub-class of polyphenols known as flavonoids are well represented in the Brassicaceae with the flavonols, quercetin, kaempferol, and isorhamnetin commonly found[26]. The flavonoids can often be found at appreciable levels with total flavonoid content in broccoli, cauliflower, and white cabbage reported by Bahorun[43] at 316, 172, and 102 µg/g, on a fresh weight basis, respectively .

More specifically, the glycosylated flavonoids and simple phenolics, such as 3-sophoroside-7-glucosides of kaempferol, quercetin and isorhamnetin and hydroxyl-cinnamates, reported in the Brassicaceae[26,44,45,46,47] are increasingly attributed with beneficial health effects such as reduced risk of age-related chronic diseases, like cancers and cardiovascular disease, and advantageous manipulation of gut microbiota[48,49,50,51,52].

Lignans

Lignans, another group of polyphenolic compounds also found in Brassicaceae, possess several biological activities, such as antioxidant and anti-oestrogenic properties, and may thus reduce the risk of certain cancers as well as cardiovascular diseases. The lignans lariciresinol and pinoresinol are particularly prevalent in the Brassicaceae[53]. This is important since these compounds are efficiently converted[54] into the 'enterolignans' enterodiol and enterolactone by the intestinal microflora. These are then readily absorbed and exert activities much like oestrogens. In essence the Brassicaceous lignans are phytoestrogens. Studies have shown these to be prevalent in curly kale, broccoli and Brussel sprouts[53].

Tannins

Tannins, complex polyphenols (often with large molecular weights), are also found in the Brassicaceae[55] and these are reported to have antinutrient effects, suppressing the availability of essential amino acids, potentially forming complexes with essential minerals, proteins, and carbohydrates and subsequently reducing their digestion either by animals of humans[56,57,58].

Post-harvest processes and the impact on nutritive and health beneficial value

In general, we do not tend to eat raw cruciferous vegetables and there are various types and extents of cooking regimes to which the crops are exposed prior to consumption: boiling steaming, microwave and frying. In addition, it is rare that we obtain these crops at point of harvested and consequently before the consumer can cook the vegetables they will have been exposed to a food packaging, storage and transportation chain and the associated changes in temperature, humidity etc.

It is safe to say that for the most part, and like virtually all other crops, packaging, transportation and cooking leads to a reduction in the nutritional value. However, cooking does open up the vegetable micro and macrostructure thereby making the nutrients more readily available for digestion, uptake and utilisation.

With respect to storage, the recent review by Jones[59] showed that, for broccoli at least, low temperature (<4°C) and high relative humidity were key to maintaining quality. They reported that glucosinolate content essentially mirrored visual quality with glucoraphanin content in broccoli florets declining by 82% after 5 days at 20°C, but by only 31% at 4°C. Rangkadilok et al[60] reported an analogous result: 50% decrease in glucoraphanin in broccoli (cv.Marathon) heads after 7 days at 20°C, but no decrease after 7 days at 4°C. Conversely, however, studies with the same variety reported an increase indole glucosinolates, during 9 days of storage at 10°C whilst total glucosinolate levels remained the same reflecting the differential glucosinolate losses and increases[61] .

The optimum way for maintaining the "at harvest" level of the health-beneficial glucosinolates and quality *per se* (appearance, taste, texture etc) is to freeze the vegetables as soon as possible. However, if this approach is taken then the vegetables need to be blanched or treated with some other heat treatment to inactivate myrosinase, the enzyme which rapidly breaks down glucosinolates to form a range of reactive chemicals including isothiocyanates. Blanching does however come at a cost with Howard et al[61] reporting a reduction in the level of the glucosinolate sulphoraphane in broccoli by 47-65% following 2 min in water at 93°C

This necessity to store at low temperature rather than harvest later as and when required was highlighted nicely by Hagen et al[62] who showed that curly kale left in the field exposed to frost for 6 weeks compared to those harvested and stored at 1°C experienced reductions in flavonols, total phenols and antioxidant capacity by 25-35% and the vitamin C by more than 50%. Conversely the soluble sugars and dry matter increased by roughly 20% and 30%, respectively. This may well have an impact on the organolpetic properties and could be a potential route to the generation of sweeter broccoli thereby masking the inherent bitterness of the health beneficial glucosinolates.

Modified and controlled atmosphere approaches (1–2% O_2 and 5–10% CO_2) in combination with temperatures of 1-5°C and a high relative humidity (98-100% for all) have been shown to preserve quality, nutritive value and the levels of health promoting compounds during storage[60],[63,64,65]

Most forms of industrial processing are associated with a dramatically shortened lifespan for cruciferous vegetables. The processes of chopping, blending, juicing, cooking, freezing/thawing all release the vegetables innate degredative enzyme systems including myrosinase. Indeed, fine chopping resulted in a major reduction in total glucosinolates after 6 hr at ambient temperature with losses of up to 75% of the total glucosinolate content reported for Brussels sprouts, broccoli and cauliflower and ca. 60% for green cabbage[66]. Interestingly, and as seen for the temperature storage studies, chopping has also been reported to be accompanied by an increase in the indole, and some aliphatic, glucosinolates. For example, fine chopping of white cabbage was accompanied by a 15-fold increase of 4-methoxy and 1-methoxy-3-indolylmethyl GLSs after 48 h storage. For broccoli, the same experiment saw all the glucosinolates levels reduced with the exception of 4-hydroxy- and 4-methoxy-3-indolylmethyl glucosinolates which increased 3.5- and 2-fold, respectively[67].

Cooking invariably leads to a reduction in the level of the glucosinolates (30-60%), although this depends upon the method used for cooking. Microwaving, pressure cooking and boiling are all associated with significant losses of glucosinolates whilst steaming is relatively innocuous by comparison[68,69]. The other components in cruciferous vegetables also suffer during the cooking process with, for example, broccoli experiencing significant losses of vitamin C, soluble sugars and protein during all cooking processes with the exception of steaming[74].

Cooking generates other changes when using rapeseed oils with prolonged exposure to heat leading to breakdown and oxidation of the PUFAs and MUFAs to volatile and oil soluble compounds that can be adverse to human health[70].

All these considerations must be borne in mind when recommending daily intake levels of Brassicaceae vegetable and oils.

Conclusions

The case for including cruciferous vegetables and oils in the diet on a nutritive basis is substantial: the benefits associated with a reduced risk of the major degenerative disease are fairly compelling. The question remains why are we not eating more? Recent figures for cruciferous vegetable production and value in Scotland give a mixed answer (Table 3). Over the last three years turnip and swede have experienced a steady reduction in area planted and production levels. However, the corresponding unit values dipped and then increased in the last year to a value above the 2009 level. Broccoli, on the other hand, maintained then increased unit value in 2011 whilst Brussels sprouts experience a modest then significant (~27%) increase in unit value in 2011. Clearly there is interest in cruciferous vegetables but a quick comparison against the other Scottish crops, which are generally regarded as healthy, show that there is some ground to be made up if they are to attract the value attributed to commodities such as soft fruit.

There are several aspects that undoubtedly impact on the relatively reduced production figures of broccoli and Brussels sprouts. All of the brassica vegetables suffer from the (perceived) stigma of bitter taste and an inability to get children to eat these during the formative years which could lead to dietary acceptance and preference through to, and during, adulthood. This will be a difficult goal to achieve from a breeding perspective as the health beneficial glucosinolates are at the root of the bitterness conundrum, with sinigrin, progoitrin and glucobrassicin the culprits in broccoli. An alternative approach would be to breed vegetables which are innately sweeter (increased soluble sugars) to mask the bitterness. Alternatively, the inclusion of the cruciferous vegetables in ready meals can facilitate this masking, for example, by combining with peas, known and accepted sweet vegetables.

The adoption and promotion of exotic cruciferous vegetables, such as pak choi (Chinese cabbage), by TV chefs, popular magazines etc have highlighted that the public are prepared to take these vegetables into their diet. Furthermore, advances in simple preparation approaches, such as the steam-in-the-bag approach, are to be applauded since they both facilitate the consumption of cruciferous vegetables due to ease of preparation and promote a cooking method that is much less detrimental to the nutritive and health beneficial value than, for example, boiling.

Generally these vegetables have been confined to the fresh/packaged market and their use as functional/nutritive/health beneficial components in blended foods, such as smoothies, have largely yet to be explored and exploited. Clearly the conundrum that is cruciferous vegetables taste versus health benefits needs to be solved before that particular approach is commercialised. However, the utility and benefits of rapeseed oil offers other alternatives to Brassicaceae utilisation with the potential for broader use in ready meals, baked goods, sauces, vinaigrettes and obvious route for exploitation.

However, now more than ever, with the consumer increasingly aware of and demanding facts regarding the health benefit of their food, the time is ripe for the expansion and exploitation of Brassicaceae, particularly given that they grow so well in Scotland.

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Table 1 The Macro-component and fat contents (per 100g) of exemplar cruciferous vegetables. Data is derived from the Fineli food composition database[22]

Nutrient factor	**Brocolli**	**Brussel Sprouts**	**Cauliflower**	**Kale**	**White Cabbage**	**Turnip**	**Swede**	**Rapeseed oil (Cold pressed)**	**Rapeseed oil (Low Euricic acid)**	**RDA***
Macro-components										
Energy (kJ (cal)	147 (35)	102 (24)	101 (24)	167 (40)	116 (28)	115 (27)	121 (29)	3700 (884)	3700 (884)	2000 - 2500
Carbohydrate, available	2	2	2.2	4.1	4.1	4.2	4.6	0	0	≤50% of total energy
Fat, total (g)l	0.3	0.5	0.3	0.6	0.2	0.3	0.3	100	100	55-95
Protein, total (g)	4.6	1.4	1.8	3.4	1.2	1	1	0	0	55
Carbohydrate Components										
Starch, total (g)	0	0	0.1	0	0	0.3	0.7	0	0	≤39% of energy
Sugars, total (g)	2	2	2.1	4.1	4.1	3.9	3.9	0	0	≤11% of energy
Fibre, total (g)	2.5	2.5	2.3	2	2.1	1.9	1.8	0	0	18% of energy total
Fibre, water-insoluble (g)	1.6	1.6	1.2	1.1	1.1	1.2	1.2	0	0	
Fat										
Fatty acids, total (g)	0.3	0.2	0.2	0.2	0.1	0.1	0.1	95.6	98.4	≤35% of energy
Fatty acids, total saturated (g)	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	6.3	5.7	
Fatty acids, total monounsaturated *cis* (g)	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	60.6	59.6	
Fatty acids, total polyunsaturated (g)	0.2	0.1	0.1	0.1	< 0.1	< 0.1	< 0.1	30.6	33	
Fatty acid 18:2 n-6 (linoleic acid) (mg)	57	29	36	29	28	24	19	20000	22080	
Fatty acid 18:3 n-3 (α-linolenic acid) (mg)	135	101	105	101	48	72	47	10000	10876	
Cholesterol (mg)	0.3	0	0	0	0	0	0	4.5	4.5	<300
Sterols, total (mg)	36.7	37	31.2	8.8	14.8	13.2	13.2	695.5	695.5	

* [72]

Table 2 The mineral and vitamin contents (per 100g) of exemplar cruciferous vegetables. Data is derived from the Fineli food composition database[22]

Nutrient factor	**Brocolli**	**Brussel Sprouts**	**Cauliflower**	**Kale**	**White Cabbage**	**Turnip**	**Swede**	**Rapeseed oil (Cold pressed)**	**Rapeseed oil (Low Euricic acid)**	**RDA**
Minerals										
sodium (mg)	6.9	5	25	5	5	4.1	4.1	0	0	600
Salt (mg)	17.6	12.7	63.7	12.7	12.7	10.4	10.4	0	0	6000
Potassium (mg)	400	320	370	320	320	300	310	0	0	2000
Magnesium (mg)	24	14	15	14	14	20	14	0	0	375
Calcium (mg)	48	42	24	42	42	35	35	0	0	1000
Phosphorus (mg)	90	41	50	41	40	50	40	0	0	700
Iron, total (mg)	1.1	0.4	0.6	0.4	0.4	0.3	0.3	0	0	14
Zinc (mg)	0.1	0.2	0.5	0.2	0.2	0.2	0.2	0	0	10
Iodide (iodine) (mg)	1	1	1	1	1	1	1	0	0	150
Selenium, total (mg)	0.4	0.3	0.4	0.3	1.5	0.3	0.3	0	0	55
Vitamins										
Vitamin A (retinol activity equivalents) (μg)	85.9	35.8	0.9	765.8	5.5	6	0	0	0	800
Vitamin D (μg)	0	0	0	0	0	0	0	0	0	5
Vitamin E (mg)	0.7	0.4	<0.1	0.9	<0.1	0	0	18.9	18.9	12
Vitamin K, tota (μg)l	110	220	20	618	60	2	2	130	150	75
Vitamin C (mg)	120	90	61.5	110	37.4	39.7	39.7	0	0	80
Folate (vitamin B9) (μg)	113.1	93.6	85.9	120	29.9	14	50.1	0	0	400
Niacin equivalents, total (vitamin B3) (mg)	1.5	1.1	1.2	1.4	0.8	1.4	1.4	0	0	16
Riboflavin (vitamin B2) (mg)	0.2	0.16	0.06	0.35	0.05	0.06	0.06	0	0	1.4
Thiamin (vitamin B1) (mg)	0.1	0.11	0.1	0.12	0.07	0.06	0.06	0	0	1.1
Vitamin B-12 (μg)	0	0	0	0	0	0	0	0	0	2.5
Vitamin B6 (constituents) (mg)	0.11	0.28	0.15	0.35	0.16	0.08	0.12	0	0	1.4
Carotenoids, total (μg)	2858.2	1353.7	44	41700	218	71.8	0	0	0	

*[72]

Table 3. The areas, outputs and values of cruciferous vegetables grown over 2009-2011. The values for other vegetables, the vegetable total and soft fruit are included for comparative purposes. Data derived from the Scottish Government*

	2009			2010			2011		
Crop	Area (Ha)	Output Tonnes (000's)	Value £ million	Area (Ha)	Output Tonnes (000's)	Value £ million	Area (Ha)	Output Tonnes (000's)	Value £ million
Vegetables									
Carrots	2,488	169.7	25.95	2,868	185.8	29.35	2,463	154.4	28.05
Peas	6,296	27.1	9.17	6,549	30.3	8.79	6,276	26.6	7.71
Turnips and Swedes	2,050	67.9	17.27	1,878	61.0	14.74	1,614	56.0	15.42
Broccoli	1,315	13.0	5.76	1,328	14.2	6.30	1,276	12.3	5.98
Brussel sprouts	685	11.6	9.37	725	10.2	8.38	776	12.8	13.39
Other vegetables	3,184	76.4	42.1	3,139	72.8	41.93	2,848	63.8	38.36
Total vegetables	16,019	365.6	109.59	16,487	374.2	109.49	15,253	325.8	108.91
Raspberries	577	3.9	14.23	540	3.0	13.74	514	3.2	21.24
Strawberries	946	18.7	53.60	931	21.6	62.31	1001	21.5	63.42

*http://www.scotland.gov.uk/Topics/Statistics/Browse/Agriculture-Fisheries/agritopics/Horticulture

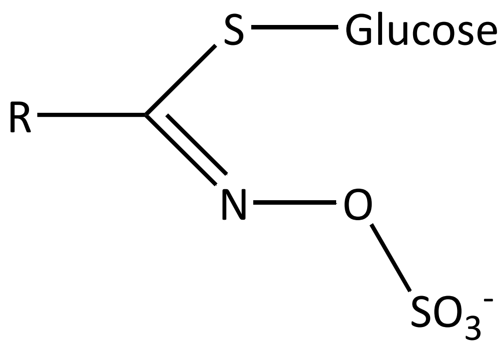

Figure 2. The generic structure of a glucosinolate. R - this represents a variety of different chemistries which are generally classified as aliphatic, indole or aromatic. For more detail see Verkerk[71].

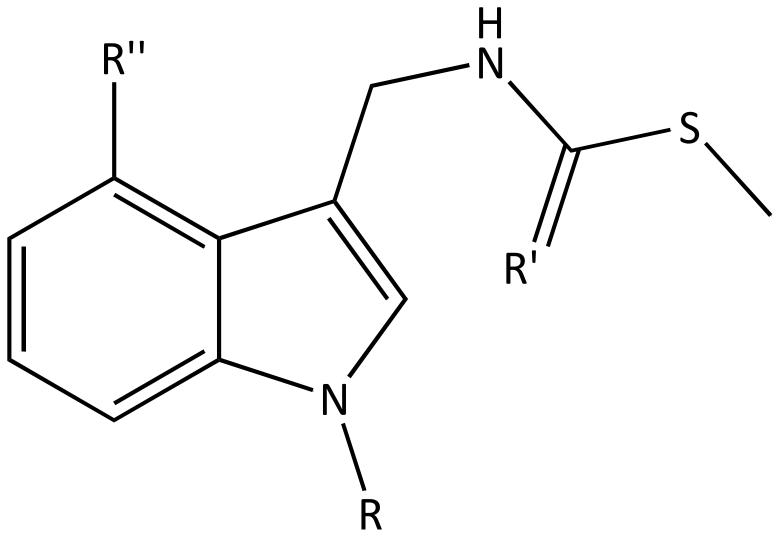

Figure 3. An example of a generic Brassicaceae indole. The substituents R and R'' can be H or OCH_3 whilst R' can be S or O [26]. It should be noted that the base chemical scaffold of the two ring structure is present in all the Brassicaceae indoles but the chemical substitution around this can vary significantly and is dependent on the (sub)species.

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