HortScience 60(4):530–537. 2025. https://doi.org/10.21273/HORTSCI18433-24

Processing Pumpkin (*Cucurbita moschata* Duchesne) Breeding Lines with Resistance to Powdery Mildew and Their Canning Quality

Elizabeth J. Indermaur, Charles T.C. Day, Hirut Betaw, Taylere Q. Herrmann, and Culyn E. DeBeer
Plant Pathology & Plant-Microbe Biology Section, School of Integrative Plant Science, Cornell AgriTech, Cornell University, Geneva NY 14456, USA

Gregory Inzinna
Plant Breeding and Genetics Section, School of Integrative Plant Science, Cornell University, Ithaca, NY 14853, USA

Olga I. Padilla-Zakour
Department of Food Science, Cornell AgriTech, Cornell University, Geneva, NY 14456, USA

Michael Mazourek
Plant Breeding and Genetics Section, School of Integrative Plant Science, Cornell University, Ithaca, NY 14853, USA

Christine D. Smart
Plant Pathology & Plant-Microbe Biology Section, School of Integrative Plant Science, Cornell AgriTech, Cornell University, Geneva, NY 14456, USA

Keywords. *Cucurbita moschata*, disease resistance, plant breeding, *Podosphaera xanthii*, powdery mildew, processing pumpkin

Abstract. **Processing pumpkin (*Cucurbita moschata* Duch.) is an economically important crop in the United States, and commercial cultivars are susceptible to cucurbit powdery mildew (CPM). Ideally, CPM would be managed with fungicides and host resistance; however, this combination of tools is currently inaccessible to growers of processing pumpkin. The objectives of this study were to identify CPM-resistant processing pumpkin breeding lines and evaluate their canning quality. An industry standard and CPM-susceptible processing pumpkin cultivar Dickinson was crossed with Bugle, a butternut squash that is resistant to CPM and carries the common resistance gene *Pm-0*. Each line evaluated was homozygous for *Pm-0* and was developed by selecting lines following three backcrosses to 'Dickinson'. Two lines with moderate and high levels of resistance were identified by a field trial in 2022 and assessed again in 2023. The same two lines were processed and canned along with 'Dickinson' and 'Bugle'. Their canning qualities were assessed and compared with a store-bought commercial standard. The dry matter (%), pH, moisture (%), soluble solids (°Brix), consistency, color, water activity, alcohol insoluble residue (AIR), and ratio of AIR to total solids were measured. The results indicated that the purées from both breeding lines more closely resembled 'Dickinson' and the commercial standard than 'Bugle'. We concluded that effective CPM resistance has been bred into a commercially promising processing pumpkin background.**

Processing pumpkin (*Cucurbita maxima* Duch. and *C. moschata* Duch.) is an economically important crop grown globally for canned and frozen food markets (Dar et al. 2017). In North America, such pumpkins are commonly grown for producing purées. In 2023, the total value of the processing pumpkin market in the United States was $21.37 million (US Department of Agriculture, National Agricultural Statistics Service 2024). Illinois produces the largest share of the crop (US Department of Agriculture, Economic Research Service 2025), which is grown primarily on large-acreage operations. Small farms also produce processing pumpkin for canned or frozen goods or sell directly to consumers at farm markets, thus contributing to late-season income.

In North America, only a few commercial pumpkin cultivars are grown for processing. Orange skin cultivars of *C. maxima* (e.g., Golden Delicious) are typically used for frozen pumpkin, while large-fruited cultivars of *C. moschata* (e.g., Dickinson Field) are used for puréed canned pie stock (Loy 2004). Several physiochemical properties are important when assessing the quality of puréed and canned pumpkin. The US Department of Agriculture (USDA) grading standards prioritize uniformly bright color, good consistency with little to no separation of free liquor, even finish or texture, good flavor, and the absence of defects (USDA Agricultural Research Service 2017). Consistency is a limiting factor; regardless of scores for the other four factors, purées with "fairly good" or "substandard" consistencies cannot be considered US Grade A.

Some of the physiochemical properties that are prioritized in the USDA grading standards (USDA ARS 2017) are difficult to categorize using subjective scoring, including consistency and color. Consistency can be objectively determined by consistometers, which measure the flow characteristics of a viscous or plastic substance. Pumpkin purée typically exhibits pseudoplastic qualities (Dutta et al. 2006; Nistor et al. 2022), for which the viscosity of a fluid decreases as shear rates increase (Gibson and Newsham 2018). Subjective scoring of intermediate color classifications can also be challenging. Color can be objectively and more precisely determined by colorimeters, which provide numeric color values based on an xyz coordinate system. The CIE $L^*a^*b^*$ color space is commonly applied to visualize colors of food products and has previously been used to assess color and pigment levels of pumpkin (*Cucurbita* spp.) purées (Dutta et al. 2006; Karadeniz et al. 2024; Nawirska-Olszańska et al. 2011; Nistor et al. 2022) and in fresh mesocarp tissue of pumpkins and squash (*Cucurbita* spp.) (Hultengren et al. 2016; Itle and Kabelka 2009; Itle et al. 2022).

Commercially grown processing pumpkin cultivars are susceptible to common fungal diseases, including powdery mildew. Powdery mildew is one of the most common diseases of cucurbits (Cucurbitaceae species). Two obligate biotrophs, *Golovinomyces cichoracearum* (DC.) V.P. Heluta and *Podosphaera xanthii* (Castagne) U. Braun & Shishkoff, can cause cucurbit powdery mildew (CPM), but *P. xanthii* is predominant in North America and is the most common on squash (*Cucurbita* spp.) (McCreight 2004). The disease is identified first by small, white colonies of mycelia and conidia on foliage, and later on entire leaves, petioles, and stems (McGrath 2017). In North America, infection is typically caused by wind-dispersed asexual conidia, while sexually derived chasmothecia are less frequently found (McGrath 2017). Symptomatic hosts develop chlorotic lesions and may prematurely defoliate (Pérez-García et al. 2009), which can reduce marketable yield (McGrath 2017). Management of CPM primarily relies on fungicides and host resistance when available.

Natural occurrences of genetic resistance to CPM have not been observed in *C. maxima* and are rarely found in wild *C. moschata* accessions. The resistance gene *Pm-0* was first introgressed into *C. moschata* from the wild species *C. okeechobeensis* subsp. *martinezii* (Contin 1978; Paris and Brown 2005). The inheritance of *Pm-0* in most cultivated cultivars is incompletely dominant and can confer practical resistance even when present in the heterozygous condition (Cohen et al. 2003; Paris and Cohen 2002). *Pm-0* is used extensively in *C. pepo* and *C. moschata* breeding, aided by the development of markers predictive of CPM resistance from *Pm-0* (Holdsworth et al. 2016). 'Dickinson Field', also known as 'Kentucky Field' (*C. moschata*), an industry standard processing cultivar (Loy 2004), predates the introgression of *Pm-0* and remains CPM-susceptible. Consequently, much of the North American processing pumpkin industry cannot use host resistance to manage CPM.

Resistant cultivars can reduce the need for fungicide applications (Coolong and Seebold 2011) and improve management when integrated with effective fungicides (McGrath and Staniszewska 1996). The objective of this study was to develop a processing pumpkin genetic background with CPM resistance. This study evaluated improved breeding lines for resistance to CPM and canning quality as it relates to USDA grading standards (US Department of Agriculture, Agricultural Research Service 2017).

Materials and Methods

Plant material

Bugle, a cultivar of butternut squash, was used as the source of the *Pm-0* gene that was introgressed into Dickinson Field (hereinafter 'Dickinson') through three cycles of backcrossing and four cycles of marker-assisted selection (Holdsworth et al. 2016). Phenotypic selection for type and productivity was performed during each cycle of backcrossing and subsequent inbreeding. Four independent lines were generated for evaluation (Table 1, Fig. 1).

Field trials

Replicated field trials were conducted to evaluate *C. moschata* breeding lines for fruit yield and susceptibility to CPM along with the resistant and susceptible parents. One trial was conducted in each of two years (2022 and 2023) at Cornell AgriTech (Geneva, NY, USA). The region is characterized by a humid continental climate with warm summers. In 2022, the field trial was established on a silt loam Odessa series soil at the Crittenden North research farm (lat. 42.880419, long. −77.014029). In 2023, the trial was established on a silt loam Lima series soil at the Research North research farm (lat. 42.878044, long. −77.024350). Fields were prepared by plowing followed by disking. In 2022 and 2023, 1.2-m-wide bare ground beds were prepared with T-Tape drip line irrigation tape (Rivulis, San Diego, CA, USA). The furrow width between beds was 4.6 m. Fertilizer (19N–7P–15.8K) was applied while beds were prepared at 112 kg/ha in both 2022 and 2023. Fertilizer rates followed standard recommendations for the growing region (Reiners et al. 2019). Irrigation and fertilization (4N–0P–6.6K) were applied via the drip line as needed to supplement rainfall so that plants received at least 2.5 cm of water per week.

Seeds were sown in 50-cell plug trays containing LM-3 All Purpose Peat Growing Mix (Lambert, Rivière-Ouelle, Québec, Canada) in the Cornell AgriTech Plant Pathology and Plant-Microbe Biology Greenhouses. Seeds were sown on 13 Jun 2022 and transplanted by hand on 1 Jul 2022. Seeds were also sown on 30 May 2023 and transplanted using a Rain-Flo 1670 Water Wheel Transplanter (Rain-Flo Irrigation, East Earl, PA, USA) with a 5.1-cm wheel on 23 Jun 2023. In both years, fertility was included at transplanting with 24N–3.5P–13.3K at 100 ppm N. Admire Pro (Bayer CropScience, St. Louis, MO, USA) was applied before transplanting as a drench on 24 Jun 2022 and 16 Jun 2023. In both years, plots were spaced with 1.8 m between plants and 2.7 m between plot ends. Each plant was fertilized with 150 g of 19N–7P–15.8K on 19 Jul 2022 and 12 Jul 2023. In both years, treatments (Table 1) were arranged in a randomized complete block design. In 2022, plots consisted of 10 plants with three replicates per treatment, which included both parental lines and four BC3 lines. In 2023, plots consisted of five plants with four replicates per treatment, which included both parental lines and only two BC3 lines that were advanced from field evaluations in 2022.

We observed CPM from natural inoculum on 15 Aug 2022 and 3 Aug 2023. Because of slow disease progression in 2023, plots were spray-inoculated with a suspension of *P. xanthii* conidia in water (mean concentration of 4.2 × 10^4 spores/mL) on 11 Aug. The presence of *P. xanthii* was confirmed via polymerase chain reaction amplification of the ITS region, followed by sequencing of the DNA amplicon, from leaf samples collected on 13 Sep 2022 and 1 Sep 2023. Disease severity (%) on upper leaf surfaces was estimated visually across entire plots on 20 Sep 2022 and 15 Sep 2023. Fruit were harvested, counted, and weighed on 30 Sep 2022 and 5 Oct 2023. The field trial was extended in 2023 because of increased precipitation and decreased temperatures that appeared to slow crop development compared with that in 2022. In 2023, representative fruit were stored at room temperature for 1 week before processing.

Table 1. Seed sources, pedigrees, and *Pm-0* homozygosity of breeding lines and cultivars evaluated.

Accession	Source	Pedigree	*Pm-0*
TR2-01	Rupp Seeds	'Dickinson' (D)	HMZ rec
TR2-02	Rupp Seeds	'Bugle' (B)	HMZ dom
TR2-03	Cornell	D × B (BC_3F_3)	HMZ dom
TR2-04	Cornell	D × B (BC_3F_3)	HMZ dom
TR2-05	Cornell	D × B (BC_3F_3)	HMZ dom
TR2-06	Cornell	D × B (BC_3F_3)	HMZ dom

HMZ dom = homozygous dominant; HMZ rec = homozygous recessive.

Pumpkin processing and canning trial

Sample preparation and storage. Pumpkins were washed, seeds were removed, and fruit flesh with skin was cut into approximately 5-cm cubes to be used for processing and analysis. Three replications of approximately 30 g of the raw fruit per accession were weighed, stored in 50-mL centrifuge tubes (Oak Ridge Nalgene; Thermo Scientific, Waltham, MA, USA), and refrigerated ahead of freeze-drying (Fig. 2). Separately, 20 kg of the 5-cm cubes per accession were steam-cooked for 20 min ('Dickinson', TR2-03, and TR2-06) or 40 min ('Bugle') in a Rational Combi Oven in 100% relative humidity at 99 °C (Model SCC WE 201G; Rational AG, Landsberg am Lech, Germany) in three replications. Cooked pumpkin was processed in triplicate in a Bertocchi CX series turbo extractor at 1950 rpm (Bertocchi Srl, Parma, Italy). A screen size of 1.5 cm with a 3.5-mm gap was used. The resulting pumpkin purée was heated in a jacketed steam kettle (Model DA-11-009 QM-14326 189; Legion Industries, Waynesboro, GA, USA) to 82 °C and subsequently placed in ten 14-oz, 7.62 cm × 11.27 cm two-piece tinplate cans with lacquered bodies and ends (Seneca Foods, Geneva, NY, USA) per replication. Cans were sealed with an atmospheric Dixie Double sealer (Model UVGMO-ALCC; Dixie Canning Company, Athens, GA, USA) and products were sterilized in an industrial retort (Terra Food-Tech CFS-75 V; RAYPA, Barcelona, Spain) with a maximum chamber temperature of 121 °C, maximum pressure of 2.13 bar, and a sterilization program of 62 min. Practices followed the procedures outlined by Featherstone (2016). Cans were stored at room temperature (approximately 20 °C) for later analyses. Representative images of opened cans are shown in Fig. 3. Pumpkin purée from three cans from each processing

Received for publication 30 Dec 2024. Accepted for publication 21 Jan 2025.
Published online 14 Mar 2025.
All data collected for each study are available on request from authors E.J. Indermaur and C.D. Smart. Seed of Cornell-developed germplasm is available from M. Mazourek.
We thank all Smart Lab members past and present for their technical support, especially Kensy Rodriguez-Herrera, Jenna Kafrawi, and Jana Fladd. We thank Danielle Heaney for her guidance and patience. We thank the Cornell AgriTech Field Research Unit and the Seneca Foods Foundation Pilot Plant staff for their support, including Roger Morse, George Howick, and Bob Martin. We also thank USDA-ARS Scientist Dr. Ben Gutierrez for helping troubleshoot equipment difficulties and Dr. Steve Reiners for his horticultural expertise.
This research was supported by the USDA National Institute of Food and Agriculture (award number 2020-51181-32139).
C.D.S. is the corresponding author. E-mail: cds14@cornell.edu.

Fig. 1. Fruit from the four breeding lines and two parents that were evaluated in the trial.

replicate was evaluated to determine the alcohol insoluble residue (AIR), soluble solids (°Brix), color, consistency, moisture content, pH, and water activity (Fig. 2). Purée from a single brand of commercially available canned pumpkin (hereafter referred to as the commercial standard) was used as a comparison.

Dry matter analysis. Three replications of approximately 30 g of raw fruit per accession were freeze-dried in uncapped 50-mL centrifuge tubes (Oak Ridge Nalgene; Thermo Scientific, Waltham, MA, USA) for 72 h. Fresh and dry weights were recorded and used to calculate dry matter (%).

pH analysis. Pumpkin purées were assessed to determine the pH using a meter kit (Environmental Express Cole Parmer P200-02 pH Meter Kit and 3-in-1 pH Electrode Holder; Cole-Parmer, Vernon Hills, IL, USA).

Moisture content analysis. Approximately 5 g of pumpkin purée was placed on a metal tray and dried in a MX-50 Moisture Analyzer (A&D Company, Tokyo, Japan).

Consistency analysis. In a consistometer, the distance that a pumpkin purée flows is inversely related to the quality of its consistency. In this study, consistency of the purées was measured with a Bostwick consistometer (CSC Scientific, Fairfax, VA, USA). Approximately 75 mL of the sample was used to fill the chamber. Distance traveled (in cm) by the sample was measured at 30-s and 1-min intervals.

Soluble solids concentration analysis. Soluble solids content as °Brix was estimated using a digital refractometer (Sper Scientific 300034 Laboratory Digital Refractometer, Scottsdale, AZ, USA).

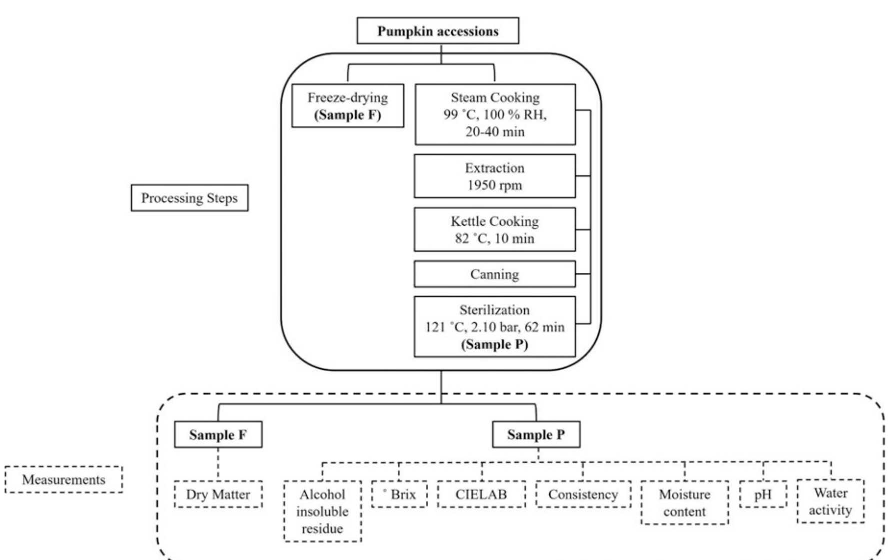

Fig. 2. Flow chart of the processing steps applied to pumpkin fruits and the analyses of the different samples obtained.

Color measurements. CIE $L^*a^*b^*$ parameters of the pumpkin purée placed in a glass cuvette were determined using an UltraScan VIS Spectrophotometer (HunterLab, Reston, VA, USA) in reflectance mode. The spectrophotometer provides numeric color values based on an xyz coordinate system. These are converted to tristimulus color space values and applied in the CIE $L^*a^*b^*$ color space. The lightness coefficient, L^*, ranges from 0 (absolute black) to 100 (absolute white). Color space value a^* ranges from $+a^*$ (red) to $-a^*$ (green), and b^* ranges from $+b^*$ (yellow) to $-b^*$ (blue).

Water activity analysis. The water activity (a_w) of purées or the ratio between the vapor pressure of a sample and distilled water was quantified with a water activity meter (AQUALAB 4TE; Addium Inc., Pullman, WA, USA).

Isolation of alcohol insoluble residue. For this study, the AIR is intended as an estimate of polysaccharides. Extracting soluble plant samples with alcohol results in insoluble residues that are cell wall components, primarily cellulose, hemicellulose, and pectin (Barnes et al. 2021). The AIR was isolated (McFeeters and Armstrong 1984) with adjustments (Fraeye et al. 2009) from pumpkin purées stored in cans at room temperature (indicated with arrows in Fig. 2). One mass unit of pumpkin purée was homogenized in five mass units of 90% ethanol. The residue after filtration was homogenized with 2.5 mass units of 70% ethanol, filtered, resuspended in 2.5 mass units of acetone, and filtered once more. The residue was dried at 40 °C in a vacuum oven for 18 h and weighed to determine the AIR percentage, which can be determined using the following equation:

$$\%\ AIR = [(x - y)/z]*100 \qquad [1]$$

where x is the weight of dried AIR plus the drying recipient, y is the weight of the drying recipient, and z is the weight of the starting sample.

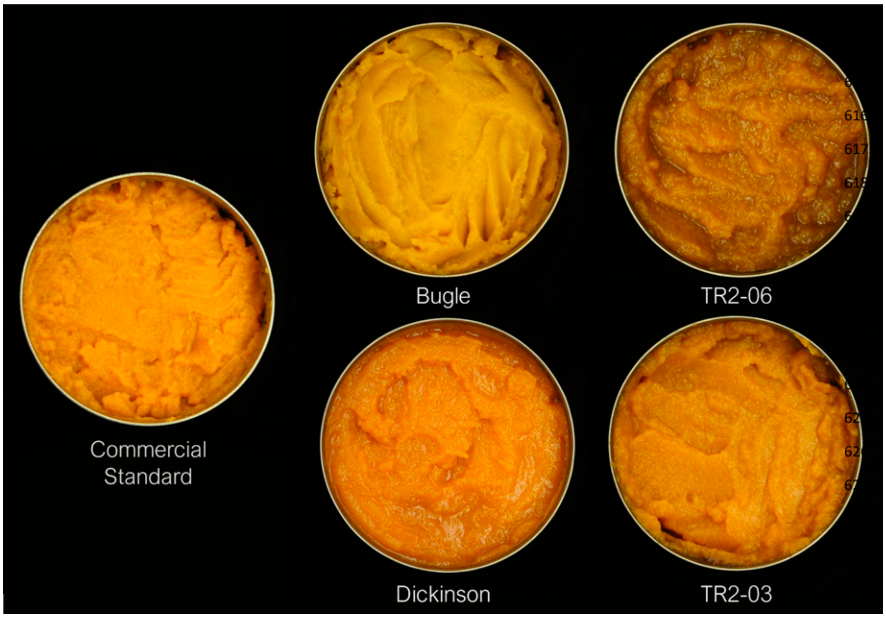

Fig. 3. Representative cans of puréed pumpkin after opening.

Ratio of AIR to total solids. To estimate the ratio of polysaccharides to the total amount of solids in the pumpkin purée, the following equation was used:

$$\textit{Ratio of AIR to total solids} = \% \, AIR/(100 - x) \quad [2]$$

where % *AIR* is the AIR percentage and x is the moisture content of a sample.

Statistical analysis

For both years (2022 and 2023) of the breeding line evaluations, experiments were organized in a randomized complete block design. In 2022, all accessions were replicated three times. In 2023, all accessions were replicated four times. In the processing and canning quality study, each accession was processed in triplicate. Three cans from each processing run were used for quality evaluations.

All calculations and analyses were performed in RStudio version 4.3.3 (R Development Core Team 2024). All data were analyzed using a linear mixed-effects model using the "lme4" package (Bates et al. 2015). For each year (2022 and 2023) of the breeding line evaluations, disease incidence and yield were analyzed independently (Table 2). For the evaluations of physiochemical properties of raw fruit and pumpkin purées, dry matter (%), pH, moisture (%), soluble solids (°Brix), consistency (cm) at 30 s and 1 min, L^*, a^*, and b^*, a_w, AIR (%), and the ratio of AIR to total solids were analyzed independently (Table 3). P values were provided in a type III analysis of variance via Satterthwaite's degree of freedom method. Pairwise comparisons were made using the "emmeans" package (Lenth 2023) with the Kenward-Roger degrees of freedom method and the Tukey method for P value adjustment. Compact letter displays were generated using the "multcomp" package (Hothorn et al. 2008). Spearman correlation matrices were generated using the "Hmisc" package (Harrell 2024).

Results

Field trials

Weather conditions differed slightly between years. In 2022, precipitation during the field experiment (1 Jul to 30 Sep) totaled 17.8 cm, and the mean minimum and maximum air temperatures were 15.6 and 26.3 °C. In 2023, precipitation during the field experiment (23 Jun to 5 Oct) was 25.3 cm, and the mean minimum and maximum air temperatures were 15.3 and 24.9 °C. Results from the field trials in both years including disease severity and yield are displayed in Table 2. Disease pressure was comparable in both years; the mean severity for 'Dickinson' was 55.0% in 2022 and 44.7% in 2023.

In 2022, CPM disease severity was significantly lower on leaves of TR2-03 than that on leaves of 'Dickinson' and was no different from that on leaves of CPM-resistant 'Bugle'. Disease severity on leaves of TR2-06 and that on leaves of TR2-04 were not different from that on leaves of either 'Bugle' or 'Dickinson', whereas TR2-05 had significantly greater CPM severity than that of 'Bugle' and was not different from that of 'Dickinson'. The number of fruit harvested per plot in 2022 was not different across breeding lines and 'Dickinson'; however, 'Bugle' yielded significantly more fruit per plot. Higher fruit counts of 'Bugle' were expected because of the smaller fruit size. Additionally, there were no significant differences in fruit weight per plot in 2022. The decision to advance select breeding lines for evaluations in 2023 was based on foliar disease severity ratings and overall agronomic rankings. As such, TR2-03 and TR2-06 were advanced for assessment in 2023 and were used in the processing study in 2023.

In 2023, a trend in CPM severity emerged. Similar to what was observed in 2022, disease severity in 2023 was significantly lower on leaves of 'Bugle' than that on leave of 'Dickinson'. Disease severity on leaves of TR2-03 was not different from that on leaves of 'Bugle', but it was significantly reduced compared with that on leaves of 'Dickinson'. Disease severity on leaves of TR2-06 was similar to that of both parents. Unlike in 2022, no significant differences in yield characteristics were found between breeding lines and parents in 2023. However, both fruit number and weight per plot followed similar numeric trends; 'Bugle' tended to produce higher numbers of smaller fruits, 'Dickinson' produced smaller numbers of larger fruits, and TR2-03 and TR2-06 exhibited intermediate phenotypes. Notably, fruit from TR2-06 was slower to mature than fruit of all other accessions in both 2022 and 2023, as

Table 2. Results of 'Dickinson' breeding line field evaluations. Disease severity was rated per plot on 20 Sep 2022 and 15 Sep 2023. Yield was calculated per 10 plants in 2022 and per five plants in 2023.

			Marketable yield			
	Foliar disease severity (%)		2022		2023	
Accession	2022	2023	Number	Weight (kg)	Number	Weight (kg)
'Bugle'	24.2 a[1]	9.3 a	42.0 b	41.2	16.3	14.0
TR2-03	25.0 a	10.3 a	10.7 a	52.2	5.3	25.6
TR2-06	31.7 ab	20.0 ab	20.0 a	72.5	7.0	23.3
TR2-04	51.7 ab	—	11.7 a	79.2	—	—
TR2-05	55.0 b	—	16.3 a	67.3	—	—
'Dickinson'	55.0 b	41.7 b	22.0 a	132.9	10	70.5
P	0.00390	0.02872	<0.0001	0.0642	0.1327	0.053

[1] Values in the same column followed by the same letter are not significantly different at $P < 0.05$ according to Tukey's honestly significant difference test.

Table 3. Physiochemical properties of ‘Dickinson’ breeding line fruit and pumpkin purée.

Accession	Dry matter (%)[i]	pH	Moisture (%)	°Brix	Consistency (cm) 30 s	Consistency (cm) 1 min	L^*	a^*	b^*	a_w	AIR (%)	Ratio of AIR to total solids
Dickinson	7.54 a[ii]	4.98 a	92.1 c	6.1 ab	1.79 b	2.92 b	44.0 a	21.3 b	31.8 ab	0.993	2.71 ab	0.36 b
TR2-03	9.25 a	5.06 ab	88.5 b	8.1 b	0.06 a	0.13 a	48.3 b	21.6 b	33.3 ab	0.992	4.38 ab	0.40 c
TR2-06	8.29 a	4.97 a	90.7 bc	7.2 b	1.34 ab	2.20 ab	45.0 a	17.1 a	29.8 a	0.991	2.53 a	0.29 a
Bugle	16.05 b	5.28 c	82.9 a	12.6 c	0.00 a	0.00 a	50.8 c	14.5 a	35.1 b	0.992	9.63 c	0.58 e
Commercial standard	–	5.16 b	90.2 bc	4.7 a	0.00 a	0.00 a	48.5 b	23.4 b	33.9 ab	0.997	5.05 b	0.54 d
P	<0.0001	<0.0001	<0.0001	<0.0001	0.005819	0.004225	<0.0001	<0.0001	0.02892	0.2023	<0.0001	<0.0001

[i] Values are shown based on three cans of purée × three processing runs per accession, except for the commercial standard, for which values are based on nine cans of purée.
[ii] Values in the same column followed by the same letter are not significantly different at $P < 0.05$ according to Tukey’s honestly significant difference test.
a_w = water activity; AIR = alcohol insoluble residue.

demonstrated by its mottled green flesh (Fig. 1). Despite the homozygous state of *Pm-0* in all BC_3F_3 progeny, the lines were not isogenic and appear to segregate for several traits, including CPM resistance, fruit maturation, and fruit weight. These traits remained consistent within accessions across years.

Canning quality

Dry matter of raw pumpkin fruit. Raw fruit across accessions differed significantly in dry matter (Table 3). ‘Bugle’ was significantly drier than all other fruit. TR2-03, TR2-06, and ‘Dickinson’ were not significantly different from one another.

pH. Pumpkin purées differed significantly in pH (Table 3). TR2-06 and ‘Dickinson’ had significantly lower pH values than those of all other accessions except TR2-03, which was also similar to the commercial standard. ‘Bugle’ had a significantly higher pH than that of all other accessions. Puréed pumpkin has pH values as high as 6.10 (Gliemmo et al. 2014) and is generally considered a low-acid food. As expected, all purées produced in this study met the Food and Drug Administration’s pH threshold of at least 4.6 to be considered a food with low acidity (US Food and Drug Administration 2024).

Moisture content. Moisture content (%) was significantly different across accessions (Table 3). As expected, based on its high dry matter (%), purée from ‘Bugle’ had the lowest moisture content of all products evaluated. The moisture content of TR2-03 was significantly higher than that of ‘Bugle’ but similar to that of both the commercial standard and TR2-06. ‘Dickinson’ had significantly more moisture than ‘Bugle’ and TR2-03, but it was not significantly different from the commercial standard or TR2-06.

Consistency. Pumpkin purées differed significantly in their consistency, which was measured as the distance that each product flowed after 30 s and 1 min (Table 3). Neither ‘Bugle’ nor the commercial standard traveled any distance in the consistometer at either time interval. TR2-03 traveled 0.06 cm after 30 s and 0.13 cm after 1 min and was not significantly different from ‘Bugle’ or the commercial standard. ‘Dickinson’ traveled significantly further than ‘Bugle’, the commercial standard, and TR2-03 at both time intervals. TR2-06 flowed an intermediate distance and was not significantly different from any of the accessions.

Soluble solids concentration. The °Brix was significantly different across accessions (Table 3). As expected, based on its high dry matter (%) and market class as a butternut squash, purée from ‘Bugle’ had significantly greater °Brix than that of all other products evaluated. Purées from TR2-03 and TR2-06 had significantly higher °Brix than that of the commercial standard, but neither was significantly different from that of ‘Dickinson’.

Color. There were significant differences between accessions in L^*, a^*, and b^* values (Table 3). Purée from ‘Bugle’ had the highest L^* value, a low a^* value, and a high b^* value (indicating lighter, less red, and more yellow purée). This color is similar to that previously found during a study in which only L^* and a^* were measured for fresh mesocarp tissue in ‘Bugle’ (Hultengren et al. 2016). ‘Dickinson’ had a lower L^* value, higher a^* value, and slightly lower b^* value than those of ‘Bugle’ (indicating a darker, more red, and less yellow purée). The commercial standard also had a lower L^* value, higher a^* value, and slightly lower b^* value compared with those of ‘Bugle’ (also indicating a darker, more red, and less yellow purée). Overall, purées from ‘Dickinson’ and the commercial standard were more similar to each other than they were to ‘Bugle’.

Both of the breeding lines had lower L^* values than ‘Bugle’ (indicating darker purées), but they were similar in their a^* or b^* values. TR2-03 had significantly higher a^* values than those of ‘Bugle’, but they were not significantly different from either ‘Dickinson’ or the commercial standard (indicating similarly red purées). However, TR2-03 had a b^* value similar to that of ‘Bugle’, which was not significantly different from that of any other accessions (indicating similarly yellow purées). TR2-06 did not have a significantly different a^* value compared to that of ‘Bugle’, but both were significantly lower than that of the other accessions (indicating less red purées). Interestingly, TR2-06 was the only purée in this study with a significantly lower b^* value than that of ‘Bugle’ (indicating a less yellow purée than that of ‘Bugle’).

Water activity. There were no significant differences in water activity (a_w) between accessions. Values ranged from 0.991 to 0.997 a_w. Pumpkin purée has previously been documented to have a_w values higher than 0.87 (Nistor et al. 2022). As expected, all purées produced in this study met the Food and Drug Administration’s threshold of at least 0.85 a_w to be considered a low-acid food (US Food and Drug Administration 2024).

Alcohol insoluble residue. The AIR (%), an estimate of polysaccharides, was significantly different across accessions (Table 3). As expected, based on its relatively high dry matter (%), low moisture content (%), and good consistency, purée from ‘Bugle’ had significantly more polysaccharides than those of all other accessions. The commercial standard had significantly less AIR (%) than ‘Bugle’, but it was not significantly different from either TR2-03 or ‘Dickinson’. TR2-06 had significantly less AIR (%) than ‘Bugle’ and the commercial standard, but it was not significantly different from either ‘Dickinson’ or TR2-03.

Ratio of AIR to total solids. There were clear significant differences in the ratio of AIR to total solids (TS) between accessions (Table 3). Purée from ‘Bugle’ had the highest proportion of AIR (%) to TS. This was expected considering the significantly higher AIR compared with that of all other accessions. Interestingly, the commercial standard had the next-highest proportion of AIR (%) to TS. We attributed this to the relatively high moisture content (and correspondingly low total solids) and relatively high AIR (%). TR2-03 had the next-highest proportion of

Table 4. Factors of the Spearman correlation matrix.

	a_w	AIR	Dry matter	pH	Moisture	°Brix	Consistency (30 s)	Consistency (1 min)	L*	a*	b*	Ratio of AIR to TS
a_w	1.00											
AIR	0.22	1.00										
Dry matter	0.44	0.77**	1.00									
pH	0.16	0.96***	0.68*	1.00								
Moisture	0.03	−0.84***	−0.80**	−0.82***	1.00							
°Brix	−0.35	0.37	0.85***	0.35	−0.71**	1.00						
Consistency (30 s)	−0.34	−0.96***	−0.80**	−0.93***	0.76***	−0.18	1.00					
Consistency (1 min)	−0.35	−0.96***	−0.80**	−0.93***	0.76**	−0.18	0.99***	1.00				
L*	0.25	0.90***	0.77**	0.89***	−0.84***	0.48	−0.87***	−0.88***	1.00			
a*	0.30	−0.14	−0.68*	−0.11	0.43	−0.80***	−0.03	−0.04	−0.25	1.00		
b*	0.54*	0.76***	0.76**	0.71***	−0.60*	0.22	−0.78***	−0.80***	0.78***	0.04	1.00	
Ratio of AIR to TS	0.23	0.92***	0.60*	0.89***	−0.63*	0.22	−0.86***	−0.87***	0.77***	0.03	0.72***	1.00

*, **, *** Correlations are significant at $P < 0.05$, 0.01, or 0.001, respectively.

a_w = water activity; AIR = alcohol insoluble residue; Ratio of AIR to TS = ratio of alcohol insoluble residue to total solids.

AIR (%) to TS, followed by 'Dickinson' and TR2-06.

Correlations between canning quality metrics. The Spearman correlation data between dry matter, pH, moisture content, consistency, °Brix, color, water activity, AIR, and the ratio of AIR to TS are reported in Table 4. The a_w values were only correlated with b* values (ρ = 0.54). Considering the similarities in a_w values and the overlap in b* values across all accessions, we hesitated to draw conclusions about the predictive ability of either value for the other. The remaining metrics are significantly correlated with many variables. For the following relationships, only significant correlations ($P < 0.01$) are presented. Consistency at 30 s and that at 1 min were negatively correlated with several values, including AIR (%), dry matter (%), pH, L*, b*, and the ratio of AIR to TS, but positively correlated with moisture (%). Moisture (%) was negatively correlated with many variables, including AIR (%), dry matter (%), pH, °Brix, and L*. In this study, the color space value L* was positively correlated with AIR (%), dry matter (%), pH, b*, and the ratio of AIR to TS. Interestingly, a* was only correlated with °Brix. The color space value, b*, was positively correlated with many variables, including AIR (%), dry matter (%), pH, and the ratio of AIR to TS.

Discussion

Currently, commercial processing pumpkin (*C. moschata*) cultivars are susceptible to CPM and lack the resistance gene *Pm-0*. The results of this study confirmed that CPM resistance has been bred into a commercially promising processing pumpkin background. In field trials in 2022 and 2023, TR2-03 had consistently less disease than its CPM-susceptible parent, 'Dickinson', and was similar to the CPM-resistant parent, 'Bugle'. TR2-06 demonstrated intermediate resistance to CPM and was not different from either parent in CPM severity in 2022 or 2023. While there were no significant differences in fruit number and weight between the breeding lines and 'Dickinson', the yields of TR2-03 and TR2-06 could be improved in subsequent crosses. In the canning quality trial, purées from TR2-03 and TR2-06 generally resembled that of 'Dickinson' and the commercial standard more than that of the butternut squash cultivar Bugle (Fig. 3). Overall, this indicated that the breeding lines had commercially promising canning quality. Purée from 'Bugle' had significantly more dry matter (%), a higher pH, less moisture content, and greater AIR, and it was significantly sweeter than all other products evaluated, including the commercial standard. These differences between 'Bugle' and the other purées was expected considering the market class of 'Bugle' as a butternut squash.

Purée from 'Dickinson' was significantly different from that of the commercial standard in several categories, including pH, consistency (at both 30 s and 1 min), L*, and the ratio of AIR to TS. Although 'Dickinson' was intended as an industry standard in the field trials, it was not considered a processing and canning standard. Some processing pumpkin grown for commercial canning is proprietary germplasm that is different from the 'Dickinson' genotype used in this study. Instead, the store-bought commercial standard was considered a processing and canning standard. Commercial facilities have carefully adjusted conditions, and changing scales for plot testing is complex. Although we followed the procedures outlined by Featherstone (2016), differences in canning qualities are possible if the same pumpkins are processed in different conditions. The store-bought commercial standard showed that the processing method developed in this study was a reasonable approximation of the commercial process.

For canned pumpkin to receive a grade "A" classification, the product must have a uniformly bright orange color and good consistency, with little to no separation of free liquor (US Department of Agriculture, Agricultural Research Service 2017). In this study, using a consistometer, we found that TR2-03 had a consistency similar to that of the commercial standard. Interestingly, by the same measure, 'Bugle' also had a desirable consistency. However, 'Bugle' differed substantially in the other metrics and was significantly lighter and less red than TR2-03 and the commercial standard. Several metrics were significantly correlated with consistency, including the AIR (%) and the ratio of AIR (%) to TS. These factors may explain the relationships between 'Bugle', TR2-03, and the commercial standard. The AIR (%), which is a measure of polysaccharides (Barnes et al. 2021), was significantly negatively correlated with consistency. Consistency has been shown to depend on the concentration of insoluble solids, especially pectin, in tomato pastes and juices (Anthon et al. 2008;Takada and Nelson 1983) as well as plum juice (Mohammadi-Moghaddam et al. 2020). In this study, we found that 'Bugle' had the highest ratio of AIR (%) to TS, followed by the commercial standard and TR2-03. The higher ratios in the commercial standard and TR2-03 may explain how the purées could have a desirable consistency with a significantly higher moisture content than that of 'Bugle'. Interestingly, 'Dickinson' had a moisture content similar to that of the commercial standard but a significantly smaller ratio of AIR (%) to TS. The negative correlation between the ratio of AIR (%) to TS and consistency explains how 'Dickinson' has poor consistency despite its moisture content being similar to that of the commercial standard. Anthon et al. 2008 also found that, in tomato paste, only removing water is not sufficient to improve consistency. In processing pumpkin, the density of insoluble solids likely plays a similar role.

Cucurbita spp. are generally considered good sources of provitamin A because of their high carotenoid content (Gross 1991). Previous studies have correlated the carotenoid content in *Cucurbita* spp. with CIE $L^*a^*b^*$ values (Itle and Kabelka 2009) and found that L^* is negatively correlated to total carotenoids, a^* is positively correlated to total carotenoids, and b^* is positively correlated to lutein levels. In this study, the colors of purées from both breeding lines were significantly different from those of 'Bugle', especially the L^* values. Representative cans are shown in Fig. 3. 'Bugle' was visually lighter and more yellow than all other purées. 'Dickinson' and the commercial standard had lower L^* values and higher a^* values than those of 'Bugle'. The lower L^*, a^*, and b^* values of TR2-06 could have been affected by the fruit maturity at harvest, but they did not substantially reduce the purée's quality. TR2-06 had L^* and b^* values similar to those of 'Dickinson' and the commercial standard, while TR2-03 had L^*, a^*, and b^* values similar to those of the commercial standard. Considering the important role that some carotenoids play as a source of provitamin A in our diets, these new lines show promise for their nutritional qualities. Additionally, the similar color and overall appearance of purée from TR2-03 compared to the commercial standard (Fig. 3) are likely important for consumer acceptance.

Conclusions

In this study, the effect of germplasm improvement on CPM resistance and processing quality in *C. moschata* was evaluated. Our results demonstrate that the field performance of the improved germplasm is similar to that of the CPM-resistant parent 'Bugle'. Our analysis of the physiochemical properties of the purées from the improved germplasm demonstrated that the improved germplasm resembles 'Dickinson' and the commercial standard. The breeding line with the overall best field performance and canning quality was TR2-03. The new 'Dickinson' × 'Bugle' breeding lines are high-quality processing pumpkins with reduced disease susceptibility and potential as hybrid parents. Research to evaluate the effects of these quality characteristics on their sensory perception is the next step in understanding the quality attributes of improved processing pumpkin germplasm. Color and consistency values should be compared with descriptive sensory analysis findings, especially perception of flavor. Data of quality attributes generated from this study and future sensory studies may be used to advance pumpkin germplasm for commercialization.

References Cited

Anthon GE, Diaz JV, Barrett DM. 2008. Changes in pectins and product consistency during the concentration of tomato juice to paste. J Agric Food Chem. 56(16):7100–7105. https://doi.org/10.1021/jf8008525.

Barnes WJ, Koj S, Black IM, Archer-Hartmann SA, Azadi P, Urbanowicz BR, Peña MJ, O'Neill MA. 2021. Protocols for isolating and characterizing polysaccharides from plant cell walls: A case study using rhamnogalacturonan-II. Biotechnol Biofuels. 14(1):142. https://doi.org/10.1186/s13068-021-01992-0.

Bates D, Mächler M, Bolker B, Walker S. 2015. Fitting linear mixed-effects models using lme4. J Stat Softw. 67(1):1–48. https://doi.org/10.18637/jss.v067.i01.

Cohen R, Hanan A, Paris HS. 2003. Single-gene resistance to powdery mildew in zucchini squash (*Cucurbita pepo*). Euphytica. 130(3):433–441. https://doi.org/10.1023/A:1023082612420.

Contin ME. 1978. Interspecific transfer of powdery mildew resistance in the genus *Cucurbita* (PhD Diss). Cornell University, Ithaca, NY, USA.

Coolong T, Seebold K. 2011. Impact of fungicide program and powdery mildew resistance in three varieties of pumpkin. HortTechnology. 21(5):533–538. https://doi.org/10.21273/HORTTECH.21.5.533.

Dar A, Sofi S, Rafiq S. 2017. Pumpkin the functional and therapeutic ingredient: A review. Int J Food Sci Nutr. 2:165–170.

Dutta D, Dutta A, Raychaudhuri U, Chakraborty R. 2006. Rheological characteristics and thermal degradation kinetics of beta-carotene in pumpkin puree. J Food Eng. 76(4):538–546. https://doi.org/10.1016/j.jfoodeng.2005.05.056.

Featherstone S. 2016. Pumpkins and squash, p 71–74. In: A complete course in canning and related processes (14th ed). Volume 3: Processing procedures for canned food products. Woodhead Publishing, Philadelphia, PA, USA.

Fraeye I, Knockaert G, Buggenhout SV, Duvetter T, Hendrickx M, Loey AV. 2009. Enzyme infusion and thermal processing of strawberries: Pectin conversions related to firmness evolution. Food Chem. 114(4):1371–1379. https://doi.org/10.1016/j.foodchem.2008.11.041.

Gibson M, Newsham P. 2018. Rheology, p 89–103. In: Food science and the culinary arts. Elsevier, Amsterdam, Netherlands.

Gliemmo MF, Latorre ME, Narvaiz P, Campos CA, Gerschenson LN. 2014. Effect of gamma irradiation and storage time on microbial growth and physicochemical characteristics of pumpkin (*Cucurbita moschata* Duchesne ex Poiret) puree. Food Sci Technol Int. 20(1):71–80. https://doi.org/10.1177/1082013212472350.

Gross J. 1991. Pigments in vegetables: Chlorophylls and carotenoids. Van Nostrand Reinhold, New York, NY, USA.

Harrell FE. 2024. Hmisc: Harrell Miscellaneous. R package version 5.1-3. https://CRAN.R-project.org/package=Hmisc.

Holdsworth WL, LaPlant KE, Bell DC, Jahn MM, Mazourek M. 2016. Cultivar-based introgression mapping reveals wild species-derived *Pm-0*, the major powdery mildew resistance locus in squash. PLoS One. 11(12):e0167715. https://doi.org/10.1371/journal.pone.0167715.

Hothorn T, Bretz F, Westfall P. 2008. Simultaneous inference in general parametric models. Biom J. 50(3):346–363. https://doi.org/10.1002/bimj.200810425.

Hultengren RL, Wyatt L, Mazourek M. 2016. A suite of high-quality butternut squash. HortScience. 51(11):1435–1437. https://doi.org/10.21273/HORTSCI10987-16.

Itle RA, Kabelka EA. 2009. Correlation between $L^*a^*b^*$ color space values and carotenoid content in pumpkins and squash (*Cucurbita* spp.). HortScience. 44(3):633–637. https://doi.org/10.21273/HORTSCI.44.3.633.

Itle RA, Kabelka EA, Olmstead JW. 2022. Heritability estimates of $L^*a^*b^*$ color space values in winter squash (*Cucurbita* spp.). HortScience. 57(2):202–214. https://doi.org/10.21273/HORTSCI15961-21.

Karadeniz F, Işık B, Kaya S, Aslanali O, Midilli F. 2024. Kinetics of nonenzymatic browning reactions in pumpkin puree during storage. Gazi University Journal of Science Part A: Engineering and Innovation. 11(1):101–111. https://doi.org/10.54287/gujsa.1400745.

McGrath MT. 2017. Powdery mildew, p 62–64. In: Keinath AP, Wintermantel WM, Zitter TA (eds). PART I: Compendium of cucurbit diseases and pests (2nd ed). Diseases and pests compendium series. The American Phytopathological Society, St. Paul, MN, USA.

Lenth R. 2023. emmeans: Estimated marginal means, aka least-squares means. R package version 1.8.8. https://CRAN.R-project.org/package=emmeans.

Loy JB. 2004. Morpho-physiological aspects of productivity and quality in squash and pumpkins (*Cucurbita* spp.). Crit Rev Plant Sci. 23(4):337–363. https://doi.org/10.1080/07352680490490733.

McGrath MT, Staniszewska H. 1996. Management of powdery mildew in summer squash with host resistance, disease threshold-based fungicide programs, or an integrated program. Plant Dis. 80(9):1044. https://doi.org/10.1094/PD-80-1044.

McCreight JD. 2004. Notes on the change of the causal species of cucurbit powdery mildew in the U.S. https://cucurbit.info/wp-content/uploads/2019/03/cgc27-3.pdf. [accessed 23 Dec 2024.

McFeeters RF, Armstrong SA. 1984. Measurement of pectin methylation in plant cell walls. Anal Biochem. 139(1):212–217. https://doi.org/10.1016/0003-2697(84)90407-x.

Mohammadi-Moghaddam T, Firoozzare A, Parak Z, Mohammad-Nia M. 2020. Physicochemical properties, sensory attributes, and antioxidant activity of black plum peel sharbat as affected by pectin and puree concentrations. Int J Food Properties. 23(1):665–676. https://doi.org/10.1080/10942912.2020.1754235.

Nawirska-Olszańska A, Biesiada A, Sokół-Łętowska A, Kucharska AZ. 2011. Content of bioactive compounds and antioxidant capacity of pumpkin puree enriched with Japanese quince, cornelian cherry, strawberry and apples. Acta Scientiarum Polonorum. 10(1):51–60.

Nistor OV, Mocanu GD, Andronoiu DG, Barbu VV, Ceclu L. 2022. A complex characterization of pumpkin and quince purees obtained by a combination of freezing and conventional cooking. Foods. 11(14):2038. https://doi.org/10.3390/foods11142038.

Paris HS, Cohen R. 2002. Powdery mildew-resistant summer squash hybrids having higher yields than their susceptible, commercial counterparts. Euphytica. 124(1):121–128. https://doi.org/10.1023/A:1015623013740.

Paris HS, Brown RN. 2005. The genes of pumpkin and squash. HortScience. 40(6):1620–1630. https://doi.org/10.21273/HORTSCI.40.6.1620.

Pérez-García A, Romero D, Fernández-Ortuño D, López-Ruiz F, De Vicente A, Torés JA. 2009. The powdery mildew fungus *Podosphaera fusca* (synonym *Podosphaera xanthii*), a constant threat to cucurbits. Mol Plant Pathol. 10(2):153–160. https://doi.org/10.1111/j.1364-3703.2008.00527.x.

R Development Core Team. 2024. R: A language and environment for statistical computing.

R Foundation for Statistical Computing, Vienna, Austria. https://www.R-project.org/.

Reiners S, Ketterings QM, Czymmek KJ. 2019. Nutrient guidelines for vegetables. Animal science publication series no. 249. Cornell University, Ithaca, NY, USA. http://nmsp.cals.cornell.edu/publications/files/VegetableGuidelines2019.pdf. [accessed 23 Dec 2024].

Takada N, Nelson PE. 1983. A new consistency method for tomato products: The precipitate weight ratio. J Food Sci. 48(5):1460–1462. https://doi.org/10.1111/j.1365-2621.1983.tb03516.x.

US Department of Agriculture, Agricultural Research Service. 2017. Canned pumpkin and canned squash grades and standards. https://www.ams.usda.gov/sites/default/files/media/CannedPumpkinandSquashStandard.pdf. [accessed 23 Dec 2024].

US Department of Agriculture, Economic Research Service. 2025. Pumpkins: Background & statistics. https://www.ers.usda.gov/newsroom/trending-topics/pumpkins-background-statistics/. [accessed 23 Dec 2024].

US Department of Agriculture, National Agricultural Statistics Service. 2024. Vegetables 2023 annual summary. https://www.nass.usda.gov/Surveys/Guide_to_NASS_Surveys/Vegetables/index.php. [accessed 23 Dec 2024].

US Food and Drug Administration. 2024. 21 CFR 113.3. https://www.ecfr.gov/current/title-21/part-113/section-113.3. [accessed 23 Dec 2024].