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Opportunities to Breed Diverse Sweetpotato Varieties for California Organic Production

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Abstract: Sweetpotatoes are a major crop in California, ranking sixth in value among organic commodities in the state. In recent years, there has been growing consumer interest in diverse specialty varieties, particularly purple types and those associated with Asian American and Pacific Islander (AAPI) communities, some of which are currently imported into the state. In this study, we screened 45 diverse sweetpotato varieties and breeding lines under California organic conditions in a preliminary characterization of their agronomic performance. We then conducted culinary evaluations with a tasting panel of students primarily identifying as Asian/Asian American to determine the preference for each type in terms of flavor and culinary appeal. Our results indicated that major tradeoffs exist among existing germplasm, with no variety or line excelling across all agronomic and culinary traits. These results suggest that sweetpotato breeding could be an effective mechanism to combine superior agronomic traits of major commercial classes with the high culinary quality of diverse materials that are not adapted to California organic production. These results provide a strong justification for the value of sweetpotato breeding to ultimately promote a more profitable, sustainable, and just food system in the region.

Keywords: sweetpotato; *Ipomoea batatas*; organic; crop biodiversity; Asian; Pacific Islander; AAPI; breeding; culinary; agronomic

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1. Introduction

Sweetpotato (*Ipomoea batatas* (L.) Lam. var. *batatas*) is a major crop for the California organic sector, with a sales value of $74,000,000 per year, ranked sixth among organic commodities in the state [1]. California is the leading producer of organic sweetpotatoes in the US and is ranked second in terms of total annual production [2]. On average, organic sweetpotato production leads to lower yields but higher selling prices for growers. Overall, organic production has a higher probability of having positive net returns for growers [3]. California is particularly well suited for organic production since the dry summer conditions are not conducive to the accumulation of various pests and pathogens. Sweetpotato production in California has experienced major growth in recent years, with a five-fold increase in harvested tonnes between 1994 and 2019 [4]. Nevertheless, no sweetpotato breeding program is currently based in the state. Market growth has been particularly rapid in certain diverse types, such as those with purple root flesh, skin, or both, and these are particularly popular among Asian American and Pacific Islander (AAPI) communities in North America [5]. Purple root colors in sweetpotato are the result in ectopic activation of MYB family transcription factors [6,7], leading to activation of anthocyanin and anthocyanidin biosynthesis pathways and the accumulation of these compounds [8,9]. Commercial breeding programs in the Southeastern United States have released numerous varieties with improved yields [10,11], root size and shape characteristics [12,13], and other beneficial qualities [14], demonstrating that these traits are heritable and amenable to breeding.

Asian American communities have long contributed to diversifying California agriculture and cuisine, but sociopolitical challenges, including exclusionary land and citizenship laws, low working wages, and language barriers limiting access to resources, still impact them today [15–17]. Very limited public investment has gone towards understanding their agricultural knowledge, history, or needs. Similarly, there has been minimal public investment in breeding of crop varieties that will serve the needs of AAPI growers and consumers, thus limiting the communities' access to Asian diaspora crops that have been selected for adaptation to California growing conditions. Sweetpotatoes are a hexaploid species resulting from complex autopolyploidizations of *Ipomoea trifida* [18,19]. *Ipomoea batatas* is native to Central and South America, although its exact center of domestication has been disputed. Within the Americas, proposed centers of origin include the Yucatan peninsula [20], Central America [21], Peru [22], or multiple centers in parallel [18]. Additionally, recent genetic and ecogeographic evidence indicates that the wild species may have reached the central Pacific by means of ocean currents or seeds borne by birds before the arrival of humans in the Americas or Polynesia [19,23]. This scenario would have entailed at least one additional independent domestication in Polynesia. Sweetpotatoes reached Asia and the Pacific by three main routes: (1) the "kumara line", the original Polynesian sweetpotatoes; (2) the "camote line", spread by Spanish traders from Mexico to Manila; and (3) the "batatas" line, spread by the Portuguese from the Caribbean and South America across the Atlantic and Indian Oceans, reaching the Pacific from the west [24]. Genotyping of the National Plant Germplasm System sweetpotato collection [25] has shown that most modern Pacific Island accessions are related to types from Central America and the Caribbean. Accessions from East Asia are highly distinct from those of the Pacific, although they too cluster more closely with Central American, Caribbean, and North American materials than they do with South American types.

In the centuries since their introduction to Asia, sweetpotatoes have been an integral part of AAPI cuisine. Today, Asia leads production of sweetpotatoes globally with 62% of total tonnage, ahead of Africa (32%), the Americas (4%), or Oceania (1%) [26]. Being considered resilient, productive, and rich in nutrition and flavor, AAPI populations have enjoyed them in a variety of culinary uses and recipes. This community has developed multiple ways to use sweetpotatoes, from baking, grilling, frying, and boiling the crop to processing it to powder and distilled liquor.

The AAPI community in North America, however, has often lacked access to sweetpotatoes with the culinary qualities they favor, including colors, flavors, and textures. Demand for Asian sweetpotatoes, and particularly those with purple pigmentation, such as Okinawa Purple, All Purple, and Red Japanese types, has grown dramatically in recent years due to demographic factors and diversifying palates. These sweetpotatoes have unique culinary properties but may not be adapted to California climates and production systems; in some cases, they are imported from thousands of kilometers away. To date, little to no information exists on the agronomic performance or consumer quality of many of these diverse sweetpotato varieties in California, especially when grown under organic conditions, despite California's dominant role in organic production of the crop.

In this study, we have explored the variation present in diverse sweetpotato germplasm when grown in California organic conditions. We assembled a panel of sweetpotato types, including diverse purple materials of interest to the AAPI community in North America. We then evaluated these in terms of agricultural productivity and profitability, as well as consumer preference traits, such as flavor and cooked appearance, as judged by an evaluator panel of primarily Asian/Asian-American students. Our results highlight the possible value of cooperative breeding projects in California, with the goal of producing new sweetpotato varieties that combine the optimal productivity with desirable culinary quality for consumers.

2. Materials and Methods

2.1. Agronomic Trials

Field testing was conducted at three certified organic field sites in California's Central Valley in 2022, as well as on a single certified organic exploratory site in Yolo county in 2021. The 2022 field sites were located in Atwater (Merced county, Atwater loamy sand), Winters (Solano county, Yolo loam), and Davis (Yolo county, Reiff very fine sandy loam). Field sites were hosted by experienced sweetpotato growers and included small scale, <10 hectares sites in Solano and Yolo counties and a large-scale, >500 hectare operation in Merced county The Solano county field trial was conducted at Namu Farm, an AAPI-owned operation run with extensive community involvement, as part of the Second Generation Seeds network (https://www.secondgenerationseeds.com/ (accessed on 16 November 2023)). The Yolo county location was hosted by the UC Davis Student Farm, and the Merced county location was hosted by STS farms and represented a larger-scale commercial operation. For each 2022 field site, irrigation was provided by surface drip irrigation. Slips were approximately 0.25 m in length at transplanting and planted into single rows of eight plants per plot, with a spacing of 1.83 m of planted space per plot and 0.762 m between planted rows. Unplanted alleys of 1.22 m were left along beds between plots. Canopies completely filled all alleys and inter-row space, so calculations of yield per hectare were based on 2.32 m^2 of area per plot, including alleys. Only yield data for 2022 were used for further analysis due to herbivory and other factors early in 2021 (see Section 4 Discussion). Planting in 2022 was conducted in a partially replicated design with a total of 45 varieties and lines, including 12 controls grown across all three locations. The cultivars chosen for evaluation included all sweetpotato accessions of Asian or Pacific origin available through the UC Davis Foundation Plant Services program, as well as varieties sourced from the US National Plant Germplasm System, Southern Exposure Seed Exchange, coauthors S. Stoddard and D. LaBonte, and F1 hybrids derived from crosses made at UC Davis. Trials were harvested at 131, 133, and 134 days after planting in Solano County, Yolo County, and Merced County, respectively. Harvested storage roots were separated into three size categories: Medium (2.5 to 5 cm in diameter, 5 to 18 cm long, may be slightly misshapen), US No. 1 (5 to 9 cm in diameter, 7.6 to 23 cm long, well-shaped, free of defects), and Jumbo (exceeding the size range of the previous categories, free of disease [11]). Roots were then weighed by size category. Before harvest, thorough screening was conducted at the Davis location to identify any fruit or true botanical seeds that could be used for future breeding.

2.2. Culinary Evaluations

Nine types of sweetpotato from the agronomic trial were advanced for culinary quality evaluations. Many of the most popular AAPI sweetpotato types in North America are linked to Japan and Japanese culture (e.g., Red Japanese, Murasaki, and Okinawa Purple), although similar varieties and preparation techniques are also enjoyed by other AAPI cultures, such as the Korean-American community. To focus culinary evaluations specifically on this major Asian and Pacific Islander community and their culinary traditions, the evaluations were conducted in collaboration with the Japanese Language and Culture Club at UC Davis. Because no major processing or commercial market exists for the crop, the tasting panel was comprised of ordinary consumers with an interest in Japanese culture. Further, since no trainings would occur for typical consumers consuming AAPI sweetpotatoes in restaurants or at home, tasters were not given any preliminary training on what they "should" prefer since such training would likely bias their preferences. Sweetpotatoes were stored in cool conditions of approximately 15 °C for four months to emulate typical storage conditions before consumption. Culinary preparation was guided based on input from members of this group. For the evaluations, sweetpotatoes were cut into cubes of approximately 2 cm on each side, wrapped in foil, and baked at 220 °C for one hour. In total, 30 participants evaluated the set of nine varieties. Of the 27 individuals who self-reported ethnic information, 24 identified as Asian/Asian-American (89%), while 3 identified as white (11%). Varieties were evaluated based on flavor and cooked visual appearance. In both cases, they were subjectively rated on a 1 to 5 scale, with 1 being inferior and 5 being superior. Varieties were given numeric designators to mask the identity of each sample and reduce bias.

2.3. Statistical Analyses

Yield data were processed as an augmented design, with 12 checks across 3 locations, treated as blocks, yielding 22 degrees of freedom. The 12 varieties grown at all field sites were then used to conduct a two-way analysis of variance (ANOVA) to determine whether variety and location had significant effects on marketable yield. Similarly, one-way ANOVAs were conducted to identify significant patterns between variety and flavor or cooked visual appearance. For each trait with significant p values from ANOVA, Fisher's least significant difference (LSD) test was implemented using the agricolae package 1.3-5 [27] in R 4.2.2. [28] to identify where significant differences existed among varieties. The DAU.test function of the agricolae package was used to run analyses of variance and means separations based on the LSD method. Visualizations were made with base R, agricolae, and ggplot2 3.4.2 [29].

3. Results

3.1. Agronomic Traits

Considerable variation existed among varieties across a range of traits, including storage root shape, size class distribution, color, and marketable yield (Figure 1). Statistically significant differences in marketable yield existed between lines ($p < 0.01$; Figures 2 and 3 and Table 1) and trial locations ($p < 0.0001$, Supplementary Figures S1 and S2). Broad-sense heritability (H^2) for yield was relatively high with 61.5% of the variance in marketable yield explained by genotype, while location accounted for 18.6% of the variance. The orange-fleshed red yam-type commercial variety Diane ranked highest in yield overall, averaging 51,028 kg/ha. Other high-yielding varieties included O'Henry (43,444 kg/ha), Viola (40,726 kg/ha), Seon-Mi (40,001 kg/ha), Beauregard (39,775 kg/ha), and Murasaki (37,788 kg/ha), none of which differed from Diane (Table 1). In contrast, among the lowest yielding varieties was Okinawa Purple, which is commercially imported to California and yielded just 535 kg/ha. Several other introductions produced no marketable yield whatsoever, despite producing considerable biomass (Table 1).

The distribution of size categories also differed between varieties (Table 1 and Supplementary Figures S3 and S4). Among varieties replicated at all field sites, L-19-56-P had the highest proportion of roots in the most economically valuable No. 1 category, at 61% (Table 1). In contrast, L-19-53-P had only 31% of roots in the No. 1 category. Significant variation existed between non-replicated varieties. For example, no roots produced by the heirloom variety All Purple were large enough to be classed in the No. 1 or Jumbo size categories, and this differed from all the control genotypes.

Table 1. Summary data of all tested sweetpotato lines and varieties. Yield data (kg/ha) are presented with correction for augmented design as implemented by the DAU.test function of the agricolae R package. Significance groups for yield based on protected LSD test ($p = 0.05$). All field trials were conducted on certified organic farms.

Variety	Root Flesh Color	Root Skin Color	Proportion Medium	Proportion No. 1	Proportion Jumbo	Marketable Yield (kg/ha)	Yield Significance Groups
Diane	Orange	Red	0.33	0.45	0.22	51,028	a
O'Henry	White	Cream	0.27	0.58	0.15	43,444	ab

Table 1. *Cont.*

Variety	Root Flesh Color	Root Skin Color	Proportion Medium	Proportion No. 1	Proportion Jumbo	Marketable Yield (kg/ha)	Yield Significance Groups
Viola	Orange	Red	0.44	0.28	0.28	40,726	abc
Seon-Mi	White	Cream	0.09	0.35	0.56	40,001	abc
Beauregard	Orange	Orange	0.23	0.27	0.50	39,775	abc
Murasaki	White	Burgundy	0.17	0.39	0.44	37,788	abc
L-19-18	Orange	Red	0.25	0.49	0.26	36,601	abc
L-19-42	Orange	Orange	0.49	0.43	0.08	34,688	abc
L-19-15	Orange	Red	0.52	0.38	0.10	31,498	abc
Carolina Ruby	Orange	Red	0.33	0.37	0.30	29,191	bcd
Morado	White	Burgundy	0.27	0.51	0.22	27,149	bcde
L-19-56-P	Purple	Purple	0.26	0.61	0.13	27,138	bcde
L-14-11	Orange	Red	0.35	0.6	0.05	25,909	bcde
Covington	Orange	Orange	0.15	0.47	0.38	25,589	bcde
L-17-189	Orange	Red	0.52	0.48	0.00	24,572	bcde
L-15-39	White	Burgundy	0.40	0.49	0.11	21,520	cde
Red Japanese	White	Burgundy	0.26	0.44	0.30	21,077	cde
L-17-182	Orange	Red	0.49	0.49	0.02	20,468	cde
Vermillion	Orange	Red	0.29	0.51	0.20	19,106	cde
Hopi	Orange	Orange	0.80	0.2	0.00	18,109	cde
L-19-53-P	Purple	Purple	0.61	0.31	0.08	13,551	cde
Camote Morado	White	Burgundy	0.16	0.61	0.23	12,635	cde
Becca's Purple	Purple	Purple	0.43	0.57	0.00	11,913	cde
All Purple	Purple	Purple	1.00	0.00	0.00	11,037	cde
Dingess Purple	Purple	Purple	0.47	0.00	0.53	10,994	cde
F1 Bonita × Diane	Variable	Variable	0.23	0.16	0.61	9688	cde
Purple-01	White	Purple	0.37	0.63	0.00	9438	cde
Molokai Purple	Purple	Purple	0.12	0.88	0.00	9155	cde
Shore Gold	Orange	Orange	0.57	0.32	0.11	8360	cde
Waimanalo	White	Burgundy	0.14	0.86	0.00	8288	de
Yellow Sunflower	Light yellow	Orange	0.17	0.28	0.55	8239	de
Porto Rico USDA	Orange	Orange	0.56	0.00	0.44	7789	de
Nancy Hall	Orange	Red	1.00	0.00	0.00	6998	de
Kekori	White	Cream	0.26	0.74	0.00	6199	de
Nam Hai	Purple	Purple	1.00	0.00	0.00	5924	de
Hayman	White	Cream	0.73	0.27	0.00	3363	e
F1 Diane × Red Japanese	Variable	Variable	1.00	0.00	0.00	2719	e
Red Jewel	Red	Orange	1.00	0.00	0.00	1859	e
Okinawa Purple	Light purple	Cream	0.00	1.00	0.00	535	e
Amish Red	-	-	-	-	-	0	e
F1 Diane × Bonita	-	-	-	-	-	0	e
Markham	-	-	-	-	-	0	e
Tonga	-	-	-	-	-	0	e
Vardaman	-	-	-	-	-	0	e

Figure 1. Visual comparison of diverse sweetpotatoes included in the trial. These materials varied in root yield, size category distribution, color, and other characteristics. Many existing heirloom varieties and landraces, including purple-fleshed varieties, produce low yields and a low proportion of roots in the No. 1 size category, despite being favored for culinary traits, such as flavor and/or visual appearance. Contents of each crate are the harvested roots of a single plot (1.83 m × 0.762 m). Varieties shown are (**a**) Okinawa Purple; (**b**) Nancy Hall; (**c**) Murasaki; (**d**) L-15-39; (**e**) Shore Gold; (**f**) All Purple; (**g**) Nam Hai; (**h**) Porto Rico USDA; (**i**) Viola; (**j**) Kekori; (**k**) Seon-Mi; (**l**) Dingess Purple; (**m**) Camote Morado; (**n**) L19-53-P; (**o**) Beauregard [10]; (**p**) L-19-18; (**q**) Molokai; (**r**) Morado; (**s**) Carolina Ruby; (**t**) Diane; (**u**) Vermillion [13]; (**v**) Waimanalo; (**w**) L-19-42; (**x**) L19-56-P; (**y**) Red Japanese; (**z**) L-17-182; (**aa**) CA O'Henry; (**bb**) L-19-15; (**cc**) L-17-189; and (**dd**) Covington [12].

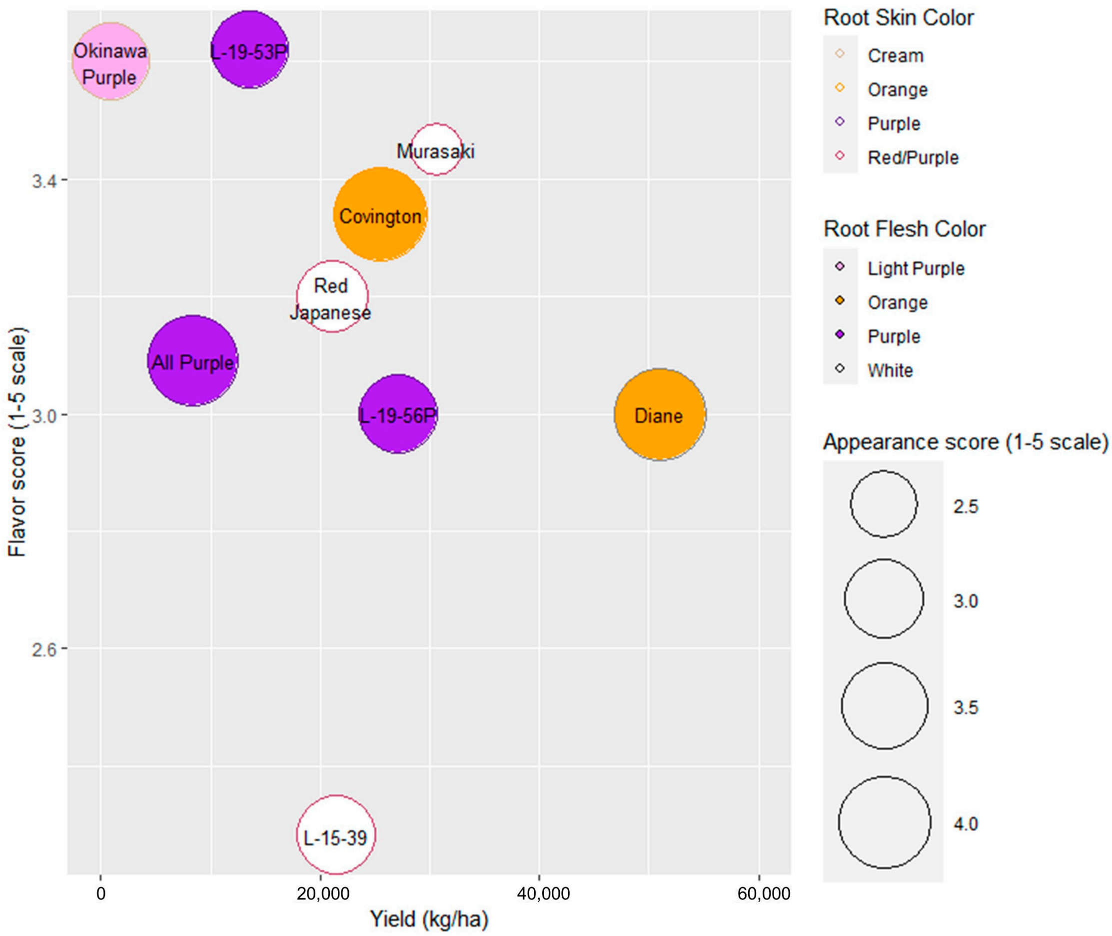

Figure 2. Summary of yield on organic farms, flavor, appearance, and color across the nine lines and varieties subjected to culinary quality evaluations. The traditional Asian type Okinawa Purple was among the highest performing in terms of flavor (Table 2). Purple-fleshed Asian and Pacific Island varieties, such Okinawa Purple and All Purple, were among the lowest yielding, despite having comparatively high rankings for flavor and/or cooked appearance. The highest yielding variety, Diane, is a commercially important orange-fleshed variety with a comparatively low flavor score. Breeding lines vary significantly in culinary and agronomic traits, highlighting the importance of selection for both. Combining the field performance of varieties such as Diane with the aesthetics of All Purple and/or the flavor of varieties such as Okinawa Purple would be a promising breeding target for California organic sweetpotato production.

Table 2. Flavor ratings of nine sweetpotato lines and varieties (1 = inferior, 5 = superior, n = 30).

Variety	Flavor	Significance Groups (LSD) [1]
L-19-53-P	3.62	a
Okinawa Purple	3.60	a
Murasaki	3.45	ab
Covington	3.34	ab
Red Japanese	3.20	ab
All Purple	3.09	ab
Diane	3.00	b
L-19-56-P	3.00	bc
L-15-39	2.28	c

[1] Least significant difference at the 95% confidence level.

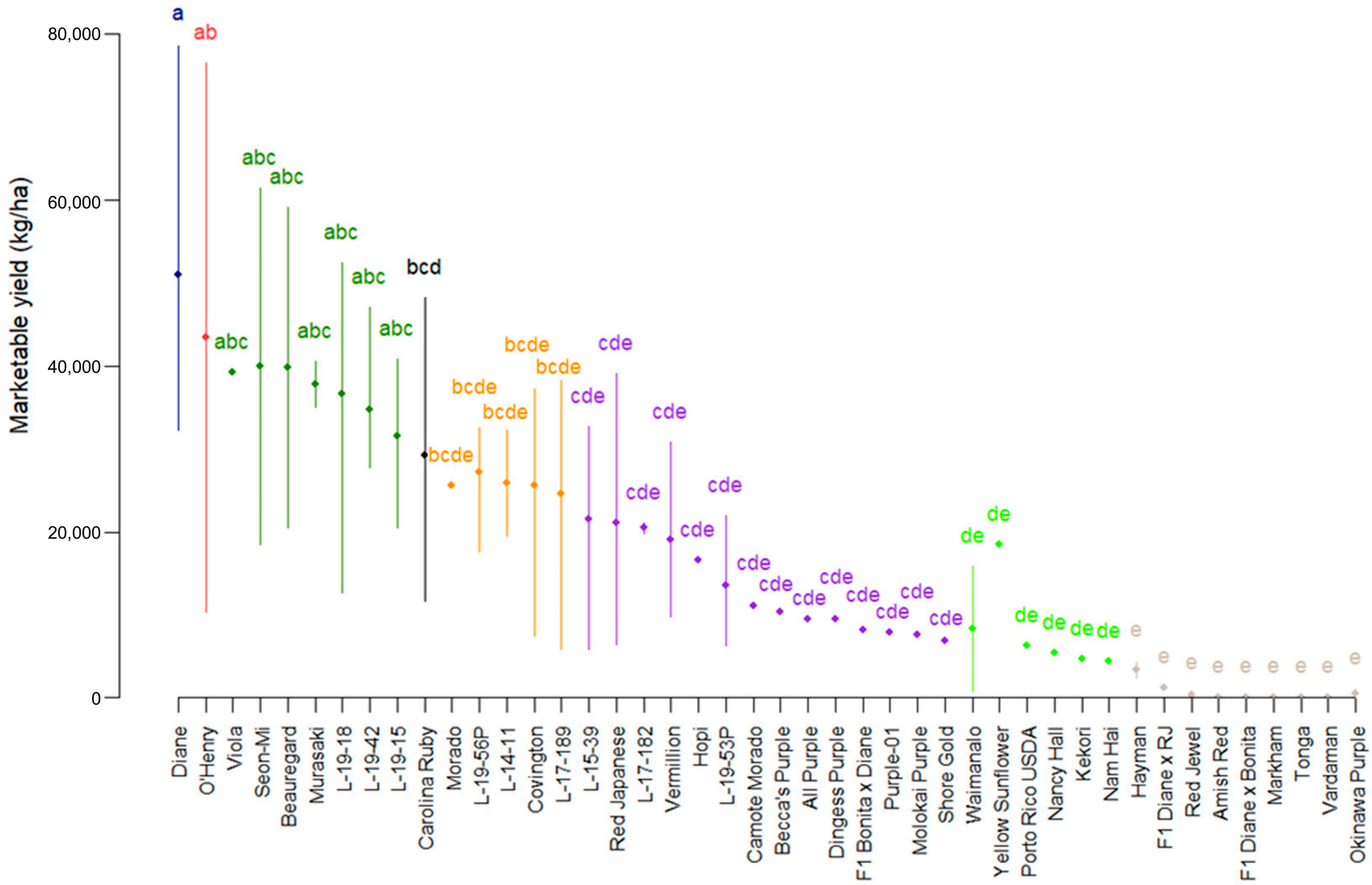

Figure 3. Marketable yield (kg/ha) of all tested sweetpotato lines and varieties. All trials were conducted on certified organic ground. Letters and colors represent significance groups based on Fisher's least significant difference (LSD) test, with correction for augmented design with the DAU.test of the agricolae R package.

3.2. Culinary Traits

Significant variation also existed between varieties for culinary properties, including flavor and cooked visual appearance. All the Asian and Pacific Island varieties and lines evaluated had high flavor scores (Table 2 and Figure 4), including Okinawa Purple (3.60 on scale of 1–5, n = 30; Table 2), Murasaki (3.45), Red Japanese (3.20), and All Purple (3.09). The highest yielding variety, Diane (3.00), differed significantly from these lines. Breeding materials showed a wide range of flavor scores, ranging from the highest scoring line L-19-53-P (3.62) to the lowest L-15-39 (2.28).

Cooked visual appearance scores were highest in orange-fleshed and dark purple-fleshed varieties (Table 3 and Figure 5). These included Covington (4.19), Diane (3.97), and All Purple (3.82), which differed significantly from all other types. While varieties such as Okinawa, Red Japanese, and Murasaki had high flavor ratings, they all were poorly rated for cooked visual appearance (scores 2.25–2.93). Broad-sense heritability for cooked visual appearance was 0.25.

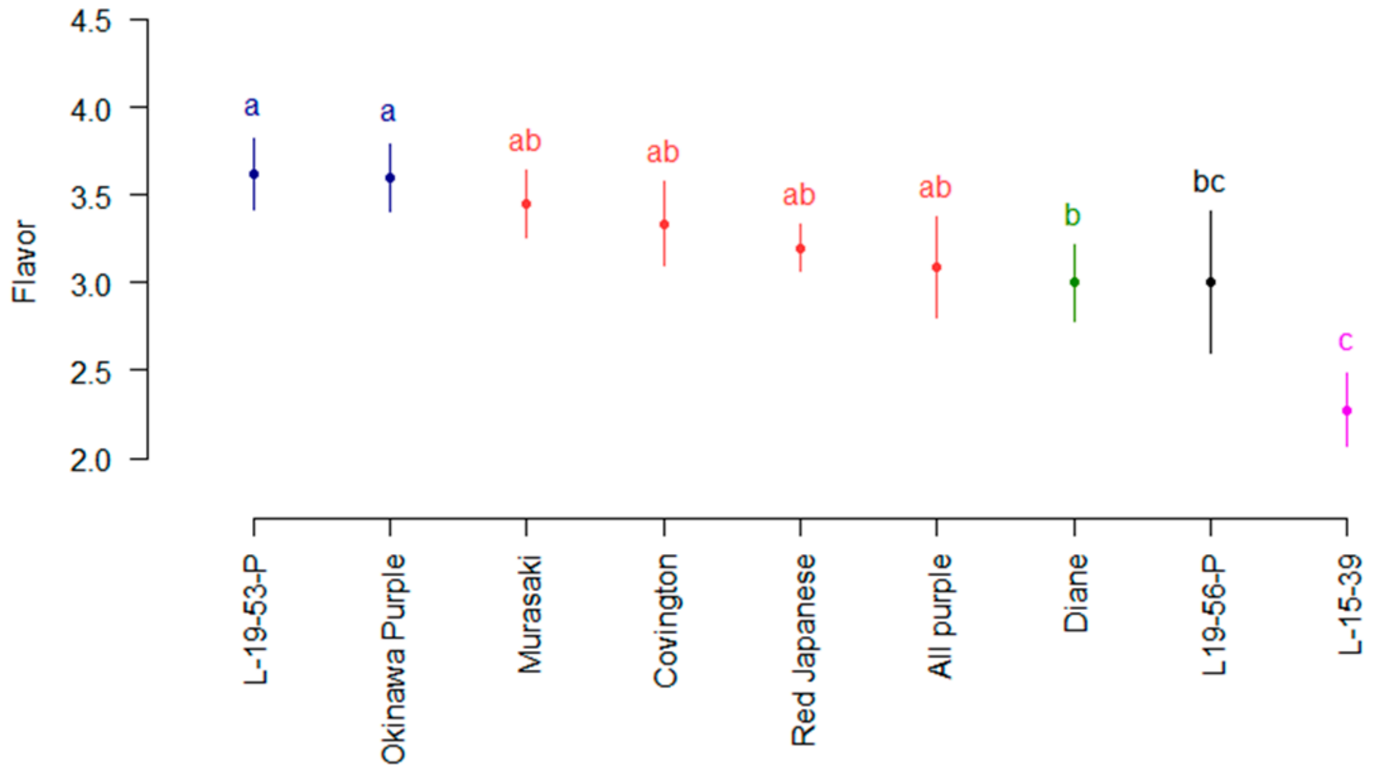

Figure 4. Plot of cooked sweetpotato flavor score by variety (1–5 scale, 5 = superior). The highest rated entries included the breeding line L-19-53-P (score = 3.62) and landrace Okinawa Purple (3.6), both of which exhibited a statistically significantly higher flavor score than the highest yielding variety, Diane. The other Asian and Pacific Island varieties Murasaki, Red Japanese, and All Purple were also highly rated and insignificantly different than Okinawa Purple. Breeding lines ranged from the best in flavor to the worst (L15-39, 2.28), highlighting the need to select for flavor quality. Bars represent standard error of the mean. Colors and letters represent significance groups based on LSD test. *n* = 30 evaluators.

Table 3. Cooked visual appearance ratings of nine sweetpotato lines and varieties (1 = inferior, 5 = superior, *n* = 30).

Variety	Appearance	Significance Groups (LSD) [1]
Covington	4.19	a
Diane	3.97	a
All Purple	3.82	a
L-15-39	3.05	b
L19-56-P	3.00	bc
L-19-53-P	2.93	bc
Okinawa Purple	2.93	bc
Red Japanese	2.67	bc
Murasaki	2.25	c

[1] Least significant difference at the 95% confidence level.

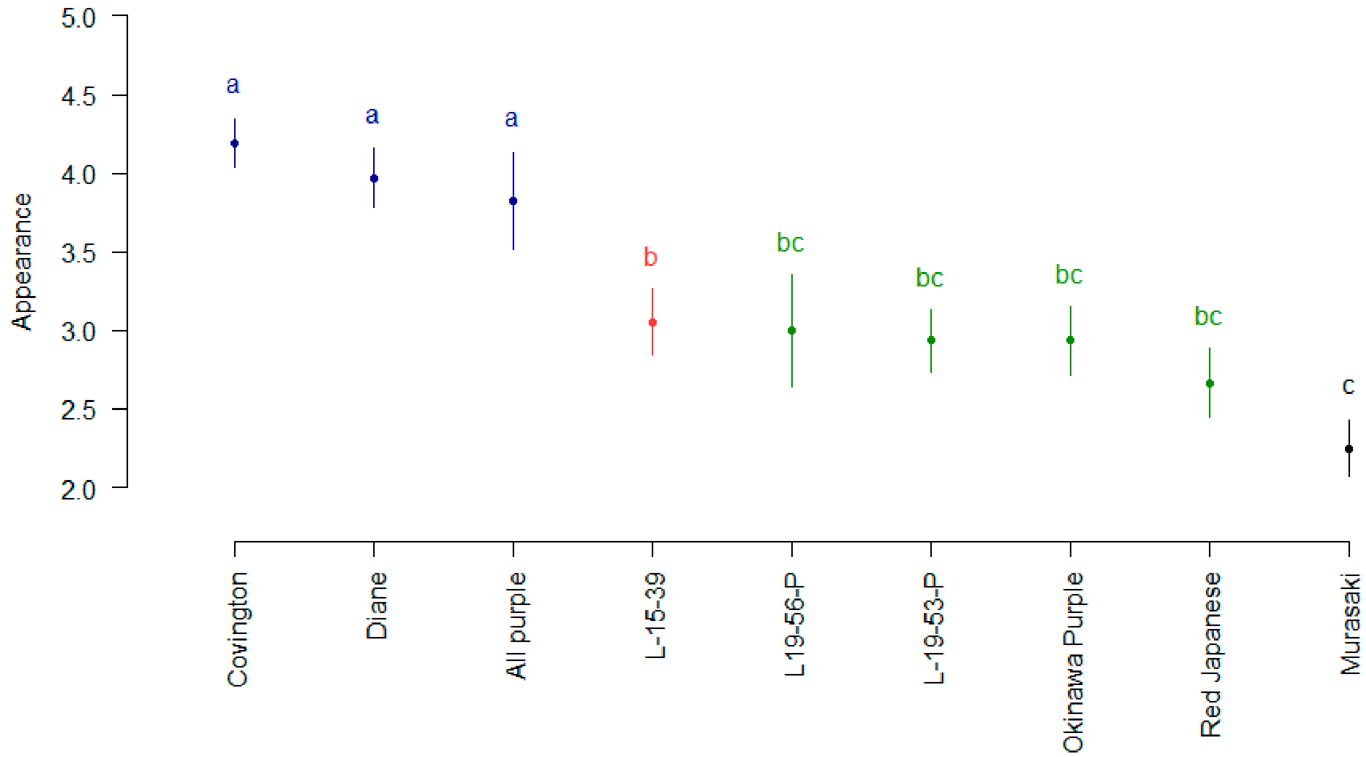

Figure 5. Plot of cooked sweetpotato appearance scores (1–5 scale, 5 = superior). The highest rated entries included orange-fleshed types Covington (4.19) and Diane (3.97). This may explain the prevalence of orange types common in the US, although they had relatively low flavor scores. All Purple was also very highly rated (3.82), and these three types had statistically significantly greater appearance scores than all other types. Bars represent standard error of the mean. Colors and letters represent significance groups based on LSD test. n = 30 evaluators.

4. Discussion

Our results demonstrate the major differences that exist among organically grown sweetpotato varieties across a range of important traits. Importantly, no currently available varieties or lines combine all the best agronomic and culinary properties demanded by California organic growers and the demographically diverse population of North America, as shown in our evaluations of diverse varieties on California organic farms and with a primarily AAPI panel of tasters interested in Japanese culture. Our results suggest that there may be opportunities to combine the best of these traits through plant breeding.

The proportion of marketable yield variance explained by genotype (61.5%) was more than three-fold higher than that attributed to location (18.6%). This is an indication that marketable yield has a highly heritable genetic basis, amenable to improvement through breeding. This also corresponds to historical selection in the crop, which has led to the release of varieties with high yields [10,11]. The five highest yielding varieties were all "yam" or "red yam" types with orange flesh and red/orange skin or "sweet" types with pale flesh and cream-colored skin. Varieties with these characteristics already dominate commercial production in the United States and have received significant attention from breeders. Of the other materials in the top significance group, all but Murasaki [14] fit these color categories. Interestingly, two of the highest yielding varieties were developed in Asia and the Pacific region. These include Viola (PI 538348, ranked third in yield, from the Solomon Islands) and Seon-Mi (PI 585070, ranked fourth in yield, from Republic of Korea). In contrast, purple-fleshed heirloom varieties, such as All Purple, Becca's Purple, Dingess Purple, Nam Hai, and Okinawa Purple, were low yielding. In all cases, these produced less than 25% of the marketable yield achieved by Diane, the highest ranking type in terms of yield. The two purple-fleshed breeding lines, L-19-53-P and L-19-56-P, each ranked higher in yield than any of the purple-fleshed heirlooms, although the differences were not statistically significant. Due to poor field performance in 2021, our yield results are based on a single year (2022) of field trials, and continued evaluations would be useful to clarify yield performance across varieties in the crop in these environments. Together, these results indicate that yield increases are likely achievable, particularly in the low-yielding purple fleshed classes. This will require continued investment in sweetpotato breeding in the target environments.

Yield disparities were particularly pronounced for larger size categories, such as No. 1 or Jumbos. Our results indicate that many purple-fleshed varieties produce small and relatively narrow roots relative to major commercial varieties. All Purple, Becca's Purple, Nam Hai, and Okinawa Purple produced no roots in the Jumbo size category, and All Purple produced none in the high-value No. 1 category. Size distribution is typically related to timing of harvest, with root size increasing as the season progresses. Varieties progress through these size stages at different rates. The recommendation for fresh consumption of California sweetpotatoes is to harvest the crop when 30% of roots reach the Jumbo size [11]. This maximizes the total crop value, balancing high yields with a high frequency of the most valuable No. 1 category. The high proportion of roots in the lower-value medium size class, as found in many AAPI-preferred types, is problematic for several reasons. The medium size class is fundamentally less profitable for growers, and providing the crop with more time to reach larger sizes requires a longer growing season, increasing field costs and resource use, while also threatening harvest altogether if cool autumn rains arrive early. An increased set of large and uniform-sized roots would be extremely useful in AAPI-preferred sweetpotatoes. Further, the roots of All Purple and the aesthetically similar Nam Hai and Becca's Purple also have a comparatively poor shape and surface texture, showing shape irregularities, such as bending and constrictions, and exhibiting a greater number of fine roots. These traits could also be addressed through breeding. However, the commonly used commercial grading system may not satisfactorily identify desired sizes and shapes for all end-users; that is, some consumers may prefer narrow roots, or even shape irregularities, for certain preparation methods or for other culturally relevant reasons. Further discussion of this issue would be warranted before beginning a breeding program on these sweetpotato types. Previous breeding efforts have demonstrated that there is a heritable genetic basis for root size and shape traits, and that selecting for these is economically justified [12].

Our culinary evaluations with an evaluator panel of students with a primarily Asian background indicated that Okinawa Purple was highly desirable in terms of flavor, while Murasaki and Red Japanese also scored favorably. In contrast, the highest yielding cultivar Diane was rated as significantly poorer in flavor than Okinawa Purple, showing that tradeoffs exist between agronomic and culinary traits among currently available germplasm. Flavor had a relatively low level of broad-sense heritability, with genotype explaining only 12.5% of the variance in the trait. The mean flavor rating of All Purple was ranked sixth of nine varieties in terms of flavor, indicating that there may be market opportunities for breeding new varieties of this phenotypic category for improved flavor. This contrasts with the results of Nwosisi et al. [30], in which All Purple was the highest ranked of 14 accessions, with significantly higher scores for flavor components than varieties we tested, such as Covington. In contrast, in our testing, Covington was ranked higher than All Purple in flavor. Unreleased breeding lines were the highest ranked and the lowest ranked in terms of flavor, and significant differences existed between varieties that were visually indistinguishable, such as the purple-fleshed lines L-19-53-P and L-19-56-P. These results demonstrate the critical importance of selection for flavor by breeders to satisfy the interests of consumers and ultimately drive market demand.

Our results showed that All Purple and the orange-fleshed commercial varieties Diane and Covington had higher scores for visual appearance than all other varieties. This visual preference of many consumers for orange flesh color may partly explain why varieties like Diane are produced on a wide scale and command a high market price [11], despite low flavor scores in our testing. Varieties like Red Japanese and Murasaki are intended to cook to a yellow flesh color, but in our culinary testing, their coloration deviated to a somewhat grayish color, possibly due to color loss in storage. If so, selection for longer shelf life and ideal cooked color may be a worthwhile breeding program component. No color deterioration was seen among orange or purple flesh types. The lower appearance scores of the purple-flesh breeding lines L-19-53-P and L-19-56-P relative to All Purple indicate that there could be room for continued improvement in the color retention of these types. The low performance of pale-fleshed varieties in cooked visual appearance relative to orange types and All Purple parallels the findings of Nwosisi et al. [30]. Broad-sense heritability for cooked visual appearance was intermediate between that of yield and flavor, with genotype explaining 25.4% of the variance in appearance. For flavor and cooked visual appearance scores, the preparation methods and tasting group were largely Japanese and Japanese-American. This coincides with the disproportionate popularity of varieties of Japanese origin in North America (e.g., Red Japanese, Murasaki, and Okinawa Purple), but results may not be reflective of preferences among other AAPI cultural groups. Future detailed analysis could include preparation methods and tasting panels of other AAPI populations.

This project has also highlighted important lessons regarding the management of sweetpotato breeding trials in California for smaller scale farms. Drip irrigation is critical for stand establishment [11], and a 2021 trial in which transplanted slips were irrigated with overhead sprinkling had very poor stand survival. Similarly, herbivory by ground squirrels led to defoliation in the 2021 trial, greatly hindering plant growth and development. Row cover was ineffective at controlling squirrel activity, but fencing the trial with partially buried poultry wire and T-posts was highly effective. These lessons were successfully applied in the 2022 trial. In both 2021 and 2022, careful screens to identify mature fruit and seeds in the Yolo county field site failed to identify the formation of even a single seed in the entire trial site. Widespread flowering across numerous varieties occurred in the trials by July of each year, and continued abundantly until harvest in mid-October, with extensive pollinator activity at flowers. In contrast, hand-pollination of much smaller numbers of plants in a winter greenhouse nursery led to a successful seed set, and these seeds were planted in the 2022 trials. The lack of field seed production was therefore likely due to environmental factors, such as high daytime temperatures and low humidity. Sweetpotato breeding programs at similar latitudes in the southeastern United States successfully use outdoor polycross nurseries, making it unlikely that photoperiod signals are responsible for the lack of seed set. Sweetpotato breeding typically entails the development of tens of thousands of genetically distinct breeding lines per year, and to generate these numbers of individuals for breeding in California, it will be important to grow polycross nurseries in modified environmental conditions (e.g., partial shade, humidification) or in other geographic regions.

Together, our results highlight the tremendous phenotypic variation that exists within the tested sweetpotato germplasm. These results show that no single variety performs optimally across agronomic and culinary traits. In particular, this study has focused on the growing demand for market types important to communities of Asian heritage, which have received comparatively little attention by breeders in North America. They have also focused on selecting evaluations on organically managed ground across a range of producer acreages. Our results indicate that major California commercial varieties are favorable in terms of yield and visual appearance, whereas Asian specialty varieties perform best in terms of flavor. Breeding could be a promising approach to combine optimal agronomic traits of commercial varieties with the culinary traits of diverse sweetpotato germplasm. Ultimately, this will promote a more profitable, sustainable, health-promoting, and just food system.

5. Conclusions

Sweetpotatoes are an important California crop, and California produces almost all of the organically grown sweetpotatoes in North America. Market growth has been particularly strong in sweetpotatoes preferred by the AAPI community, such as purple types. In our organic field trials, the highest yielding genotypes were orange and pale-fleshed varieties, whereas purple varieties generally had low yields and poor root size. Yield showed relatively high broad-sense heritability, suggesting that the trait is largely genetic and amenable to breeding. In contrast, sweetpotato genotypes with purple skin or flesh performed best in flavor preference evaluations, with mixed results for culinary appearance evaluations. Unreleased breeding lines showed a broad distribution in flavor, highlighting the need to select for this trait. Together, our results suggest that breeding could be effective for combining the high organic yields and good root size of commercial varieties with the culinary qualities of preferred purple types.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/agriculture13122191/s1, Figure S1: Yield of 15 focal varieties and breeding lines across three certified organic farms, including twelve replicated types and three unreplicated types. Varieties preferred by the AAPI community, particularly All Purple and Okinawa Purple, had low yields relative to major commercial orange-fleshed varieties such as Diane. These results show that a major opportunity for plant breeding exists, to combine AAPI-preferred culinary traits with greater agronomic productivity and economic accessibility. The highest mean yields were achieved at the location in Merced County, which is the commercial production center for the state. The sandy soils in this location also led to reduced scarring and root damage during harvest compared to the other locations. Figure S2: Yield data of all sweetpotato lines and varieties tested across locations. Figure S3: Yield of 15 focal sweetpotato lines and varieties by size category. The No. 1 size category has the highest value per unit weight. Yield data for the varieties not grown at all sites (Murasaki, All Purple, and Okinawa Purple) represents data corrected for augmented design. Figure S4: Proportion of sweetpotato marketable yield in the No. 1 size category, by variety or line.

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Conflicts of Interest: Co-author K.L. operates an organic farm growing specialty AAPI produce, including sweetpotatoes. All other trials and all data analysis was conducted by other co-authors. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

References

1. Wei, H.; Goodhue, R.; Muramoto, J.; Sumner, D. *Statistical Review of California's Organic Agriculture 2013–2016*; California Department of Food and Agriculture: Sacramento, CA, USA, 2022.
2. CDFA. *California Agricultural Statistics Review 2021–2022*; California Department of Food and Agriculture: Sacramento, CA, USA, 2023; p. 157.
3. Nwosisi, S.; Illukpitiya, P.; Nandwani, D.; Arebi, I.T.; Nwosisi, O. Organic and conventional sweetpotato production in the Southeastern of United States: A comparative analysis. *Agric. Food Secur.* **2021**, *10*, 1–9. [CrossRef]
4. USDA. National Agricultural Statistics Service Data. 2021. Available online: https://quickstats.nass.usda.gov/ (accessed on 16 November 2023).
5. Truong, V.; Avula, R.; Pecota, K.; Yencho, G. Sweetpotato production, processing, and nutritional quality. In *Handbook of Vegetables and Vegetable Processing*; John Wiley & Sons: Hoboken, NJ, USA, 2018; pp. 811–838.
6. Hou, W.; Yan, P.; Shi, T.; Lu, P.; Zhao, W.; Yang, H.; Zeng, L.; Yang, J.; Li, Z.; Fan, W. Modulation of anthocyanin accumulation in storage roots of sweetpotato by transcription factor IbMYB1-2 through direct binding to anthocyanin biosynthetic gene promoters. *Plant Physiol. Biochem.* **2023**, *196*, 868–879. [CrossRef]
7. Li, L.-X.; Wei, Z.-Z.; Zhou, Z.-L.; Zhao, D.-L.; Tang, J.; Yang, F.; Li, Y.-H.; Chen, X.-Y.; Han, Z.; Yao, G.-F. A single amino acid mutant in the EAR motif of IbMYB44. 2 reduced the inhibition of anthocyanin accumulation in the purple-fleshed sweetpotato. *Plant Physiol. Biochem.* **2021**, *167*, 410–419. [CrossRef] [PubMed]
8. Truong, V.; Hu, Z.; Thompson, R.; Yencho, G.; Pecota, K. Pressurized liquid extraction and quantification of anthocyanins in purple-fleshed sweet potato genotypes. *J. Food Compos. Anal.* **2012**, *26*, 96–103. [CrossRef]
9. Truong, V.-D.; Deighton, N.; Thompson, R.T.; McFeeters, R.F.; Dean, L.O.; Pecota, K.V.; Yencho, G.C. Characterization of anthocyanins and anthocyanidins in purple-fleshed sweetpotatoes by HPLC-DAD/ESI-MS/MS. *J. Agric. Food Chem.* **2010**, *58*, 404–410. [CrossRef] [PubMed]
10. Rolston, L.; Clark, C.; Cannon, J.; Randle, W.; Riley, E.; Wilson, P.; Robbins, M. Beauregard'sweet potato. *HortScience* **1987**, *22*, 1338–1339. [CrossRef]
11. Stoddard, C.S.; Davis, R.M.; Cantwell, M. *Sweetpotato Production in California*; Vegetable Production Series, Publication 7237; University of California Vegetable Research and Information Center, Division of Agriculture and Natural Resources: Richmond, CA, USA, 2013.
12. Yencho, G.C.; Pecota, K.V.; Schultheis, J.R.; VanEsbroeck, Z.-P.; Holmes, G.J.; Little, B.E.; Thornton, A.C.; Truong, V.-D. 'Covington'sweetpotato. *HortScience* **2008**, *43*, 1911–1914. [CrossRef]
13. LaBonte, D.R.; Clark, C.A.; Smith, T.P.; Villordon, A.Q.; Stoddard, C.S. 'Vermillion'Sweetpotato. *HortScience* **2021**, *56*, 979–981.
14. LaBonte, D.R.; Villordon, A.Q.; Clark, C.A.; Wilson, P.W.; Stoddard, C.S. 'Murasaki-29'sweetpotato. *HortScience* **2008**, *43*, 1895–1896. [CrossRef]
15. Tsu, C.M. *Garden of the World: Asian Immigrants and the Making of Agriculture in California's Santa Clara Valley*; Oxford University Press: Oxford, UK, 2013.
16. Garcia, M. *From the Jaws of Victory: The Triumph and Tragedy of Cesar Chavez and the Farm Worker Movement*; University of California Press: Berkeley, CA, USA, 2012.
17. Daniels, R. *Asian America: Chinese and Japanese in the United States since 1850*; University of Washington Press: Siettle, WA, USA, 2011.
18. Roullier, C.; Duputié, A.; Wennekes, P.; Benoit, L.; Fernández Bringas, V.M.; Rossel, G.; Tay, D.; McKey, D.; Lebot, V. Disentangling the origins of cultivated sweet potato (*Ipomoea batatas* (L.) Lam.). *PLoS ONE* **2013**, *8*, e62707. [CrossRef]
19. Muñoz-Rodríguez, P.; Carruthers, T.; Wood, J.R.; Williams, B.R.; Weitemier, K.; Kronmiller, B.; Ellis, D.; Anglin, N.L.; Longway, L.; Harris, S.A. Reconciling conflicting phylogenies in the origin of sweet potato and dispersal to Polynesia. *Curr. Biol.* **2018**, *28*, 1246–1256.e1212. [CrossRef] [PubMed]
20. Austin, D.F. The taxonomy, evolution and genetic diversity of sweet potatoes and related wild species. In *Exploration, Maintenance, and Utilization of Sweetpotato Genetic Resources*; International Potato Center: Lima, Peru, 1988; pp. 27–60.
21. Zhang, D.; Cervantes, J.; Huamán, Z.; Carey, E.; Ghislain, M. Assessing genetic diversity of sweet potato (*Ipomoea batatas* (L.) Lam.) cultivars from tropical America using AFLP. *Genet. Resour. Crop Evol.* **2000**, *47*, 659–665. [CrossRef]
22. Luo, Z.; Yao, Z.; Yang, Y.; Wang, Z.; Zou, H.; Zhang, X.; Chen, J.; Fang, B.; Huang, L. Genetic fingerprint construction and genetic diversity analysis of sweet potato (*Ipomoea batatas*) germplasm resources. *BMC Plant Biol.* **2023**, *23*, 355. [CrossRef] [PubMed]
23. Montenegro, Á.; Avis, C.; Weaver, A. Modeling the prehistoric arrival of the sweet potato in Polynesia. *J. Archaeol. Sci.* **2008**, *35*, 355–367. [CrossRef]
24. Roullier, C.; Benoit, L.; McKey, D.B.; Lebot, V. Historical collections reveal patterns of diffusion of sweet potato in Oceania obscured by modern plant movements and recombination. *Proc. Natl. Acad. Sci. USA* **2013**, *110*, 2205–2210. [CrossRef] [PubMed]
25. Wadl, P.A.; Olukolu, B.A.; Branham, S.E.; Jarret, R.L.; Yencho, G.C.; Jackson, D.M. Genetic diversity and population structure of the USDA sweetpotato (*Ipomoea batatas*) germplasm collections using GBSpoly. *Front. Plant Sci.* **2018**, *9*, 1166. [CrossRef] [PubMed]
26. FAOSTAT. Yield Production Data. 2022. Available online: https://www.fao.org/faostat/en/#data/QCL (accessed on 16 November 2023).

27. de Mendiburu, F. *Package 'agricolae'*, R Package, version 2019, 1; R Foundation for Statistical Computing: Vienna, Austria, 2019.
28. R Core Team. *R: A Language and Environment for Statistical Computing*; R Foundation for Statistical Computing: Vienna, Austria, 2022.
29. Wickham, H. ggplot2. *Wiley Interdiscip. Rev. Comput. Stat.* **2011**, *3*, 180–185. [CrossRef]
30. Nwosisi, S.; Nandwani, D.; Hui, D.; Ravi, R. Sensory evaluation of organic sweetpotato cultivars. *Int. J. Veg. Sci.* **2017**, *23*, 536–551. [CrossRef]