Are Isoursenol and γ-Amyrin Rare Triterpenes in Nature or Simply Overlooked by Usual Analytical Methods?

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Supporting Information

ABSTRACT: Among pentacyclic triterpenes commonly found in plants, γ-amyrin and isoursenol are seldom reported and considered rare in nature. It was hypothesized that these triterpenes are instead routinely overlooked due to inadequate spectral characterization. γ-Amyrin was prepared by HCOOH isomerization of α-amyrin, and isoursenol was isolated from products of a heterologously expressed oxidosqualene cyclase. With precise NMR and GC-MS data, a metabolomics strategy was used to identify isoursenol and γ-amyrin in a wide range of plants.

Triterpenes and their triterpenoid derivatives are widely distributed in plants as specialized metabolites of medicinal, agricultural, and ecological importance. More than 100 triterpene skeletons are constructed by oxidosqualene cyclases (OSC). Much of this structural diversity arises in plants from OSCs that make a mixture of oleanane (1–7) and ursane (8–18) derivatives. These pentacyclic triterpenes are generally well documented (Graphical Abstract†), with detailed spectral characterization (Figure 1).

Two notable exceptions are γ-amyrin (urs-13(18)-en-3β-ol, 13) and isoursenol (15). Prior to 1970, 13 and 15 were isolated and characterized by melting point and optical rotation but not by NMR or MS. Only limited spectral data for identifying 13 and 15 were reported in later references, which include a recent erroneous structure elucidation of 13 (see Figure S1). Largely due to this lack of data, we and others have overlooked 15 in biological samples.

We had often anticipated the presence of 13 and 15 in metabolomics studies and as OSC products but had no NMR or GC-MS guidance to identify them in triterpene mixtures. Now serendipity has led us to 13 and 15. Here we describe their preparation, spectral characterization, and broad distribution among higher plants.

Recently we encountered a GC-MS study of 13 in Stefan Bauer’s 2002 Ph.D. dissertation. Bauer tentatively proposed that tomato wax contains 13 on the basis of MS fragmentation and GC retention time patterns. This extensive discussion of 13 was not indexed by Chemical Abstracts, nor was 13 mentioned in Bauer’s subsequent papers on tomato wax lipids.

We repeated Bauer’s extraction and purification of tomato wax triterpenes and found a chromatographic fraction that showed a small GC-MS peak corresponding to Bauer’s data for 13 (Figure 2A). Unable to locate any useful NMR data for 13, we estimated 1H and 13C NMR chemical shifts from quantum mechanical calculations. Nine 1H–13C signal pairs from an HSQC spectrum of crude hexane extracts of tomato wax matched well with the predicted values (Table S12), which proved to be more accurate than all experimental NMR data ever reported for 13. We attempted to obtain enough material for 2D NMR characterization by repeatedly purifying the silica-gel fraction by reversed-phase HPLC. However, the near coelution of δ-amyrin (2) and 13 by HPLC gave at best an ~20:1 ratio of 2:13 (Figure 2B). Considering Bauer’s similarly futile efforts, we discontinued our efforts to isolate 13 from tomato wax.

Seeking an alternative route to 13, we envisioned synthesis from α-amyrin (14) via the Δ11,13(18) diene or acid isomerization. Given the high cost of 14, we explored its isomerization to 13 on a low milligram scale. Treatment of 14 with triflic acid (50 mM in CDCl3 at 23 °C) gave only 3% 13 in a 63:17:7:6:3:3 mixture of 14, 2, 18-epi-β-amyрин (20), canarenes (21), unidentified triterpenes, 1, and 13 (Figure S4). As in other work, our TfOH isomerizations equilibrated most of the triterpenes in Figure 3A. CF3COOH gave at best a 50:30:10:4 mixture of 14, canarenes, triterpene epimers, and 13. No reaction occurred in AcOH at 90–95 °C for 20 h (Figure S5).

We then tried isomerization in formic acid. Relative to acetic acid, HCOOH is more acidic by 1 pKₐ unit, has a 10-fold higher dielectric constant, and can add reversibly to olefinic bonds. In a series of HCOOH isomerizations of 14 ranging from 170 h at 40 °C to 4 h at 93 °C (Figure S6), the product consistently contained ~4% 13 and ~2% total 1–3 (from the 2% impurity of 3 in 14). The amount of recovered 14 dropped with rising temperature from 93% to 40% due to formation of canarenes (21) via dehydration to the C3 cation, A-ring contraction, and backbone rearrangement. The results indicate that HCOOH isomerization of 14 is limited to the ursene energy trough (magenta bars in Figure 3A), with 13 as the only isomer formed.

Based on these exploratory findings, 14 (20 mg) was isomerized in supersaturated HCOOH solution at 65 °C to a 94:6 mother-liquor mixture of 14 and 13 as formate esters 14f.
and 13f. Partial HCOOH evaporation enriched the mother liquor to a 3:1 ratio of 14f:13f, and precipitated 14f was recycled for further isomerization. After saponification, preparative HPLC removed 14 and most other impurities, and analytical HPLC mostly removed 2 to give ~1 mg of 13 in 93% purity (Figures 2C and S7F). NMR data at the precision required for mixture analysis are given for 13 and acetate 13a (Tables 1, S7, S8, S10, S12).
were characterized by GC-MS and NMR (Tables 1 and S9–S12), which matched known $^{13}$C chemical shifts and EI-MS of OSC byproduct. Our less frequent detection of the number of plants proven to make $^{13}$C was not accompanied by epimerization.

Like $\gamma$-amyrin, isoursenol (15) is an established substance. Its structure was determined in 1961–65 by synthesis from $^{14}$, $^{15}$a, $^{15}$b acidic rearrangement back to $^{14}$, $^{15}$a and a photooxidative reverse rearrangement. $^{60}$ In 1966, 15 was isolated from tree leaves of an asterid and rigorously identified by isomerization to $^{14}$ and careful comparison with reported $^{6a,c}$ values for mp and $[\alpha]_D$. More recent references cite this early work but provide little useful spectral data. $^{17}$

While investigating the enzymatic products of an Arabidopsis thaliana OSC (PEN6), we observed in a triterpene mixture a downfield olefinic NMR signal with the distinctive coupling pattern of taraxerol (dd, 8 and 3 Hz) but at a different chemical shift. Sensing that this unknown was a taraxerol analogue, we obtained quantum mechanical estimates of NMR chemical shifts. Sensing that this unknown was a taraxerol analogue, we obtained quantum mechanical estimates of NMR chemical shifts. Sensing that this unknown was a taraxerol analogue, we obtained quantum mechanical estimates of NMR chemical shifts.

After chromatographic purification, 15 and its acetate 15a were characterized by GC-MS and NMR (Tables 1 and S9–S12), which matched known $^{13}$C chemical shifts and EI-MS fragmentation for 15a. We also reproduced the reported $^{15a,c}$ acid-catalyzed isomerization of 15 to 14 by using dilute TIOH. As in our $\gamma$-amyrin experience, a lack of useful spectral data had caused 15 to be overlooked in tomato wax, $^{9}$ PEN6 products, $^{10}$ and our own plant analyses. $^{15}$

With precise NMR and GC-MS data now available for 13 and 15, we looked for their presence in a variety of plants by using established methods for analyzing complex mixtures. $^{16a}$ First we revisited our existing spectra and found 13 also in PEN6 products and 15 also in tomato wax. The strongest evidence was from analysis of HSQC results (Figures 4 and S8 and Tables S6 and S15).

Among ~25 additional plants we studied, $^{18}$ 15 was found in 18 plants and 13 was in 4 of these plants (Figure 5). Our results raise the number of plants proven to make 15 from 3 to 23 and for 13 from 0 to 6. Figure 5 illustrates the broad taxonomic distribution of 15 and 13. Most plants containing 14 also make 15 as a minor OSC byproduct. Our less frequent detection of 13 is attributable to steric hindrance of cation deprotonation (Figure S47) and to a lack of the spectral markers that allowed detection of 15 at trace levels.

We identified 13, 15, and other triterpenes in complex mixtures by comparing observed HSQC chemical shifts, GC retention times, and MS fragmentation against spectral databases. An Excel macro searched thousands of HSQC peaks against the precise data in Table 1 to give an objective appraisal of evidence for 13 and 15.

Midpathway OSC byproducts 4–6 and 15–17 normally represent <1% of total triterpenes. However, kale contained nearly 1 mg/kg of 15 (3:2:1 ratio of 14, 3, and 15), suggesting a

### Table 1. $^1$H and $^{13}$C NMR Data for Methyl Signals of 13 and 15 $^{14}$

<table>
<thead>
<tr>
<th>atom</th>
<th>$\delta$ _C</th>
<th>$\delta$ _H mult (J)</th>
<th>$\delta$ _C</th>
<th>$\delta$ _H mult (J)</th>
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<tr>
<td>23</td>
<td>28.07</td>
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<td>28.00</td>
<td>0.975, s</td>
</tr>
<tr>
<td>24</td>
<td>15.48</td>
<td>0.771, s</td>
<td>15.47</td>
<td>0.799, s</td>
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<tr>
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<td>16.33</td>
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<td>15.20</td>
<td>0.915, s</td>
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<tr>
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<tr>
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</tr>
<tr>
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<td>1.102, s</td>
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<td>1.086, d (7.6)</td>
<td>27.48</td>
<td>1.021, d (6.9)</td>
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<tr>
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<td>0.843, d (7.0)</td>
<td>22.46</td>
<td>0.977, d (6.6)</td>
</tr>
</tbody>
</table>

$^{14}$Conditions: ~2 mM in CDCl$_3$, 25 °C, 800 MHz; $^{13}$C chemical shifts ($\pm$0.01 ppm) were referenced to CDCl$_3$ (77.00 ppm); $^1$H chemical shifts ($\pm$0.001 ppm) were referenced to SiMe$_4$; coarse $^1$H shift. Sensing that this unknown was a taraxerol analogue, we obtained quantum mechanical estimates of NMR chemical shifts. Sensing that this unknown was a taraxerol analogue, we obtained quantum mechanical estimates of NMR chemical shifts. Sensing that this unknown was a taraxerol analogue, we obtained quantum mechanical estimates of NMR chemical shifts.

Figure 4. Detection of 13 and 15 in HSQC spectra. (A) Upfield methyl region of crude hexane extracts of tomato wax. (B and C) Expansions showing peaks for 13 and 15. (D and E) Similar HSQC expansions show 13 and 15 in the triterpene fraction of PEN6 products.

Figure 5. Observation of 13 and 15 in diverse plant species. Relative amounts of 13 and 15 are indicated by the symbol sizes; symbols in boxes denote previous isolations of 15. In this simplified AGP III phylogeny, branch lengths have no significance. Figure S43 shows a more detailed phylogeny, with genus and species names.
possible defense function in cruciferous vegetables. We detected 13 and 15 in many other common plant foods. Some traditional diets might contain up to 1 mg/day of 13 and 15 among an abundance of biologically active triterpenoids having medicinal and health benefits.

Regarding the title question, we have shown that 13 and 15 are widespread in nature but routinely overlooked by usual analytical methods. How many more secondary metabolites are similarly overlooked in plants and microorganisms? A metabolomics approach can reveal a vast complexity of hydrophobic substances. Plant metabolic profiling, still in its infancy, might benefit from our GC-MS and HSQC strategy for mixture analysis,\(^9\) which can definitively identify and quantify numerous nonpolar metabolites at 1 µg levels.

**ASSOCIATED CONTENT**

**Supporting Information**

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.orglett.5b01851.

Experimental procedures, plant analyses, molecular modeling, GC-MS and NMR figures (PDF)

Excel macro to analyze HSQC data for the presence of specific compounds (ZIP)

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**Notes**

The authors declare no competing financial interest.

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