Glycoalkaloids in Potatoes

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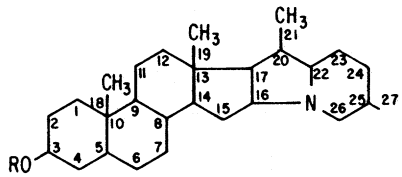
ABSTRACT

The glycoalkaloids present in the cultivated potato plant might result in their being unacceptable by present-day food standards, if that vegetable were introduced today. The alkaloids are derived biosynthetically from cholesterol. The range of glycoalkaloids found in nature is given. Two main methods of determining these alkaloids have been developed, enabling a general screening procedure to be employed by growers. The advent of protoplast techniques has opened up the possibility of many new species and they present the chemist with new problems. There can be a conflict between the requirement of pest- and disease-resistant potatoes and those with low levels of glycoalkaloids. Damage and microbial infection to potatoes may cause glycoalkaloids to develop. In the end, the consumer must be the final arbiter.

INTRODUCTION

In the one-hundred-fifty years since glycoalkaloids were first isolated from potatoes, these compounds have been the subject of much controversy and concern. If potatoes were introduced as a new food product today in the United States or the United Kingdom, there is some question as to whether they would be acceptable by the food safety standards of both countries because of their glycoalkaloid content. Numerous reviews on the chemistry (Prelog & Jeger, 1953; Schreiber,

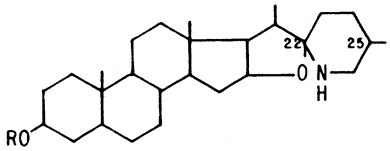
1968; Ripperger & Schreiber, 1981) and biochemistry (Roddick, 1974; Jadhav & Salunhke, 1975) and physiological activity (Zitnak, 1977; Jadhav *et al.*, 1981) have appeared. The emphasis of this review will deal with the current status of research on glycoalkaloids, particularly in relation to food safety. To put this work in the proper context, a brief summary of glycoalkaloid chemistry is presented.



I R = H

I_a R = H, Δ^5 UNSAT.

I_b R = H Δ^5 UNSAT., 23 O-C(=O)-CH_3



II R = H

II_a R = H, Δ^5 UNSAT.

Although glycoalkaloids are found in other genera (*Lycopersicon* and *Cestrum*), we will restrict our discussion to those found in *Solanum* species, emphasizing the glycoalkaloids of the cultivated potato plant, *S. tuberosum*. The aglycones, or alkaloid portion, of *Solanum* glycoalkaloids contain the steroidal nucleus and are, in fact, biosynthetic products of cholesterol (Heftmann *et al.*, 1967). The two most common skeletal types occurring in *Solanum* are the solanidanes (I) and spirosolanes (II). The alkaloids are usually found in plant tissue as

TABLE 1
Composition of Glycoalkaloids

Glycoalkaloid	*Aglycone*	*Aglycone structure*	*R carbohydrates*
α-Solanine	Solanidine	I_a (20S, 22R, 25S)	Solatriose
α-Chaconine	Solanidine	I_a (20S, 22R, 25S)	Chacotriose
Solasonine	Solasodine	II_a (22R, 25R)	Solatriose
Solamargine	Solasodine	II_a (22R, 25R)	Chacotriose
Tomatine	Tomatidine	II (22S, 25S)	Lycotetraose
Solacauline	Soladulcidine	II (22R, 25R)	Polyatriose
α-Solamarine	Tomatidenol	II_a (22S, 25S)	Solatriose
β-Solamarine	Tomatidenol	II_a (22S, 25S)	Chacotriose
Demissine	Demissidine	I (20S, 22R, 25S)	Lycotetraose
Leptine I	Acetylleptinidine	I_b (20S, 22R, 25S)	Chacotriose
Leptine II	Acetylleptinidine	I_b (20S, 22R, 25S)	Solatriose
Commersonine	Demissidine	I (20S, 22R, 25S)	Commertetrose

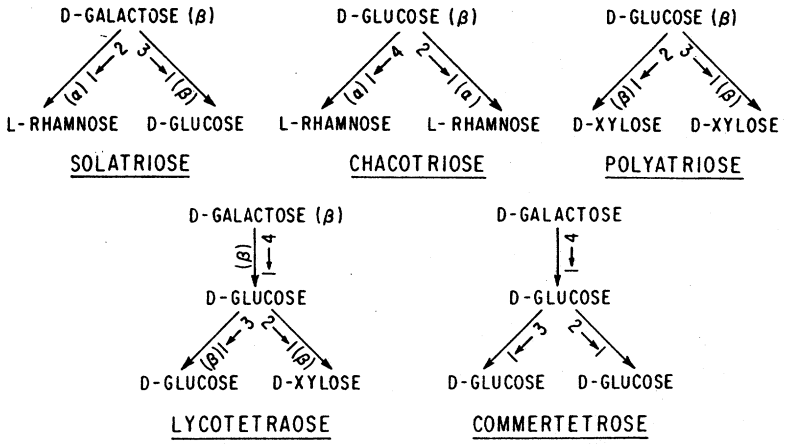


Fig. 1. Carbohydrate moieties of glycoalkaloid.

glycosides (derivatized at the 3,β-hydroxyl), thus the terms glycoalkaloids or steroidal glycoalkaloids. A partial listing of glycoalkaloids containing the solanidane or spirosolane aglycone is given in Table 1. The carbohydrate structures are shown in Fig. 1. As mentioned, the alkaloids are biosynthetically derived from cholesterol and divergence of the biosynthetic path to the solanidane or spirosolane structure occurs at a relatively late stage (Fig. 2); therefore, it is not surprising that either one

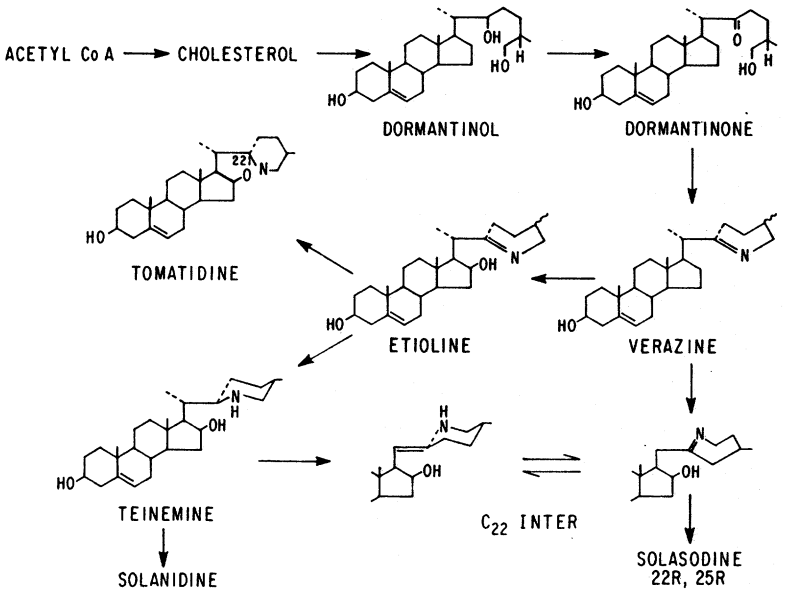


Fig. 2. Biosynthesis of glycoalkaloid aclycone.

or both ring structures are found in a particular species. Although the structure of the carbohydrate moiety of the glycoalkaloid may be of minor interest from a chemical or chemataxonomic standpoint, it may be of considerable biological significance, particularly with respect to toxicity. Thus, chemical characterization, of necessity, must include analysis of the carbohydrate portion of the glycoalkaloid. Table 2 illustrates the type of diversity of glycoalkaloids one can find in nature, which contain the same aglycone but differ in carbohydrate structure.

TABLE 2
New Solasodine Glycoalkaloids

Glycoalkaloid	*Carbohydrate*[a]	*Species*	*Reference*
Solardixine	3-1 2-1 2-1 -Gal–Glu–Glu–Rham	*S. lactiniatum* *S. khasianum*	Bite *et al.* (1969)
Solasurine	-Glu–Rham	*S. elaeagnifolium* *S. aviculare*	Seth & Chatterjee (1968–1971)
Solashabanine	Gal, 3 Glu, Rham	*S. lactiniatum*	Bite *et al.* (1972)
Solaradinine	Gal, 4 Glu, Rham	*S. lactiniatum*	Bite *et al.* (1972)
Solapersine	Gal, Glu, 2 Xyl	*S. persicum*	Novuzov *et al.* (1975)
Solatifoline	Glu, Gal, Rham	*S. platanifolium*	Puri (1975)

[a] Glu = Glucose.
Gal = Galactose.
Rham = Rhamnose.
Xyl = Xylose.

STRUCTURE OF GLYCOALKALOIDS

The chemical characterization of glycoalkaloids has been greatly facilitated by the use of NMR and mass spectrometry. In many cases, complete characterization of the aglycone can be accomplished by Nuclear Magnetic Resonance NMR (^{13}C primarily). NMR assignments for the more common *Solanum* alkaloids have appeared in the recent literature (Badeglia *et al.*, 1977; Weston *et al.*, 1977). Assignments for the carbons in the carbohydrate moiety are ambiguous and, therefore, of less utility in characterizing this portion of the molecule (Mahato *et al.*, 1980). Glycoalkaloids are quite amenable to permethylation analysis for carbohydrate characterization. We have developed a modified Hakomori procedure for such an analysis (Herb *et al.*, 1975). The glycoalkaloid

(1–2 mg) is permethylated, using dimsyl sodium and methyl iodide. After destruction of the excess dimsyl sodium with water, the permethylated glycoalkaloid is extracted with benzene rather than chloroform. Since the permethylated glycoalkaloid, because of the steroidal aglycone, partitions completely into the benzene layer and dimethyl sulfoxide does not, the permethylated compound can be isolated without the problem of dealing with contamination from solvent or reagent. In the usual manner, the permethylated glycoalkaloid is hydrolyzed, and the partially methylated sugars are reduced and then acetylated. Gas chromatography/mass spectrometry (GC/MS) of these derivatives (using OV-225 SCOT columns) is generally sufficient for unambiguous characterization. Using this technique, we have been able to characterize a series of glycoalkaloids containing the commeratetrose glycoside (with solanidine, tomatidine, or demissidine as the aglycone).

GLYCOALKALOID ANALYSIS

A considerable effort in the chemistry of glycoalkaloids has been devoted to developing analytical methods for glycoalkaloid determination in plants and plant products. There have been two main aspects in the development of analytical methodology: (a) the development of rapid, sensitive methods for the determination of the total glycoalkaloid content (TGA) of market potatoes and (b) a general method for glycoalkaloid determination (both concentration and composition) in *Solanum* species that are potential breeding material. The need for rapid TGA analysis reflects concern about the variability of glycoalkaloid concentration in commodities such as potatoes. Environmental conditions in the field can significantly affect glycoalkaloid levels in potatoes (Sinden & Webb, 1974) (Table 3). Methods have been developed (Table 4) that enable potato growers and marketers to determine glycoalkaloid levels in a general screening procedure, or on a spot basis in suspect samples. These methods ultimately rely on colorimetric titrations, and the degree of accuracy one obtains depends on the extent of purity of the glycoalkaloid fraction. Most of the colorimetric assays, e.g. phenol–sulfuric acid method, are relatively non-specific and therefore the purer the glycoalkaloid fraction, the more accurate the results; impurities, with these methods, tend to give abnormally high results. The thin layer chromatographic method (TLC), at best, can only be considered semi-quantitative. More sophisticated

TABLE 3
Variation of Glycoalkaloid Concentration with Location

Location	*mg/100 g fw*[a]	*Location*	*mg/100 g fw*[a]
Parma, ID	20·5	Lexington, KY	10·2
Fairhope, Al	16·0	Ithaca, NY	9·8
Cheyenne, WY	13·3	Riverhead, NY	9·5
Charleston, SC	11·3	Prosser, WA	7·8
Salisbury, MD	10·7	Beltsville, MD	7·3
Presque Isle, ME	10·6		

[a] fw = fresh weight.

chromatographic procedures, less accessible to non-chemists, have recently been developed; for example, Bushway *et al.* (1979) have used high pressure liquid chromatography (HPLC) for the analysis of solanine and chaconine in a variety of potato products. A protocol, from the standpoint of food safety, would most likely involve using one of the 'quick and dirty' methods to determine if a sample is equivalent to, or exceeds, acceptable glycoalkaloid levels (*ca.* 20 mg/g fresh weight in potatoes) followed by one of the more accurate methods if acceptable levels are exceeded.

The methods summarized in Table 4 are satisfactory for plant and plant products of known and invariable glycoalkaloid composition. This

TABLE 4
Rapid TGA Analytical Methods

Isolation	*Quantitation*	*Specificity*	*Reference*
Extraction/precipitation	Colorimetric (H_2CO—H_2SO_4)	+ + +	Rooke *et al.* (1943)
Extraction/precipitation	Colorimetric ($SbCl_3$)	+ +	Bretzloff (1971)
Extraction/hydrolysis	Colorimetric (BrpH Br_2)	+ + +	Fitzpatrick & Osman (1974)
Extraction/hydrolysis	Colorimetric (BrThy BLUE)	+ + +	Coxon *et al.* (1979)
Extraction/TLC	Colorimetric ($SbCl_3$)	+ +	Cadle *et al.* (1979)
Extraction/precipitation	Colorimetric	+ +	Dabbs & Hilton (1953)

is the case for most market potatoes which are derived from the species, *S. tuberosum*. However, in the last 50 years there has been an attempt on the part of potato breeders to develop natural disease and pest resistance by introducing uncultivated *Solanum* species into breeding programmes. For example, a clone, USDA x-9656, which is a hybrid of *S. tuberosum* and *S. demissum*, was introduced in the 1940's for resistance against the late-blight pathogen, *Phytophthora infestans*. Today, many other *Solanum* species are being considered for breeding, because of the resistance that these species exhibit towards pests and microorganisms. With the advent of protoplast techniques, a whole new vista of producing hybrids of incompatible species is now also possible. This presents a new problem to the chemist with regard to glycoalkaloid analysis; even though we may know the glycoalkaloid composition of the parents, we cannot accurately predict the glycoalkaloid composition of the individual progeny (Sanford & Sinden, 1972; McCollum & Sinden, 1979). Not only will there be variable composition with respect to the glycoalkaloids found in the parents, there is also the possibility of finding glycoalkaloids not present in either parent. For this, and other reasons, too complicated to discuss in this brief review, a more inclusive method for determining glycoalkaloid levels and composition is required. A gas chromatographic method for determining glycoalkaloid composition was developed in our laboratory that requires permethylation and high temperature GC (Herb *et al.*, 1975). HPLC methods, while simpler to carry out, are not capable of the same degree of resolution as GC. TLC analysis, in conjunction with GC, can be an effective means of characterizing glycoalkaloids in an unknown sample. Using this procedure, we have analyzed the glycoalkaloids in a number of species of interest to the breeders (Table 5). The analysis of four clones of *S. acauli* demonstrates the variability in composition one may observe in a single species (the possibility that *S. acauli* is not a pure species, but a hybrid, could account for this variation).

Quantitation of TGA in species other than *S. tuberosum* may also require analytical methods different from the ones discussed above. For many of the 'fast' analytical methods, one must precipitate the glycoalkaloid fraction. Since most glycoalkaloids are insoluble in aqueous base, this can be easily accomplished. The few that are soluble under these conditions must be measured by other techniques; however, one cannot assume that a particular glycoalkaloid can be quantitatively precipitated from an aqueous plant extract because it is insoluble in base. A recent experience is illustrative. We have developed a method for

TABLE 5
Glycoalkaloids of Selected Solanum Species

Species	*β-Chaconine*	*α-Chaconine*	*Glycoalkaloid α-Solanine*	*Solamarines*[a]	*Demissine*	*Tomatine*
S. ajanhuiri[b]	3·5[c]	39·0	57·3			
S. curtilobum		34·8	46·4	5·3	13·4	
S. stenotonum	5·5	69·8	24·7			
S. juzepczukii		14·0	37·8	7·7	40·4	
S. acaule 1[d]					95·5	
S. acaule 2					62·1	30·9
S. acaule 3					88·2	11·6
S. acaule 4					64·0	34·0

[a] Combined value for α- and β-solamarine.
[b] All species are cultivated except for *S. acaule*.
[c] Values represent per cent of total glycoalkaloids.
[d] Four clones of species *S. acaule* were analyzed.

measuring TGA that does not require precipitation (Fitzpatrick & Osman, 1974). This method is based on titrating the free aglycone after hydrolysis of the glycoalkaloid. In collaboration with the Beltsville Agricultural Research Center, we wished to determine the TGA of a plant extract that was known to contain only demissine and solanine, two glycoalkaloids that are insoluble in aqueous base. Using our method, we obtained values twice that from methods that required precipitation. We subsequently showed that the glycoalkaloids were only partially precipitated (about 50%) using standard techniques that, under most circumstances, result in complete precipitation. Although we do not know what causes this phenomenon, the fact that solubility can be affected by other constituents in the plant extract must be considered when attempting TGA analysis of *Solanum* species other than *S. tuberosum*.

GLYCOALKALOIDS AND HUMAN HEALTH

The degree of effort that has been expended on developing analytical techniques is a reflection of the concern about toxicity of these compounds, and their presence in our food supply. The potato industry in the United States has used, as a guideline, a maximum of 20 mg TGA/100 g fresh weight of potato tuber for glycoalkaloid content. How this figure was determined, and the historical controversy about just how toxic glycoalkaloids are, is beyond the scope of this paper. Although experimental toxicity studies with animals, particularly mice (Nishie *et al.*, 1971, 1975) would indicate that these compounds are relatively non-toxic, empirical data concerning cases of potato poisoning in humans are sufficient cause for the potato industry to be concerned about glycoalkaloid levels. A recent review summarizes present knowledge of glycoalkaloid toxicity (Roddick, 1982); however, since human toxicity data for glycoalkaloids are lacking, as is usually the case in these circumstances, the controversy will continue.

Since breeders can produce potatoes that contain little or no glycoalkaloids, are we really dealing with a non-issue? Unfortunately, the question is not that simple to answer. As previously mentioned, breeders are interested in developing plant lines that are resistant to pests and disease. Glycoalkaloids have been shown to be effective in the control of certain pests (Tingey *et al.*, 1978; Raman *et al.*, 1979). Kuhn & Gauhe

(1961) isolated the leptine glycoalkaloids (23-acetylsolanidine aglycone) from the species *S. chacoense*, which is resistant to the Colorado potato beetle (CPB) (Stürckow & Löw, 1961). In recent field tests (Sinden *et al.*, 1980), glycoalkaloid composition and concentration were shown to be factors in CPB resistance. In an attempt to incorporate CPB resistance, *S. chacoense* was used in a breeding programme that eventually lead to the Lenape cultivar (Akeley *et al.*, 1968). This variety was never released because of reports of illness due to consumption of these potatoes (Zitnak & Johnston, 1970). Therefore, although studies have shown that glycoalkaloids are a vector in resistance to pests, the presence of these compounds in the edible portion of the plant at toxic levels precludes the use of these compounds as means of resistance. A more complete understanding of the biosynthetic control mechanism in the plant is a prerequisite to any resistance programme based on glycoalkaloids.

The appearance of new potato products may present a problem vis à vis glycoalkaloids. In the United States, fried potato skins have become somewhat popular in restaurants. The TGA distribution in the potato tuber is shown in Table 6. The greatest concentration of glycoalkaloids is

TABLE 6
Distribution of Glycoalkaloids in Tubers

Tuber part	*mg/100 g Dry weight*	*Part = % of tuber*
Skin	64	2
Peel		
(Skin and outer cortex)	68–75	11
Flesh	21	90

found just below the skin; therefore, these products can contain high levels of glycoalkaloids. Producers of this commodity can take precautions to ensure low TGA levels in these products.

De novo synthesis of glycoalkaloids after harvesting is a potential hazard in potatoes. There is much evidence to suggest that mechanically damaged (Wu & Salunhke, 1976) and light-exposed tubers (which usually have green areas due to high chlorophyll content (Jadhav & Salunhke, 1975)) contain abnormally high concentrations of glycoalkaloids. Our analysis of market potatoes that were damaged (Fitzpatrick *et al.* 1978) did not indicate glycoalkaloid concentrations at hazardous levels. Injury

to tubers can also result in the synthesis of glycoalkaloids that are not normally found in the healthy tuber. Shih & Kuč (1974) have reported the presence of the solamarines in Kennebec slices after incubation; these compounds are not found in undamaged, healthy tubers.

In conclusion, the potato industry has been well aware of the health problems related to potato glycoalkaloids and, in general, it has tried to limit glycoalkaloid levels even though there may be some advantage to having high levels of these compounds present in the plant. As with most produce, there is no effective means of monitoring potatoes in the market place that may contain high TGA because of mishandling or microbial infection; the consumer must use judgment in using foods of questionable quality. For example, potato tubers that appear to be contaminated or green (as mentioned, chlorophyll levels correlate with glycoalkaloid levels) should be discarded. The potato grower should be responsible for growing low glycoalkaloid potatoes, the distributor for delivery of a good product, but the consumer is still the final arbiter.

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