The handle http://hdl.handle.net/1887/19839 holds various files of this Leiden University dissertation.

**Author:** Joosten, Lotte  
**Title:** Pyrrolizidine alkaloid composition of the plant and its interaction with the soil microbial community  
**Issue Date:** 2012-09-20
The Genotype Dependent Presence of Pyrrolizidine Alkaloids as Tertiary Amine in *Jacobaea vulgaris*

Lotte Joosten, Dandan Cheng, Patrick P. J. Mulder, Klaas Vrieling, Johannes A. van Veen and Peter G. L. Klinkhamer

Lotte Joosten and Dandan Cheng contributed equally to this work.

*Phytochemistry* (2011) 72: 214-222

**Abstract**

Secondary metabolites such as pyrrolizidine alkaloids (PAs) play a crucial part in plant defence. PAs can occur in plants in two forms: tertiary amine (free base) and N-oxide. PA extraction and detection are of great importance for the understanding of the role of PAs as plant defence compounds, as the tertiary PA form is known for its stronger influence on several generalist insects, whereas the N-oxide form is claimed to be less deterrent. We measured PA N-oxides and their reduced tertiary amines by liquid chromatography–tandem mass spectrometry (LC-MS/MS). We show that the occurrence of tertiary PAs is not an artifact of the extraction and detection method. We found up to 50% of tertiary PAs in shoots of Jacobine-chemotype plants of *Jacobaea vulgaris*. Jacobine and its derivatives (jacoline, jaconine, jacozone and dehydrojaconine) may occur for more than 20% in reduced form in the shoots and more than 10% in the roots. For 22 PAs detected in F₂ hybrids (*J. vulgaris × Jacobaea aquatica*), we calculate the tertiary amine percentage (TA% = the tertiary amine concentration/(tertiary amine concentration + the corresponding N-oxide concentration) × 100). We found that the TA% for various PAs was genotype-dependent. Furthermore, TA% for the different PAs were correlated and the highest correlations occurred between PAs which share high structural similarity.
Introduction

Pyrrolizidine alkaloids (PAs) are a well known class of defence compounds with a wide variety of structures. From several genera of Asteraceae, Boraginaceae, Orchidaceae and Fabaceae, more than 360 structurally different PAs have been isolated (Rizk 1991; Hartmann and Witte 1995). It is known that PAs are present as mixtures of the tertiary alkaloids and the respective N-oxides in plants (Rizk 1991). It is generally accepted that in Senecio and Jacobaea plants PAs occur mainly or even exclusively in N-oxide form (Hartmann and Toppel 1987; Hartmann et al. 2004; Cao et al. 2008; Kempf et al. 2010).

In several Senecio and Jacobaea species, such as Senecio vulgaris, PAs are synthesized in the roots primarily as senecionine N-oxide (Hartmann and Toppel 1987; Toppel et al. 1987). Subsequently, senecionine N-oxide is transported to the shoot, where by specific enzymes, further diversification into different individual PAs takes place (Hartmann and Dierich 1998). The water soluble N-oxide form is considered to be ideal for phloem transport (Hartmann et al. 1989) and storage in cell vacuoles (von Borstel and Hartmann 1986; Ehmk et al. 1988).

Generalist insect herbivores reduce N-oxides in the gut to tertiary PAs, where these tertiary PAs are passively taken up into the body and when converted into pyroroles they are toxic by acting as highly reactive alkylating agents in mammals and fruit flies (Mattocks 1986; Frei et al. 1992). Since the PA N-oxides are reduced in the herbivore’s gut, we could expect that it displays the same degree of toxicity as the respective tertiary amines. However in several studies was shown that individual PA N-oxides showed less deterrent or toxic effects for some generalist insect herbivores compared to the tertiary PAs (Dreyer et al. 1985; van Dam et al. 1995; Macel et al. 2005). Van Dam et al. (1995) found that three PAs from Cynoglossum officinale equally deterred feeding by Spodoptera exigua larvae, but the tertiary PA formed deterred feeding more efficiently than the corresponding PA N-oxides. Macel et al. (2005) showed that retrorsine N-oxide was significantly less repellent to the locust Locusta migratoria compared to the corresponding tertiary PA. After 6 days on a diet of retrorsine N-oxide 60% of the thrips Frankliniella occidentalis survived against 0% on the tertiary PA. Specialist insects, i.e., some butterflies and moths (Lepidoptera), certain chrysomelid leaf beetles (Coleoptera) and the grasshopper Zonocerus variegates are adapted to PAs; sequestrate the tertiary PAs and specifically convert them into N-oxides which they store and utilize for their own chemical defence (Boppré 1986; Lindigkeit et al. 1997; Dobler 2001; Nishida 2002; Narberhaus et al. 2003). For many years, PAs were typically isolated by acid-base extraction in combination with zinc reduction. Gas chromatography (GC) with flame ionisation detection (FID), nitrogen phosphorus detection (NPD) or mass spectrometric detection (MS) have typically been used as analytical methods. Recently liquid chromatography–tandem mass spectrometry (LC-MS/MS) has been introduced for measuring PAs in plant material. Unlike GC-related methods, LC-MS/MS and NMR can detect both tertiary amines and N-oxides without an additional reducing step (Crews et al. 2010; Joosten et al. 2010). However, NMR needs relatively high concentrations of PAs for detection. LC-MS/MS is therefore a suitable and sensitive method to detect both forms of PAs.

We used LC-MS/MS to detect both forms of PAs. We found consistently large amounts of tertiary amines in Jacobaea vulgaris plants (Joosten et al. 2009 and 2010). However, the general tendency in literature is that tertiary amines are present only in very small amounts and maybe are due to artifacts during extraction or detection (Hartmann and Toppel 1987; Hartmann 1999; Hartmann and Ober 2000). PA N-oxides from Senecio plants are relatively unstable and are easily converted into their reduced form, the pre-toxic tertiary PAs under various experimental conditions. For example, the reduction increased upon prolonged heating of the sample (e.g. soxhlet extraction), when the amino acid cysteine was added and in the presence of plant material (Hartmann and Toppel 1987; Hösch et al. 1996). Therefore we tested our method for possible artifacts by several PA reduction and oxidation experiments with chemical agents and plant material.

Further proof of the presence of tertiary amines in living plant tissue can be obtained by showing that the concentrations of tertiary amines have a genetic basis and result from transformations by specific enzymes. It is already known that variation in composition and concentration of PAs in J. vulgaris has a large genetic component (Vrieling et al. 1993; Macel et al. 2004). In order to assess the genetic basis in the variation, the occurrence of the tertiary amine form, we conducted a crossing of J. vulgaris, which has high levels of tertiary amines, with the closely related Jacobaea aquatica (syn. Senecio aquaticus), which has low levels of tertiary amines (Cheng et al. 2011).

Here we report on studies to obtain a better understanding of the (bio)chemistry of PAs in above- and belowground plant parts of J. vulgaris and hence on the mechanisms of their activity as defence compounds against herbivores. Thus, we investigated: (1) the chemical reduction of three different PA N-oxides (representatives of the three structural groups) to assess the chemical PA (in)stability towards two different reducing agents; (2) the chemical oxidation of three different tertiary PAs to assess the chemical PA (in)stability towards an oxidation agent; (3) spontaneous reduction of three different PA N-oxides in the presence of possibly reducing agents as well as the spontaneous N-oxidation of three different tertiary PA in the presence of possibly oxidation agents naturally occurring in plant material of several different Asteraceae species; (4) the spontaneous reduction of PAs during freeze-drying compared to immediate PA extraction from freshly ground material under liquid nitrogen; (5) the PA distribution in five different J. vulgaris genotypes by using an LC-MS/MS method for simultaneous measurement of PA N-oxides and tertiary PAs and (6) the genotype effect on the tertiary alkaloid relative content (TA%) for different PAs in the hybrids and the correlation between the TA% of different PAs.

Material and Methods

Standard PA extraction for LC-MS/MS

Freeze-dried plant material (approximately 10 mg) was extracted in 1 ml 2% formic acid. Heliotrine was added as internal standard to the extraction solvent at a concentration of 1 μg/ml. The plant extract solution was shaken for 30 min. After centrifugation the residual plant material was removed by filtering the extraction solution through a 0.2 μm nylon membrane (Acrodisk® 13 mm syringe filter). An aliquot of 25 μl filtered solution was diluted with 975 μl water and 10 μl was injected in the LC-MS/MS system.

Standard PA analysis by LC-MS/MS

A Waters Acquity ultra performance liquid chromatographic (UPLC) system coupled to a Waters Quattro Premier XE tandem mass spectrometer (Waters, Milford, PA, USA) was used for PA determination. Chromatographic separation was achieved on a Waters Acquity BEH C18 150 x 2.1 mm, 1.7 μm, UPLC column, kept at 50 °C and ran with a water/acetonitrile linear gradient containing 6.5 mM ammonia at a flow of 0.4 ml/min. The gradient started at 100% water and during analysis the acetonitrile percentage was raised to 50% in 12 min.

The MS system was operated in positive electrospray mode and data were recorded in multiple monitoring mode using two selected precursor ion to product ion transitions per compound. Cone and collision energy settings were optimized for the individual compounds. Obtained peak areas were...
internally calibrated using the internal standard and the individual compounds were quantified against a standard solution of the PAs in an extract of the non-PA containing asterid Tanacetum vulgare to mimic the plant matrix. Seventeen individual PA standards were available for this study, representing over 90% of the total amount of PAs present in the plants extracts. Senecionine, seneciphylline, retronoine and their N-oxides as well as senkirkine were available from commercial sources (Phytolab, Vestenbergsgreuth, Germany; Phytoplan, Heidelberg, Germany). Integerrimine was obtained as a kind gift of Dr. Trigo (UNICAMP, Campinas, Brazil). Riddelliine and its N-oxide were obtained as a kind gift from Dr. Chou (NCTR, Jefferson, AR, USA). Acetylseneciphylline was obtained by acetylation of seneciphylline with acetic anhydride and pyridine. Jacobine and erucifoline were isolated from J. vulgaris plant material (PRISNA, Leiden, the Netherlands). The identity of the standards isolated was confirmed by 1H-NMR and LC-MS analysis. N-oxides of integerrime, jacobine, erucifoline and acetylseneciphylline were prepared by N-oxidation according to the method of Christie et al. (1949), adapted by Chou et al. (2003). The remaining PAs, being tertiary PAs as well as N-oxides, were quantified by using the response of a structurally related standard. Data processing was conducted with Masslynx 4.1 software.

### Chemical reduction of PA N-oxides

A mixture of three PA N-oxides (senecionine N-oxide, jacobine N-oxide and erucifoline N-oxide, 1 μg/ml) was exposed to the reducing agent sodium metabisulphite (Na₂S₂O₃) in a range of 5 concentrations (0, 0.01, 0.03, 0.1, 0.3, 1 mM) in 2% formic acid solution. After 1, 4 and 24 h of incubation at room temperature the solutions were diluted 10-fold with water and injected in the LC-MS/MS system. The same mixture of standards was also exposed to the amino acid cysteine at three concentrations (1, 10 and 1000 mM), in two different solutions, 2% formic acid and water.

The relative amount of tertiary PA present in a sample was calculated as the measured concentration of tertiary PA divided by the sum of the concentration of tertiary PA and corresponding PA N-oxide.

A three-way ANOVA with two replications was used to analyze if PA type (senecionine N-oxide, jacobine N-oxide and erucifoline N-oxide), reducing agent concentration (0, 0.01, 0.03, 0.1, 0.3, 1 mM) and incubation time (1, 4, 24 h) have a significant influence on the relative concentration of tertiary PAs formed by reduction of the added PA N-oxides. The analysis was made by General Linear Model (GLM) univariate analyses procedure with the relative concentration of tertiary PAs as the dependent variable and PA type, reducing agent concentration and incubation time as fixed factors. All tests were conducted with SPSS 17.0 for Windows.

### Chemical N-oxidation of tertiary PAs

The three individual tertiary PAs (senecionine, jacobine and erucifoline), were added to five concentrations (0.01, 0.03, 0.1, 0.3, 1 mM) of the oxidation agent hydrogen peroxide (H₂O₂) in 2% formic acid solution. After 1, 4 and 24 h of incubation at room temperature the solutions were diluted 10-fold with water and injected in the LC-MS/MS system.

The relative amount of N-oxide present in the sample was calculated as the measured concentration of the PA N-oxide divided by the sum of the concentration of PA N-oxide and the corresponding tertiary PA.

The same statistical test was used as for the chemical reduction experiment described above, to analyze if PA-structural group (senecionine, jacobine and erucifoline), reducing agent concentration (0, 0.01, 0.03, 0.1, 0.3, 1 M) and incubation time (1, 4, 24 h) did have a significant influence on the relative concentration of PA N-oxides formed by N-oxidation of the added tertiary PAs.

### PA N-oxide reduction and PA N-oxidation in the presence of plant material

Three PA N-oxides (senecionine N-oxide, jacobine N-oxide and erucifoline N-oxide) and three tertiary PAs (senecionine, jacobine and erucifoline) were added separately to dry plant material of five different flowering Asteraceae species collected in the field, S. gigantea, E. canabinum, S. sylvaticus, J. erucifolia (syn. Senecio erucifolius) and J. vulgaris (erucifoline chemotype). S. gigantea contains no PAs, E. canabinum contains the lycopsis type of PAs, S. sylvaticus contains the triangularine type of PAs, and J. erucifolia contains the senecionine type of PAs. Dried, ground plant material of the shoot (approximately 100 mg) was wetted with 500 μl distilled water containing senecionine N-oxide, jacobine N-oxide and erucifoline N-oxide (10 μg of each PA) in 3-fold and incubated for 1 h. As a control, from each plant species one sample was wetted with water containing no PA N-oxides. After adding 10 ml 2% formic acid and heliodule as internal standard (1 μg/ml), the plant extract was shaken for 30 min. After centrifugation, the residual plant material was removed by filtering the extraction solution through a 0.2 μm nylon membrane. An aliquot of 25 μl filtered solution was diluted with 975 μl water and injected in the LC-MS/MS system.

### Species description

J. vulgaris (syn. Senecio jacobaeus) is a suitable system to study PAs. This species is native in Europe and West Asia but invasive in North America, Australia and New Zealand. In previous studies, up to 30 different PAs were detected in J. vulgaris (Witte et al. 1992; Macel et al. 2004; Kowalchuk et al. 2006; Joosten et al. 2009). Based on their structural features, major PAs in J. vulgaris can be divided into 3 structural groups: senecionine-like, comprising senecionine, integerrimine, retronoine and (acetyl)senechiphylline; jacobine-like, comprising jacobine, jacinone, jaconine, and dehydrojaconine; erucifoline-like, comprising erucifoline and acetylerucifoline (Table 2).

Based on the PA composition, 4 chemotypes of J. vulgaris were distinguished: Senecionine-chemotype, largely lacking jacobine- and erucifoline-like PAs; Erucifoline-chemotype, lacking jacobine-like PAs; Jacobine-chemotype, containing high levels of jacobine-like PAs; mixed chemotype, containing both jacobine- and erucifoline-like PAs in similar amounts (Witte et al. 1992; Macel et al. 2004). J. aquatica is a close relative but not a sister species to J. vulgaris (Pelsel et al. 2003). These two species naturally hybridize in some areas and the hybrids can backcross into the parental populations (Kirk et al. 2004 and 2005).

### Effect of freeze-drying on the tertiary PA content

Freeze-drying is a general used method to dry plant material before analyzing PAs in plant material. In this way enzymatic activity can be prevented or at least strongly reduced. We tested if the freeze-drying can lead to spontaneous reduction of PAs. To compare freeze-dried material to the original plant condition we extracted PAs from fresh plant material as control treatment. Liquid nitrogen was used to ground fresh plant material under deep frozen conditions.

### Plant material

One genotype of J. vulgaris originating from a population near Wageningen was used to study if reduction can take place during freeze-drying. The plants were propagated by tissue culture. In total eight clones per treatment (PA extraction of fresh material versus PA extraction of freeze-dried material) were...
used. The plants were potted in 1.3 l pots filled with potting soil (Slingerland Potgrond, Zoeterwoude, the Netherlands). The plants were kept in a climate room for 6 weeks (humidity 70%, light 16 h at 20 °C, dark 8 h at 20 °C) and randomly distributed every 8-10 days.

**PA extraction from fresh and freeze-dried material**

The shoot of each plant was cut lateral in two pieces with scissors so each part had an equal number of leaves of similar size, one shoot part for the control treatment and the other part for the freeze-drying treatment. The control part of the shoot was weighted, immediately ground under liquid N2 and in frozen condition mixed in 20 ml of 2% formic acid containing 0.2 μg/ml heliotrine as internal standard. From this point on the standard PA extraction for LC-MS/MS was performed as described above. After weighting, the other half of the shoot was immediately stored at -20 °C before being freeze-dried. After freeze-drying, the standard PA extraction for LC-MS/MS was performed.

**Data analysis**

As described above. An aliquot of 25 μl filtered solution was diluted with 975 μl water and injected in the LC-MS/MS system.

**PA analysis for J. vulgaris**

Plant material and PA analysis

Five different genotypes of *J. vulgaris* were used representing two chemotypes: three Jacobine-chemotypes and two Erucifoline-chemotypes. Two Jacobine-chemotypes originated from two different populations in Meijendel near The Hague and the third originated from a population near Wageningen. The two Erucifoline-chemotypes originated from a Dutch population near Vilt (Limburg) and a German population near Kassel. The five different genotypes were propagated by tissue culture. In total, 609 plants were used in this study, among which 562 were *F*1 individuals. The plants were potted in 1.3 l pots filled with 95% sandy soil, collected from Meijendel, 5% potting soil (Slingerland Potgrond, Zoeterwoude, the Netherlands) and 1.5 g/l Osmocote (Scotts®, Geldermalsen, the Netherlands, N,P,K = 15:9:11). The plants were randomly distributed and kept in a climate room for 6 weeks (humidity 70%, light 16 h at 20 °C, dark 8 h at 20 °C). After 6 weeks the plants were harvested and prepared for LC-MS/MS analysis as described above.

**Data analysis**

Of the 37 detected PAs, 9 were otonecine structural group PAs for which no corresponding *N*-oxide existed and 6 were absent or close to the detection limit in some samples. The remaining 22 PAs were used to calculate the relative concentration of tertiary amine as TA% = the tertiary amine concentration/(tertiary amine concentration + the corresponding *N*-oxide concentration) × 100. The genotype effect on TA% was statistically analyzed by a Kruskal-Wallis test with the TA% as the independent variable and genotype (including parental, *F*1 and *F*2, 106 genotypes in total) as the grouping variable. Spearman correlation matrix between the 11 kinds of TA% was calculated based on the mean TA% per genotype in root and shoot. *P*-values of the correlations were adjusted by Holm’s method (Holm 1979). To determine if different type of plant material (root/shoot) had a different degree of the correlation between TA%, a paired *t*-test was done with the correlation values as the independent variable. Depending on the PA-structural group the specific PAs belong to, the correlations were divided into 6 categories: Category 1, correlation between the PAs of the senecionine-like PAs; Category 2, correlation between the PAs of the jacobine-like PAs; Category 3, correlation between the PAs of the erucifoline-like PAs; Category 4, correlation between the PAs of the senecionine- and jacobine-like PAs; Category 5, correlation between the PAs of the senecionine- and the erucifoline-like PAs; Category 6, correlation between the PAs of the jacobine- and the erucifoline-like PAs. Differences between the correlation values belonging to the different categories were analyzed with a one-way ANOVA with the correlation values as the
Results

Chemical reduction of PA N-oxides
The chemical reduction of the three PA N-oxides, senecionine N-oxide, jacobine N-oxide and erucifoline N-oxide, with sodium metabisulfite into their tertiary amines showed a significant difference ($F_{2, 47} = 10.8, P < 0.001$) in rate of reduction at any concentration of sodium metabisulfite added. Averaged over all incubation times (1, 4, 24 h) and reducing agent concentrations (0.01, 0.03, 0.1, 0.3, 1 mM) 42.2% (SE ± 0.63) of the jacobine N-oxide was reduced while 45.8% (SE ± 0.63) for both senecionine N-oxide and erucifoline N-oxide (Supplementary data Figure 1). However, the difference is not significant due to the analytical error, which is estimated at 10%.

Exposure of the three PA N-oxides to 1 M cysteine produced no measurable amount of tertiary amines after 24 h under acidic conditions (2% formic acid). However, under neutral conditions (water) with 1 M cysteine a very slow reduction occurred: after 24 h the production of senecionine, jacobine and erucifoline was respectively 1.9%, 4.2% and 2.7% (data not shown). The amounts of tertiary amines formed were too low to draw definitive conclusions about a difference in reactivity of the PA N-oxides towards cysteine and other potential sulfur-containing plant components. It should be pointed out that under the extraction conditions used in this study, the PA N-oxides displayed no measurable reactivity whatsoever towards cysteine. Interestingly, we found that 1 M cysteine catalyzed the isomerisation of senecionine N-oxide into integerrimine N-oxide notably under acidic conditions. After 24 h approximately 30% of senecionine N-oxide has isomerised to integerrimine N-oxide, under neutral condition this was only 14%. In the absence of cysteine the isomerisation in formic acid was less than 1% after 24 h.

Chemical N-oxidation of tertiary PAs
For the chemical oxidation under acidic conditions of the three macrocyclic tertiary PAs, senecionine, jacobine and erucifoline, with hydrogen peroxide (HOOH) proceeded much faster under neutral conditions (data not shown). Averaged over all incubation times (1, 4, 24 h) and oxidation agent concentrations (0.01, 0.03, 0.1, 0.3, 1 mM), 2.8% (SE ± 0.14) of the jacobine N-oxide was oxidized while 1.0 (SE ± 0.14) and 1.1% (SE ± 0.14) for senecionine and erucifoline, respectively. The chemical oxidation of senecionine and erucifoline takes place with approximately the same rate, but that the oxidation of jacobine significantly proceeded faster ($F_{2, 105} = 48.6, P < 0.001$). The difference in rate was irrespective to the HOOH concentration. After 24 h with 1 M peroxide approximately 22.2% (SE ± 1.5) of jacobine had been converted to its N-oxide, while for senecionine the conversion was only 6.4% (SE ± 1.5) and for erucifoline 7.5% (SE ± 1.5) (Supplementary data Figure 2).

Extraction of tertiary PAs and PA N-oxides in the presence of dried plant material of five different Asteraceae species
The three PA N-oxides, senecionine N-oxide, jacobine N-oxide and erucifoline N-oxide, in presence of dry plant material of 5 flowering Asteraceae species showed no measurable induced formation of tertiary amine PAs by naturally reducing agents if present (data not shown). All PA N-oxides added were recovered with LC-MS/MS after extraction. Only a very small amount (2%) of the added senecionine N-oxide was reduced in the presence of Solidago gigantea and Eupatorium cannabinum plant material, but the concentrations measured were close to the detection limit. In the presence of Senecio sylvaticus no reduction was observed for all three PA N-oxides. In the control samples (no PA N-oxides added) of Jacobaea erucifolia and J. vulgaris senecionine N-oxide, erucifoline N-oxide and its tertiary PAs were already present in the plant material but jacobine or jacobine N-oxide were not present in detectable amounts. Since senecionine N-oxide and erucifoline N-oxide were naturally present in the plant, we could not draw any conclusions on the reduction of these PAs, as the added N-oxide volumes were negligible. For the jacobine N-oxide added it could be shown that there was no reduction by naturally occurring reducing agents present in J. erucifolia and J. vulgaris.

The three tertiary PAs, senecionine, jacobine and erucifoline, in presence of dry plant material of several flowering Asteraceae species showed no detectable induced oxidation of PAs by naturally occurring oxidation agents (data not shown). All PAs added were recovered after extraction.

Effect of freeze-drying on the tertiary PA content
The total PA concentration and the concentration of the individual PAs was not significantly different comparing the freeze-dried with fresh plant material (Table 1). The freeze-dried (lyophilized) materials had a higher TA% for all individual PAs compared to the corresponding fresh materials, which illustrates that the freeze-drying process caused some reduction from N-oxide to tertiary amine. The reduction is not PA specific, because the relative reduction amount was not significantly different between the PAs (Table 1, ANOVA, $F_{6, 41} = 0.69, P = 0.70$).

Table 1. Effect of sample treatment on the observed concentration of total PA, individual PA, relative concentration of tertiary amines (TA%), and relative reduction amount.

<table>
<thead>
<tr>
<th>PA(^a)</th>
<th>Concentration(^b) (mg/g dry wt)</th>
<th>TA(^c)</th>
<th>Relative reduction amount(^d) (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Freeze-dried</td>
<td>Fresh</td>
<td>Paired t-test</td>
</tr>
<tr>
<td>Total PA</td>
<td>0.544</td>
<td>0.794</td>
<td>ns</td>
</tr>
<tr>
<td>sn</td>
<td>0.042</td>
<td>0.047</td>
<td>ns</td>
</tr>
<tr>
<td>ir</td>
<td>0.014</td>
<td>0.017</td>
<td>ns</td>
</tr>
<tr>
<td>sp</td>
<td>0.095</td>
<td>0.108</td>
<td>ns</td>
</tr>
<tr>
<td>acsp</td>
<td>0.012</td>
<td>0.008</td>
<td>ns</td>
</tr>
<tr>
<td>jl</td>
<td>0.435</td>
<td>0.560</td>
<td>ns</td>
</tr>
<tr>
<td>jl</td>
<td>0.007</td>
<td>0.008</td>
<td>ns</td>
</tr>
<tr>
<td>er</td>
<td>0.011</td>
<td>0.011</td>
<td>ns</td>
</tr>
<tr>
<td>ac</td>
<td>0.020</td>
<td>0.020</td>
<td>ns</td>
</tr>
<tr>
<td>acer</td>
<td>0.014</td>
<td>0.014</td>
<td>ns</td>
</tr>
</tbody>
</table>

\(^a\) Abbreviations: sn = senecionine; ir = integerrimine; sp = seneciphylline; acsp = acetylseneciphylline; jl = jacobine; jl = jacoline; jz = jacozine; er = erucifoline; acer = acetylerucifoline

\(^b\) Concentration was the absolute concentration of PAs as tertiary amines and N-oxides

\(^c\) TA% = (concentration of tertiary amines in freeze-dried material – concentration of tertiary amines in fresh material)/ (concentration of the corresponding N-oxide concentration) × 100.

\(^d\) Relative reduction amount = (concentration of tertiary amines in freeze-dried material – concentration of tertiary amines in fresh material)/ concentration of the corresponding N-oxides in fresh material

ns: not significant, * P < 0.05, ** P < 0.01, *** P < 0.001

References

Chapter 4 | The Genotype Dependent Presence of Pyrrolizidine Alkaloids as Tertiary Amine in Jacobaea vulgaris
PA distribution in *Jacobaea vulgaris*

A total of 27 different PAs (N-oxides + tertiary amines) were found in roots and shoots of the five genotypes. Dehydrojaconine, spartioidine and senecivernine were found in trace amounts and did only occur in detectable amounts as tertiary PA, while all other individual PAs were found in both forms.

The mean TA% in the roots of Jacobine-chemotypes and both plant parts of Erucifoline-chemotypes were all below 6.2%, while the TA% in the shoots of Jacobine-chemotypes was approx. 6 times higher, resulting in a significant chemotype x plant part interaction (ANOVA, $F_{1,78} = 53.07$, $P<0.001$). In the roots no significant difference between the chemotypes (Mean TA% roots Jacobine and Erucifoline-chemotype = 5.3% and 5.7%, respectively) was found while in the shoots the difference was highly significant (Mean TA% shoots Jacobine and Erucifoline-chemotype = 37.0% and 6.1%, respectively).

In the roots of all genotypes on average 94.7% of all PAs were in N-oxide form (Figure 1). Senecionine N-oxide, seneciphylline N-oxide and acetylseneciphylline N-oxide were the most abundant PAs in the roots with on average 71.0% of the total PA root concentration (Figure 4). The Jacobine-chemotypes from Meijendel (Meijendel A and B) contained jacobine N-oxide as one of the dominant root PAs, while the Erucifoline-chemotypes (Vilt and Kassel) contained erucifoline N-oxide as a dominant PA (Figure 2), with respectively 14.3% (for jacobine) and 14.9% (for erucifoline) of the total PA root concentration.

The four most dominant PAs in the shoots of the Erucifoline-chemotypes were senecionine, seneciphylline, erucifoline and acetylerucifoline. In the shoots of this chemotype, a lower concentration of PAs were in the tertiary PA form as compared to the Jacobine-chemotypes only 3.6% and 8.2% of the total shoot PA concentration for Vilt and Kassel, respectively (Figure 1). The TA% in the shoots was higher in the Jacobine-chemotypes. In particular, the chemotypes from Meijendel contained a high percentage of tertiary PAs (Figure 1). In the shoots of this chemotype, on average 45.5% of the total shoot PA concentration occurred as tertiary PA. In the Jacobine-chemotype from Wageningen, tertiary forms comprised nearly 20% of the total shoot PA concentration (Figure 1).

The TA% is in fact only determined by the presence of the jacobine-like PAs. Jacobine and its derivatives jaconine, jacoline, jacozin and dehydrojaconine showed the highest percentage in reduced form (Figure 2). In the two Jacobine-chemotypes from Meijendel on average only 17.0% of the total senecionine and seneciphylline concentration was present as tertiary PAs while for jacobine this was 54.1%.
Relative tertiary amine concentration in *Jacobaea* hybrids

Of the 37 detected PAs in the *Jacobaea* hybrids, 9 were otonecine-group PAs with no corresponding N-oxides and 6 were absent or close to the detection limit in some samples. The remaining 22 PAs were used to calculate the relative concentration of tertiary amine as TA%.

The TA% of the seneconine-like and erucifoline-like PAs in the roots were lower than 10%, which demonstrates that more than 90% of these PAs were present in N-oxide in the roots. But the jacobine-like PAs had TA% ranging from 10% till 56%. Except for seneconine, intergerrimine and acetylerucifoline, the TA% of all the other PAs was genotype dependent in the roots. In the shoots, the TA% were higher than those in the roots (for all 11 PAs, paired t-test, df = 608, P < 0.001). Particularly for jaconine, the TA% was up to 80% in the shoots. The TA% of all the individual PAs were genotype dependent in the shoots (Table 2). Generally there was a significant positive correlation between the TA% both in the roots and in the shoots. The correlation coefficients were not significantly different between the shoots and roots (paired t-test, df = 54, t = -0.393, P = 0.696), but correlation coefficients differed between structural groups (ANOVA, F_{5,106} = 10.69, P < 0.001). Correlation coefficients of TA% within structural groups are always higher as TA% correlation between different structural groups (Supplementary data Figure 3).

**Discussion**

We observed that the tertiary amine proportion was different among PAs and genotypes. Two possible and nonexclusive hypotheses may explain this pattern. Firstly, the chemical transformation and perhaps allocation of PA N-oxides, is accompanied by a continuous slow reduction of the original N-oxides. Thus, the most peripheral on a time scale oldest” PAs like jacoline and jaconine, which are far down the pathway (Supplementary data Figure 4), show the highest TA% and the “youngest” PAs, i.e. seneconine or interger-rimine, have the lowest TA%. The observation that the TA% values in shoots are always higher than the values for the respective PAs in roots goes in the same direction (Hartmann 2010, personal communication). Secondly, specific (re-)oxidation of the tertiary PAs might explain the pattern. The reduction of PA N-oxides in the plant is an unspecific, chemical process induced by the presence of endogenous reducing compounds and (traces of) transition metal salts. Meanwhile, there is a, biochemically based, process operating to re-oxidize the reduced tertiary amines for PA transport. Enzyme(s) that may be involved seem to work well for seneconine-like and erucifoline-like PAs but work less well for jacobine-like PAs. Possibly, the substrate specific enzyme is affected when alterations at positions 15 and 20 (addition of O, H2O, HCl, etc.) to work well for seneconine-like and erucifoline-like PAs but work less well for jacobine-like PAs. Possibly, the second hypothesis could explain the TA% difference among the PAs and the genotypes. Furthermore, it may get more support from a biochemical point of view, since the plant has to use an enzyme to produce the back-bone seneconine N-oxide at the beginning of the PA pathway. Seneconine N-oxygenase (SNO) was isolated (from the larvae of special-ist insect *Tyria jacobaeae*, less relevant for plants) and *Crotalaria scassellatii* seedlings. The enzymes were tested with different PAs as substrates and showed that they specifically oxidized tertiary PAs (Lindigkeit et al. 1997; Chang and Hartmann 1998). These enzymes might be highly preserved and similar in the various PA containing plants. A very interesting follow-up of this study could be the identification, isolation and characterization of this putative N-oxidation enzyme(s) and exploration of genetic variation concerning these enzymes. It would also be interesting to see if the TA% can be influenced by external factors, like a high metal content in the soil, or by application of reducing compounds to the leaves.

**Table 2.** The concentration of tertiary and N-oxide PA, TA% and the genotype effect on the TA% in two parental, two F1 and 102 F2 genotypes from a cross between *J. vulgaris* and *J. aquatica.*

<table>
<thead>
<tr>
<th>Plant Part</th>
<th>Structural group</th>
<th>Pyrrolizidine alkaloid</th>
<th>Code</th>
<th>Concentration (mg/g dry wt)</th>
<th>TA%a x2 b</th>
<th>Pc</th>
</tr>
</thead>
</table>

Our results showed that jacobine-like PAs had a higher TA% than the other PAs. This coincides with the role of jacobine-like PAs as important defence compounds. Several studies showed that jacobine and jaco-nine were especially feeding deterrent for generalist insect herbivores (Macel et al. 2005; Leiss et al. 2009), while some specialists, preferred plants containing high concentrations of jacobine (Macel and Klinkhamer 2010). From an evolutionary and ecological point view, it represents a next step in the arm-race between plants and herbivores as a number of studies show that tertiary amines are more toxic than their respec-tive N-oxides (Dreyer et al. 1985; van Dam et al. 1995; Macel et al. 2005). Further research on the chemistry and biology of PA N-oxides and tertiary PAs and their influence on generalist and specialist insects are required to better understand the ecological significance of these highly interesting compounds.
TA% was genotype-dependent. This means that the variation found for relative tertiary amine content was not caused by an intrinsic structural instability of the PA molecule or by chemical attack. Also, it was not observed that naturally occurring agents in plant material caused reduction or oxidation during our extraction method. Plant material of different species did not induce any transformation of PAs from one form into the other. From our results we can conclude that the high concentrations in tertiary form for jacobine-like PAs are not due to instability or higher sensitivity for reducing agents in the extraction and analytical processes, but likely are the result of a change induced by (bio)chemical processes in the plant itself. We cannot exclude that a minor amount of reduction occurs during harvesting and the freeze-drying, but it seemed to affect all PA N-oxides to the same extent. We did find that in the Jacobine-chemotype plants a much higher level of tertiary PA present compared to the Erucifoline-chemotypes. By crossing J. vulgaris Jacobine-chemotype with the closely related J. aquatica, which lacks jacobine, and measuring PA N-oxide determination, we showed that the occurrence of tertiary PAs is not an artifact of the freeze drying, extraction or detection method. The three main PA N-oxides during our extraction method. The main component of this variation in PA N-oxides is the jacobine-chemotype plants a much higher level of tertiary PA present compared to the Erucifoline-chemotypes. By crossing J. vulgaris Jacobine-chemotype with the closely related J. aquatica, which lacks jacobine, and measuring PA N-oxide determination, we showed that the occurrence of tertiary PAs is not an artifact of the freeze drying, extraction or detection method. We showed that the occurrence of tertiary PAs is not an artifact of the freeze drying, extraction or detection method. Also it was not observed that naturally occurring agents in plant material caused reduction or oxidation of the added PAs during our extraction method. Plant material of different species did not induce any transformation of PAs from one form into the other. From our results we can conclude that the high percentages in tertiary form for jacobine-like PAs are not due to instability or higher sensitivity for reducing agents in the extraction and analytical processes, but likely are the result of a change induced by (bio)chemical processes in the plant itself. We cannot exclude that a minor amount of reduction occurs during harvesting and the freeze-drying, but it seemed to affect all PA N-oxides to the same extent. We did find that in the Jacobine-chemotype plants a much higher level of tertiary PA present compared to the Erucifoline-chemotypes. By crossing J. vulgaris Jacobine-chemotype with the closely related J. aquatica, which lacks jacobine, and measuring PA N-oxide determination, we showed that the TA% was genotype-dependent. This means that the variation found for relative tertiary amine content has a genetic base, since the environmental conditions of the plants during growth and analysis were kept equal for all plants.

Acknowledgements

We are grateful to Kelly Stolk, Anniek de Vreede, Cilke Hermans, Karin van der Veen-van Wijk, Ciska Raaijmakers and Henk Nell for their technical assistance. We thank Prof. Dr. Thomas Hartmann for his helpful comments on the manuscript and the hypothesis on slow unspecific reduction of PA N-oxides. We thank the China Scholarship Council (CSC) of the Ministry of Education for financial support.

References

Hartmann T, Toppel G (1987) Seneconine N-oxide, the primary product of pyrrolizidine alkaloid biosynthesis in root cultures of Senecio vulgaris. Phytochemistry 26:1639-1643

Chapter 4 | The Genotype Dependent Presence of Pyrrolizidine Alkaloids as Tertiary Amine in Jacobaea vulgaris

Chapter 4 | The Genotype Dependent Presence of Pyrrolizidine Alkaloids as Tertiary Amine in Jacobaea vulgaris

**Supplementary data**

**Figure S1.** Reduction of PA N-oxides after incubation (1h, n = 2) in 2% formic acid solution with sodium metabisulfite (Na$_2$S$_2$O$_5$) in five different concentrations (0.01, 0.03, 0.1, 0.3, 1 mM). sn = senecionine; jb = jacobine; er = erucifoline. Error bars: ±1SD. The tertiary amine formed is the relative amount of tertiary PA present in a sample, which was calculated as the measured concentration of tertiary PA divided by the sum of the concentration of tertiary PA and the corresponding PA N-oxide.

**Figure S2.** Oxidation of PA tertiary amines after incubation (24h, n = 2) in 2% formic acid solution with hydrogen peroxide (H$_2$O$_2$) in 5 different concentrations (0.01, 0.03, 0.1, 0.3, 1 M). snox = senecionine N-oxide, jbox = jacobine N-oxide, erox = erucifoline N-oxide. Error bars: ±1SD. The N-oxide formed is the relative amount of N-oxide present in the sample which was calculated as the measured concentration of tertiary PA divided by the sum of the concentration of tertiary PA and the corresponding PA N-oxide.

![Image of Figure S1](image1)

![Image of Figure S2](image2)
Figure S3. The correlations between genotype mean TA% of the PAs. Two parental, two F1 and 102 F2 genotypes were used. Numbers in the cells are the correlation coefficients. The background color of the cells is related to the number: black (>0.75); dark grey (0.50~0.75); light grey (0.25 ~ 0.50); white (< 0.20 and (or) p-value is not significant). ns: not significant, * p<0.05, **p<0.01, ***p<0.001. In the cells along the diagonal line are the codes for PAs. Sn = senecionine; ir = integerrimine; rt = retrorsine; sp = seneciphylline; acsp = acetylseneciphylline; jb = jacobine; jl = jacoline; jz = jacozine; er = erucifoline; acer = acetylerucifoline. Correlation coefficients above the diagonal line are for shoots, below the diagonal for roots.

Figure 4. Possible biosynthetic pathways of diversification of PAs in the Jacobaea section. With the exception of senecivernine, senecionine is the common precursor of all other PAs. Since the substrate specificity of the enzymes involved is not known, two scenarios are illustrated: (a) = senkirkine is assumed as common precursor of all otonecine derivatives; (b) = the otonecine derivatives originate independently from the respective retronecine derivatives. Two main reactions exist: conversion of retronecine to otonecine (reaction 1) and site-specific epoxide formation (reaction 2). Further structural diversification requires six simple one-step-reactions marked by letters a–f: a = Z/E-isomerization at C20; b = 13, 19-dehydrogenation; c = site-specific hydroxylations; d = hydrolysis of 15, 20-epoxide; e = chlorolysis of 15, 20-epoxide; f = site-specific O-acetylations. (Adapted from Pelser et al., 2005)

Figure 5. The structure of the major PAs detected in Jacobaea plants and which occur in both tertiary amine and N-oxide form. Only the structures of the free base form are shown.