Yield and Quality Potential of Hop, *Humulus lupulus* L.[1,2]

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ABSTRACT

The USDA hop breeding and genetics project at Oregon State University has accumulated more than 600 diverse hop genotypes from many parts of the world during the past 50 years. The genetic potential of this germ plasm has barely been tapped, particularly with regard to traits of interest to growers or brewers. By using selected lines for breeding, we were able to: combine high cone yield and high α-acids content, modify the α- and β-acids content and proportions, combine high α-acids content with superior storage stability, create an array of lines with cohumulone content varying from below 20% to above 65% independently of α-acids content, select lines differing in oil content by a factor of about four, and significantly modify the composition of essential oils.

Key words: *α-Acids, β-Acids, Essential oils, Hop yield, Quality, Storage*

Hops are grown in many parts of the world, primarily to flavor fermented malt beverages. Most brewers agree that hop soft resins and particularly the α-acids have a desirable and measurable effect on beer taste. They disagree, however, on the value of certain hop oil constituents and on the origin and importance of the so-called "hoppy" aroma and flavor.

The USDA hop germ plasm collection at Corvallis, OR, contains female and male genotypes that differ significantly in agronomic and quality characteristics. This article illustrates the genetic yield and quality potential for hop improvement that could benefit both growers and brewers.

[1]Presented at the 48th Annual Meeting, Kansas City, MO, May 1982.
[2]Contribution of the U.S. Department of Agriculture, Agricultural Research Service in cooperation with the Agricultural Experiment Station, Oregon State University. Technical paper 6684.
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EXPERIMENTAL

About 250–500 female hop breeding lines and commercial varieties from five-hill experimental plots were machine-harvested each year using a Wolf type I-80 picker at the USDA experimental hop yard near Corvallis, OR. Green cone yield was measured to the nearest 50 g, and moisture content was calculated from a 100–200-g sample that was oven-dried for 20 hr at 85°C. Yields were calculated from experimental plots at a plant density of 1,912 plants per hectare (774 plants per acre), which is comparable to the most common American commercial practice. Cones were kiln-dried at 55°C overnight (about 12 hr), rehumidified to 9% moisture content, compressed into 500-g bales with a density of about 176–192 kg/m^3, which is similar to commercial American bales, and stored in a freezer at −20°C until analyzed by standard ASBC procedures. A 250-g subsample of the original sample was stored for six months in the dark at room temperature, reanalyzed, and evaluated for storage stability as described by Likens et al (4).

Lupulin glands of male hops were collected as described earlier (5) and analyzed by standard ASBC procedures adapted for analysis of isolated glands (5).

RESULTS AND DISCUSSION

Hop growers are primarily interested in cone yield per unit area. Yield, however, depends on a number of factors that directly or indirectly influence production. Vigor, side-arm length, branching pattern, number of cones per plant, and cone size and weight have a direct effect on cone yield. Disease resistance, insect resistance, and pickability have direct and indirect effects on hop production. Maturity, tolerance to mechanization, and reduction of labor input affect the grower's net profit and his ability to remain competitive.

The hop processor and the brewer are interested in other traits. Content of α-and β-acids storage stability of the resins, α- and β-acids composition, and essential oil content and composition

affect the quality of his product and its acceptance in the marketplace.

Yield

High cone yields and high α-acids content are not mutually exclusive. The correlation coefficient between these two traits in machine-harvested samples during the four-year period 1978–1981 at Corvallis ranged from statistically nonsignificant to low but significantly positive (Table I). However, many hop genotypes with inherently low α-acids content are included in this group.

When hop genotypes with very low cone production and low α-acids content were excluded, the correlation between yield and α-acids content was not significant in three out of four years, and only marginally significant in 1979 (Table I).

The lack of a significant relationship between yield and α-acids content became particularly evident in recent years as more high-α selections from our breeding program were evaluated in yield tests. New high-α varieties and breeding lines developed in the United States in recent years (2,10,12) clearly demonstrate that high α-acids content and high yield potential are independent genetic traits that can be combined in a single genotype.

The new high-α varieties Eroica, Galena, and Nugget (USDA 21193) compared to a Bullion control for four years at Corvallis (Table II) clearly showed that both yield and α-acids content can be increased concurrently, resulting in substantially higher α-acids production per unit area than is possible with older high-α varieties.

There is substantial room for improvement of cone yields. Hop yields in the United States from 1979 to 1981 averaged 2,093 kg/ha (14). The best year, 1980, saw a near record hop production averaging 2,282 kg/ha. Yields ranged from 2,684 kg/ha for the varieties Bullion and Brewer's Gold to 1,794 kg/ha for Fuggle (14).

Experimental yields in excess of 3,810 kg/ha have been obtained occasionally with selected breeding lines grown in small field plots near Corvallis. The combination of such high yields with the highest α-acids content in our breeding material could result in α-acids production of over 672 kg/ha, an unrealistic figure at present. However, the new hop variety Eroica averaged 3,700 kg cones per hectare in a 2.4-ha Idaho commercial field in 1980, with an α-acids content ranging from 13.1 to 13.5%, equivalent to a production of 490 kg α-acids per hectare (11).

These results indicate that a combination of high cone yields and high α-acids content could result in a doubling of the present α-acids production per unit land area.

α- and β-Acids Content

Many brewers consider α-acids to be of major importance for beer flavoring. α-Acids content in the present USDA hop germ plasm collection ranges from zero to nearly 18% on a dry weight basis for females analyzed on a cone basis, and from zero to about 63% in the lupulin glands of males (Table III). The highest α-acids content in our collection during the past four years occurred in the progeny of crosses made since 1970: USDA 21193 recently released and named Nugget, (average 14.3% α, range 13.3–17.0%; USDA 21253 (average 16.5% α, range 15.5–17.4%); USDA 21251 (average 16.8% α, range 15.4–17.7%); and USDA 21255 (average 14.1% α, range 13.1–14.9%).

The range of β-acids in the USDA hop collection is smaller than that of α-acids for females and larger for males (Table III). No hop genotype with zero β-acids content has yet been found. However, selection for low β-acids content without adverse effects on α-acids content has been promising.

Our breeding efforts, in addition to increasing α-acids content, have also focused on increasing the α ratio, a measure of the ratio α/β, by reducing β-acids content (Table IV). Comet, a commercial hop variety released in 1974 (16), had 10.2% α-acids and 5.8% β-acids with an α ratio of 64 in a 1981 test. Its offspring, USDA 21055, from a cross involving a male containing genes for high α-acids content inherited from both Brewer's Gold and the native American male USDA 60026M, in the same test averaged over 14% α- and 4.6% β-acids content with an α ratio of 76. USDA 21055, when crossed to the males 21109M and 21070M, respectively, which both have Brewer's Gold and European germ plasm in their pedigrees, gave rise to USDA 21290 and 21298. The latter both have a very high α ratio, partly due to reduced β-acids content (Table IV). Such hops may be particularly attractive to hop

TABLE I
Correlation Between Cone Yield and α-Acids Content of Hops at Corvallis During 1978-1981

	Nonselected		Selected[b]	
Year	No. of Samples	r-Value[a]	No. of Samples	r-Value[a]
1978	151	0.024 NS	37	−0.275 NS
1979	294	0.252 **	64	−0.271 *
1980	308	0.268 **	101	0.062 NS
1981	463	0.071 NS	124	0.021 NS

[a] * = Significant at $P = 0.05$. ** = $P = 0.01$. NS = Not significant.
[b] α ≥10%, Yield ≥ 1,120 kg/ha. Multiply kg/ha by 0.892 to calculate lb/acre.

TABLE II
Cone Yield and Quality of New High-α American Hop Varieties at Corvallis During 1978-1981

	Yield (kg/ha)[a]		α-Acids (%)		β-Acids (%)	
Variety	Mean	Range	Mean	Range	Mean	Range
Eroica	1,802	1,569–2,421	11.5	9.3–12.5	4.6	4.2–5.4
Galena	1,407	919–2,298	11.7	11.0–12.3	7.8	7.3–8.4
Nugget	2,348	1,100–3,806	13.8	11.0–15.7	4.8	4.6–5.4
Bullion (control)	2,067	1,963–2,467	9.9	8.8–10.4	5.2	4.7–6.1

[a] Multiply by 0.892 to calculate lb/acre.

TABLE III
Range of Yield and Quality Traits in the USDA Hop Germ Plasm Collection at Corvallis During 1978-1981

Trait	Females (bale samples)	Males (isolated resin glands)
Yield (kg/ha)	72–3811	···
α-Acids (%)	0.0–17.7	0.0–62.9
β-Acids (%)	1.0–11.3	2.9–76.8
α- + β-Acids (%)	4.1–24.6	4.9–90.2
α-Ratio[a]	0.0–83	0.0–81
Cohumulone (%)	13–66	12–62
α Remaining after six months at room temperature (%)	17–92	30–99
Essential oils (ml/100 g)	0.1–5.1	···
Ratio of humulene to caryophyllene	0.5–4.0	0.2–7.0

[a] $\frac{\alpha}{\alpha+\beta}$ expressed as percent of soft resin content.

TABLE IV
Genetic Modification of the α Ratio of Hops in Test Crosses

Genotype	Parentage	α-Acids (%)	β-Acids (%)	α Ratio[a]
Comet	···	10.2	5.8	64
USDA 21055	Comet, Br. Gold, 60026M	14.9	4.6	76
USDA 21290	21055; 21109M	9.2	1.2	88
USDA 21298	21055; 21070M	15.2	2.8	84

[a] $\frac{\alpha}{\alpha+\beta}$ expressed as percent of soft resin content.

extractors who are primarily interested in α-acids content. This gradual improvement since 1970 came as a result of three cycles of crossing and selection, indicating the presence of both major genes for α-acids content and minor modifying genes that affect β-acids content.

Other high-α selections with a consistently high α ratio are USDA 21248, 21250, and 21254. All have α ratios above 75, equivalent to a ratio of α-/β-acids content in excess of 4 and a high α-acids content ranging from 11 to more than 15%.

The soft resin content of hop lupulin glands expressed as the sum of α-plus β-acids averages about 73% of the gland content (5). Extensive lupulin analyses during the past eight years have shown that male lines with 80% soft resins in their glands are not unusual. The current maximum soft resin content in the USDA hop germ plasm collection is nearly 25% of cone weight for females and 90% of gland content for males (Table III).

α-Acids Composition

Although it has been known for 30 years that α-acids are composed of three major and two minor components (7,8), relatively little attention has been paid to α-acids composition. The three major isomers, humulone, cohumulone, and adhumulone, account for most of the α-acids in hops (13,15). Hops with high humulone and low cohumulone content, such as certain European aroma hops, appear to have a beneficial effect on beer foam stability (1,9) and also impart a pleasant bitterness to beer (9).

The cohumulone content of the breeding and germ plasm material in the USDA hop collection over the past four years has ranged from 13 to 66% for females and from 12 to 62% for males (Table III). Bullion, Brewer's Gold, and Cluster consistently have a relatively high cohumulone content (about 35–40%). Indigenous European hops and many older European aroma hop varieties have low cohumulone in their α-acids fraction, frequently in the range of 18–24%. Such hops, therefore, have largely humulone in their α-acids fraction, since adhumulone is generally low and varies relatively little among hop varieties (13,15).

A cross between the experimental hop USDA 65009 and the male 63015M made in 1970 first demonstrated the ease of modifying cohumulone content by genetic means. USDA 65009 has an average cohumulone content of about 40%. With a relatively constant adhumulone content of about 15%, this hop averages about 45% humulone in its α-acids fraction. The seedling progeny of the cross showed a surprising range of cohumulone content in females, from 22% for selection 7005-194 (now USDA 21193, named Nugget) to 85% for selection 7005-14, surpassing parental values at both ends of the spectrum.

Another 1970 cross involved USDA 65009 and the male USDA 64035M. The latter has an even lower cohumulone content than 63015M, averaging about 18–20% over a five-year period. The cohumulone content of the female progeny from this cross ranged from 16% (selection 7006-398) to a high of 37% (selection 7006-95).

Male offspring of both crosses showed a somewhat narrower spread in cohumulone content, ranging from lows of 15 and 18% (selections 7006-94M and 7005-118M, respectively) to a high of 30% (selection 7006-179M). Before high performance liquid chromatography instruments were available, only a small fraction of the progeny was analyzed for α-acids composition. Therefore, the true range of cohumulone content from these crosses has probably not been established.

Selections from the above two crosses also showed a wide range in α-acids content, from 13.5 and 15.2% for selections 7006-398 and 7005-111, respectively, to lows of 4.2 and 4.5% for selections 7005-238 and 7006-456, respectively. Some high-α-acid selections, such as Nugget and 7006-398, also had low cohumulone content. This disproves previous assumptions that high α-acids content and low cohumulone content cannot be combined in a single plant.

Storage Stability

This trait may be indicative of natural resistance to oxidation when hops are stored at ambient temperatures. Hops with high α-acids content were thought to be poor "keepers," perhaps because the two most widely known high-α-acid hops, Bullion and Brewer's Gold, have poor storage stability. The results of a test cross made in 1970 do not support the widely accepted notion that hops with high α-acids content are poor "keepers."

The female parent USDA 65009, mentioned previously, has poor storage stability, whereas the male USDA 63015M has excellent storage stability. Nugget, which originated from the test cross, retained 67–83% of its original 15% α-acids content after six months at room temperature. Bullion retained only about 35–40% under identical conditions.

The storage stability of samples from USDA hop genotypes stored six months at room temperature ranged from 17 to 92% α-acids retention for females and from 30 to 99% α-acids retention for males (Table III). The controls Bullion and Brewer's Gold retained 35–40% and Cluster 70–80% of the original α-acids content under identical conditions.

Essential Oil Content and Composition

High essential oil content in hops has sometimes been considered an indicator of poor storage stability. However, there is little evidence to support this assumption. The essential oil content of female hops in the USDA collection has ranged from 0.10 ml/100 g to 5.1 ml/100 g. Cluster hops, considered low in essential oils, generally average from 0.7 to 1.1 ml/100 g, whereas Bullion averages about 2.5 ml/100 g. Most other commercial hop varieties fall between these two extremes.

The essential oil composition may be of greater interest to brewers than the total oil content. Myrcene frequently accounts for over half of the total oil fraction. It polymerizes quickly and disappears as hops age (3). Humulene appears to be a desirable oil component. It is thought to be at least partly responsible for the pleasant "hoppy" aroma (6).

Essential oils of many European aroma hops preferred by some brewers have a high humulene (H), a low caryophyllene (C) content, and an H/C ratio in excess of 3. This relationship may be useful for selecting new potential aroma hop varieties.

The genetic potential of hops for humulene content expressed by the H/C ratio ranges from 0.5 to 4.0 for females and from 0.2 to 7.0 for males in the USDA hop germ plasm collection (Table III). This ratio can be modified by breeding, as shown by a test cross between Yakima Cluster, a low H/C-ratio hop, and the European male 64037M, which has a high H/C ratio (about 3.4). Selection 6903-107 from this cross has a balanced α- and β-acids content and an H/C ratio in excess of 4.0. This high-yielding hop is now scheduled for brewing trials to establish its aroma potential.

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[Received January 10, 1983]