HortScience 60(10):1655–1664. 2025. https://doi.org/10.21273/HORTSCI18689-25

A Unified Crop Ontology for Standardizing Phenotypic Data Collection in Bottle Gourd [*Lagenaria siceraria* (Molina) Standl.]

Marlie E. Lukach
Department of Plant Breeding & Genetics, School of Integrated Plant Science, Cornell University, George McT. Kahin Center for Advanced Research on Southeast Asia, 640 Stewart Avenue, Ithaca, NY 14053, USA

Halit Yetişir
Department of Horticulture, Faculty of Agriculture, Erciyes University, Yenidoğan, Turhan Baytop Sokak No:1, 38280 Talas/Kayseri, Türkiye

Chutchamas Kanchana-Udomkan
Department of Horticulture, Faculty of Agriculture, Kasetsart University Kamphaeng Saen Campus, 1 Moo 6 Tambon Kamphaeng Saen, Amphur Kamphaeng Saen, Nakhon Pathom, 73140, Thailand

Zachary Stansell
Horticulture Section, School of Integrative Plant Science, Cornell University, USDA-ARS, Plant Genetic Resources Unit, 21 Crabapple Dr, Geneva, NY 14456, USA

Moira J. Sheehan
Breeding Insight, Cornell University, CALS Surge Facility, 525 Tower Rd, Ithaca, NY 14053, USA

Jean-Luc Jannink
Department of Plant Breeding & Genetics, School of Integrated Plant Science, Cornell University, Emerson Hall, 236 Mann Dr, Ithaca, NY 14053, USA

Keywords. bottle gourd, calabash, germplasm characterization, ontology, underutilized crops

Abstract. **Underutilized crops have considerable cultural, culinary, and historical value but lack widespread cultivation or extensive research. With these gaps in commercialization efforts, maximizing available information is crucial for breeding adapted and improved cultivars, conserving genetic resources, and, ultimately, promoting broader adoption. Crop ontologies provide a framework for describing a crop's relevant attributes by standardizing data collection protocols across various research endeavors. These ontologies enhance the value of the broader pool of genetic resources and facilitate greater interoperability among collaborative conservation and improvement efforts. To maximize impact, a crop ontology should prioritize the inclusion of traits from markets, cultures, and regions with connections to the given crop. The bottle gourd [*Lagenaria siceraria* (Molina) Standl.] is an underutilized, under-researched crop originating in Africa, but has regional significance across Europe, Asia, and the Americas. We developed a crop ontology for bottle gourds via literature reviews using 35 previous characterization studies from 10 countries, related cucurbit ontologies, and multisite and multiyear collaborative phenotyping efforts with Kasetsart University (Thailand), the US Department of Agriculture National Plant Germplasm System (United States), Cornell University (United States), and the University of Erciyes Melikgazi Kayseri-Türkiye (Turkey). The crop ontology emphasizes traits important for localized use and includes 300 traits that describe vegetative, floral, fruit, and seed phenotypes critical to horticultural variation and culturally diverse uses. Furthermore, our bottle gourd ontology provides a foundation for future conservation and improvement efforts, as well as a framework for creating ontologies that could be applied to other underutilized crops.**

Lagenaria siceraria (Molina) Standl., commonly known as the bottle gourd or calabash, is a vining crop in the Cucurbitaceae family, which broadly includes gourds, watermelons, melons, squash, and cucumbers. Bottle gourds are considered one of the earliest domesticated crops, with their use dating to more than 10,000 years ago (Chomicki et al. 2020). They have been widely adapted to diverse climates and production systems, including nonirrigated deserts, and high-humidity tropical and temperate conditions, with production as far north as Canada and northern Europe. Evidence suggests that bottle gourds originated in southern Africa but traveled across continents and oceans, leading to two additional independent centers of domestication in Eurasia and South America, helping expand their cultural significance to nearly every continent (Kistler et al. 2014; Zhao et al. 2024). Bottle gourds are commonly referred to as underutilized crops because they fit the common definition of crops that are regionally important, often with strong historical and cultural ties, but lack the research and resources for improvement that many major crops such as corn and soy have received (Padulosi et al. 2001).

Despite their modern classification as an underutilized crop, bottle gourds have been used historically by various groups of people for diverse purposes, as demonstrated by its use as a food crop and as a raw material to create a wide array of practical, everyday objects (Fig. 1). As food, the immature fruits, leaves, stems, seeds, and flowers are consumed by humans and animals, and used in traditional medicine (Ahmad et al. 2022; Dilshad and Sunhail 2022; Islam et al. 2021). The mature, dried fruits are used to make durable goods and containers, including water vessels, musical instruments, relics, and art. In addition to bottle gourds' cultural use and use as a food crop, they have also been recognized as a valuable source of rootstock. Bottle gourds have been used to confer abiotic stress tolerance, such as tolerance to salinity (Huang et al. 2009; Yan et al. 2018), drought conditions (Morales et al. 2023), low temperature (Jang et al. 2022), and heavy metals (Nawaz et al. 2018); biotic stress tolerance, which includes resistance to pest and diseases such as powdery mildew (Kousik et al. 2018), gummy stem blight (Mahapatra et al. 2023), root-knot nematodes (Özarslandan et al. 2011), fusarium wilt (Huh et al. 2012), and crown rot (Kousik et al. 2012); increased yield (Karaca et al. 2012; Suárez-Hernández et al. 2022; Yetişir and Sari 2018); and improved nutritional value to other cucurbits (Çandir et al. 2013; Karaca et al. 2012; Mahapatra et al. 2023), most notably watermelons, when used as a rootstock. These resistance traits have additional implications for using bottle gourds as a climate-smart crop, especially in regions affected by drought and increasing temperatures (Mkhize et al. 2024).

Despite the multifaceted importance of bottle gourds culturally and historically, and their source of resistance, global acreage devoted to them is a fraction of major vegetable crops. For example, during 2023, the aggregated group of pumpkins, squash, and gourds—which includes bottle gourds along with a plethora of cucurbit crops from other genera, such as winter squash and pumpkins (*Cucurbita* sp.), winter melons (*Benincasa hispida*), snake gourds (*Trichosanthes cucumerina*), and bitter gourds (*Momordica charantia*)—had a harvested area of only 1.5 million ha, whereas tomatoes alone had an estimated total global area harvested of 13.3 million ha (FAOSTATS 2025). India is one of the largest producers of bottle gourds (Islam et al. 2021). Between 2018 and 2019,

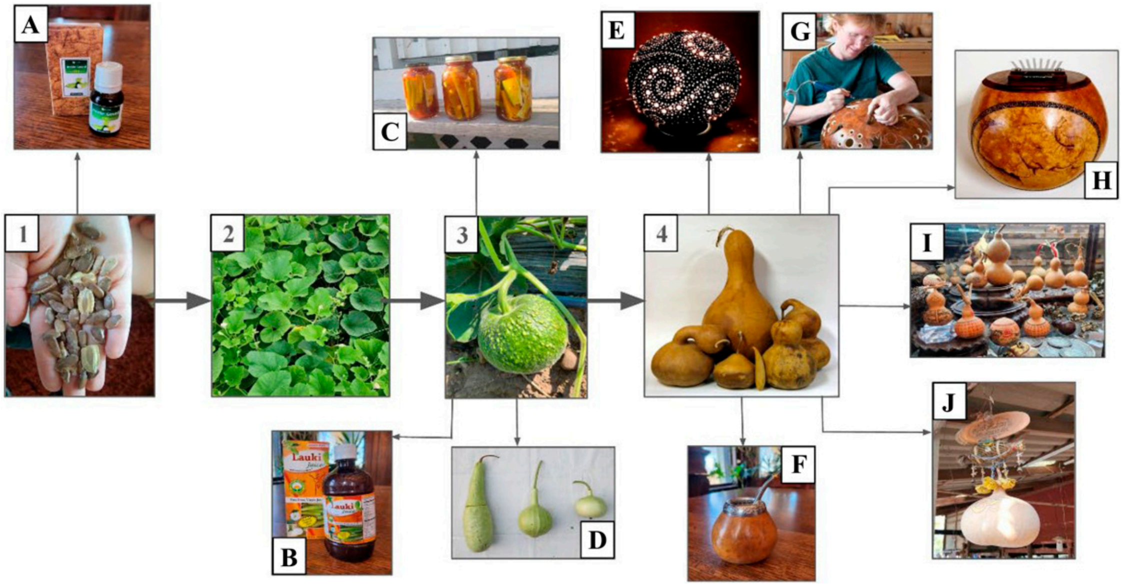

Fig. 1. Variety of uses of bottle gourd at the seed stage (**1**), such as when seed oil is used in traditional medicine (**A**), and at the vegetative stage (**2**), such as stir frying using young leaves (not pictured). During the immature fruit stage (**3**), the juice of immature fruit is used in traditional medicine (**B**) and may also be pickled as *Lauki Ka Achar*, South Asian pickled bottle gourds (**C**). (**D**) In addition, the Thai bottle gourd is used for fresh eating and in soup. During the dried fruit stage (**4**), the gourds can be made into decorative lamps (**E**) and the traditional South American drink maté, which is shown here served in the gourd (**F**). (**G**) Graham Ottoman of Gourdlândia (Ithaca, NY, USA) demonstrates how to carve designs in a dried gourd. (**H**) The gourd may be used to create a *kalimba*, a traditional African instrument. (**I**) Chinese gourds are used for good luck and protection charms. (**J**) Gourds are also displayed as talismans outside the home to afford protection.

bottle gourd production in India comprised ∼186,000 ha of a total estimated 10.1 million ha used for producing vegetable crops, which equates to only ∼1.8% of production (National Horticulture Board Ministry of Agriculture & Farmers Welfare Government of India 2019).

This lack of broad-scale production is a result, in part, of the scarcity of high-performing cultivars. Although many bottle gourd landraces are still used in small-scale subsistence farming and home gardening, few high-performing cultivars have been commercialized for the market. In a survey of several prominent international vegetable seed companies, we found East-West Seed (Nonthaburi, Thailand) has three varieties (East-West Seed 2024), HM Clause (Davis, California, USA) has four varieties in their India program and one variety in their Vietnam breeding program (HM Clause 2025), and Bayer's Indian branch (Maharashtra, India) currently has only a single variety available (Bayer AG 2024). This is in stark contrast to the variety availability in related crops such as squash and pumpkins (*Cucurbita* sp.). Johnny's Selected Seeds (Winslow, Maine, USA), a popular US-based seed company, alone carries 82 squash varieties and 78 pumpkin varieties (Johnny's Selected Seeds 2025).

The issue of germplasm accessibility is also present in germplasm repositories worldwide. Although there are germplasm repositories that hold hundreds of bottle gourd germplasm, many of the accessions are unavailable for distribution, and those that can be requested for research purposes have limited characterization data available (Table 1). Currently, the US Department of Agriculture (USDA) National Plant Germplasm System (NPGS) Germplasm Resources Information Network (GRIN)–Global (USDA-ARS 2025a) holds the most known available accession of bottle gourd with 197 accessions. Of these 197 accessions, only three have seed images, and 97 accessions have limited fruit and maturity metrics. Similar trends were observed across other bottle gourd collections, with only a handful of accessions having available information. This lack of data makes it difficult for germplasm curators, growers, plant breeders, and other researchers to make informed choices about which accessions capture specific aspects of diversity or target particular market types. Whether it be creating a core collection of the accessions that capture the maximum amount of diversity, breeding better regionally adapted cultivars, or better understanding pathways of secondary metabolites, without characterization data, picking accessions that are ideal candidates for the research is like drawing names blindly from a hat.

Underutilized crops such as bottle gourds face significant barriers to research and conservation because of a lack of information, be that for characterized germplasm, standardized and accessible passport, phenotypic data, and a limited research community. This dynamic creates a challenging, Catch-22–type cycle that underutilized crops face toward improvement efforts. Despite their cultural importance and potentially high societal or economic value, data on underutilized crops are frequently limited. In some cases, no data may be available, whereas in others, data are poorly documented and stakeholders have limited familiarity with the crop or a poor understanding of its contextual use. This paucity of preliminary research can, in turn, limit new public investment in research, creating additional barriers to knowledge acquisition that are required to drive broad adoption.

This is incredibly challenging for crops with traits that vary by market, region, or culture. For instance, the lack of consistency in terminology for descriptors such as crunchy or hard to describe fruit texture can lead to vastly different interpretations and perceptions of desirability, depending on linguistic and cultural contexts. A single trait may go by multiple synonyms or name variations. Across crops, traits to measure seed weight may be called "100 grain weight," "weight of 100 seeds," or "hundred-seed dry weight" (Andrés-Hernández et al. 2021). All three could be listed separately, but essentially measure the same underlying phenotype. When researchers work with underutilized crops, even using existing terminology for other crops can create confusion, as one trait may be assigned multiple names depending on the resource used to select the terminology.

Received for publication 30 Apr 2025. Accepted for publication 24 Jun 2025.
Published online 29 Aug 2025.
Funding for this work was provided by the US Department of Agriculture (USDA)–Agricultural Research Service (ARS) Crop Germplasm Committee grant (agreement no. 58-8060-2-008) "Characterization of Bottle Gourd (*Lagenaria siceraria*) Accessions" and USDA Foreign Language and Area Studies Fellowship stipend funding. Breeding Insight is a USDA-ARS initiative hosted by Cornell University and supported by the USDA (agreement nos. 8062-21000-043-004-A, 8062-21000-052-002-A, and 8062-21000-052-003-A).
We thank the American Gourd Society members for reviewing the ontology and providing feedback, as well as Graham Ottoson for allowing us to use her images of bottle gourd uses for Fig. 1.
M.E.L. is the corresponding author. E-mail: ml946@cornell.edu/marlielukach@gmail.com.

Table 1. Germplasm repositories with bottle gourd accessions.

Germplasm repository	Location	Accession (including unavailable and historical)	No. of available accessions	Characterization information provided	Link
Kenya Agriculture and Livestock Research Organization (KALRO)	Kenya	478	32	Location accessions collected	See Kenya Agricultural & Livestock Research Organization (2024)
USDA National Plant Germplasm System GRIN-Global	United States	500	197	Location accessions collected. Ninety-seven 97 accessions have limited data on fruit shape, size, and maturity. Three accessions have seed images.	See US Department of Agriculture–Agricultural Research Service (2025a)
Tropical Vegetable Research Center at Kasetsart University Kamphaeng Saen	Thailand	Unknown	114	Location accessions collected. Comprehensive data on fruit, flower, seed, and vegetative traits on most accessions. Not available to the public.	NA
World Vegetable Center	Taiwan	390	129	Location accessions collected. Two accessions have fruit images.	See World Vegetable Center (2025)
India Counsil of Agricultural Research–National Bureau of Plant Genetic Resources	India	780	Unknown	Location accessions collected. Limited data on fruit, flower, seed, and vegetative traits on some accessions.	See National Bureau of Plant Genetic Resources–Indian Council of Agricultural Research (2012)
Leibniz Institute of Plant Genetics and Crop Plant Research	Germany	73	73	Location most accessions collected. Comprehensive data on fruit, flower, and vegetative traits on 17 accessions. Thirty-seven accessions include a photo of fruit.	See IPK Gatersleben (2020)
Genetic Resources Center, National Agriculture and Food Research Organization (NARO)	Japan	155	132	Location accessions collected. Comprehensive data on fruit, flower, seed, and vegetative traits on 18 accessions. Fifteen accessions include various photos.	See Genebank project, NARO (2025)
Instytut Hodowli i Aklimatyzacji Roślin National Center for Plant Genetic Resources: Polish Gene Bank	Poland	2	2	Location accessions collected.	See Instytut Hodowli i Aklimatyzacji (2025)

GRIN = Germplasm Resources Information Network; KPS = Kamphaeng Saen; NA = not applicable; USDA = US Department of Agriculture.

Ontologies play a crucial role in addressing these challenges. Crop ontologies (sometimes called trait ontologies) provide a systematic framework and vocabulary for standardizing data collection and making information more findable, accessible, interoperable, reusable (FAIR) and, in cases of culturally important crops, include collective benefit, authority to control, responsibility, ethics—or CARE—principles (Carroll et al. 2020; Hauschke et al. 2021). By creating universal crop descriptors that cover attributes such as fruit shape, texture, and taste, researchers can ensure that data from different studies are comparable and useful across regions, disciplines, and market types. These standardized descriptors serve as a foundation for further research, promoting collaboration and unlocking the full potential of crops such as bottle gourds.

We developed a bottle gourd crop ontology with three core objectives: 1) to strive to capture comprehensively all relevant crop attributes to all stakeholders across market classes and end uses, 2) to generate a standardized and well-defined data structure to maximize data comparison and utility across regions and disciplines, and 3) to provide a foundational framework for further research, promote collaboration, and improve the accessibility of bottle gourds on a global scale. Through the development and application of a comprehensive and precise crop ontology, bottle gourds can transition from an underutilized crop to one with renewed global significance, bridging the gap between traditional knowledge and modern agricultural research with FAIR public data.

Materials and Methods

Globally, only a few breeding programs focus on bottle gourds, with limited international cooperation through consortia or agency-based collaboration. Therefore, a literature review was conducted to generate an initial, broad, and inclusive preliminary list of traits. Google Scholar was used to find articles because of its ability to search for articles across both major and minor journals. Search terms related to crop descriptors, characterization, diversity, and variation were used to identify papers containing trait information, including *Lagenaria*, bottle gourd, gourd, germplasm, characterization, crop description, trait description, morph*, diversity, and variet*. Searches included articles written at any time, and articles were sorted by relevance to the search terms. Searches were limited to articles written in or translated into English. The articles identified from the initial search were filtered to only those that contained characterization data and/or trait descriptions, from which "raw" traits were extracted.

Each raw trait was compared with other similarly described raw traits and merged where overlap occurred. For traits with multiple names, the most commonly used name was maintained as the primary name, with any other variant names recorded in the Synonyms column of the crop ontology template. Each raw trait was added to the crop ontology format created by Breeding Insight, which was simplified based on the full template from Pietragalla et al. (2024). Raw traits that appeared to assess more than one trait were broken into multiple, separate traits to improve clarity and specificity. To annotate trait frequency and market-specificity more comprehensively, raw traits were ranked by frequency across the selected articles used for trait extraction and grouped by trait type (e.g., seed, vegetative, flower, root, fruit).

Additional trait information was collected directly from stakeholders from several countries to increase the global scope. The American Gourd Society (Kokomo, IN, USA), curators from the USDA NPGS (Geneva,

Table 2. List of studies for trait references.

Citation	Year	Location	No. of accessions	Seed traits	Vegetative traits	Flower traits	Fruit traits	Root traits
Abhishek et al. (2020)	2020	India	52	—	X	X	X	—
Ali et al. (2020)	2020	Pakistan	3	—	X	—	—	X
Buthelezi et al. (2019)	2019	South Africa	14	X	X	X	X	—
Chakraborty and Chaurasiya (2023)	2023	India	30	X	X	X	X	—
Chimonyo and Modi (2013)	2013	South Africa	6	X	X	—	X	—
Decker-Walters et al. (2000)	2000	United States	74	X	—	—	X	—
Dubey et al. (2022)	2022	India	30		X	X	X	—
Gbotto et al. (2022)	2022	Côte d'Ivoire	173	X	X	—	X	—
Ghorpade et al. (2019)	2019	India	21	—	—	—	—	—
Harika et al. (2012)	2012	India	25	X	X	X	X	—
Ibrahim (2021)	2021	Egypt	12	—	—	—	X	—
Ibrahim et al. (2024)	2024	Egypt	10	—	X	—	—	—
Iqbal et al. (2018)	2018	Pakistan	10	—	X	X	X	—
Kalyanrao et al. (2016)	2016	India	15	X	X	X	X	—
Kandasamy et al. (2019)	2019	India	20	X	X	X	X	—
Koffi et al. (2009)	2009	Côte d'Ivoire	30	X	X	X	X	—
Kumar et al. (2024)	2024	India	24	X	X	X	X	—
Mahapatra et al. (2022)	2022	India	91	X	X	X	X	—
Mashilo et al. (2017)	2017	South Africa	36	—	—	—	X	—
Maurya et al. (2020)	2020	India	28	—	X	X	X	—
Mladenovic et al. (2012)	2012	Serbia	40	X	X	—	X	—
Morapedi (2021)	2021	Botswana	5	X	X	X	X	—
Morimoto et al. (2005)	2005	Kenya	425	X	—	—	X	—
Raghu et al. (2018)	2018	India	4	X	X	X	X	—
Ram et al. (2007)	2007	India	25		X	X	X	—
Rambabu et al. (2017)	2017	India	21	X	X	X	X	—
Sachin et al. (2017)	2017	India	31	—	X	—	X	—
Sari et al. (2021)	2021	United States	163	X	—	—	—	—
Sharma and Sengupta (2013)	2013	India	16	—	X	X	X	—
Sivaraj and Pandravada (2005)	2005	India	54	X	—	—	X	—
Taş et al. (2018)	2018	Turkey	322	X	X	X	X	—
Thakur et al. (2015)	2015	India	22	—	X	X	X	—
Yetişir and Aydin (2019)	2019	Turkey	22	X	—	—	X	—
Yetişir et al. (2008)	2008	Turkey	182	X	X	X	X	—

NY, USA & Griffin, GA, USA), the Tropical Vegetable Research Center at Kasetsart University Kamphaeng Sean, Thailand and the Department of Horticulture Faculty of Agriculture of the Kayseri, Türkiye provided feedback on the ontology. Traits in the ontology were also compared with existing crop descriptor guides for bottle gourds and related cucurbit (e.g., *Cucurbita* sp.) species from the Protection of Plant Varieties and Farmers' Rights Authority Government of India, NPGS GRIN-Global, European Cooperative Program of Plant Genetic Resources, and the Tropical Vegetable Research Center at Kasetsart University Kamphaeng Saen.

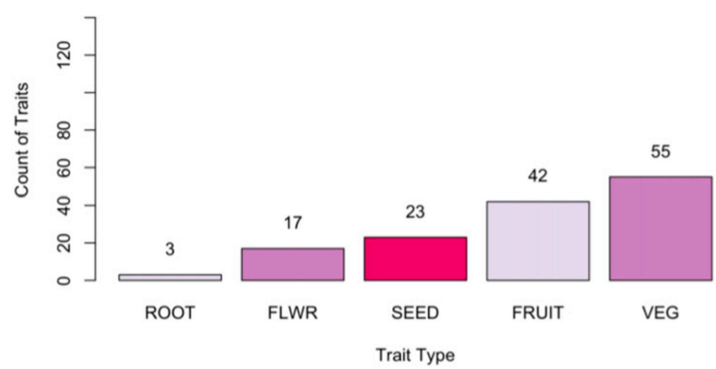

Fig. 2. Ranking of the 140 final raw traits from the literature review base on trait type: root, flower (FLWR), seed, fruit, and vegetative (VEG).

Results

The initial literature search yielded ~70 articles with search term hits. All initial articles found were written or translated into English. After reviewing each article, 35 contained characterization data and/or trait descriptions (Table 2). Together, these articles represented the phenotypic evaluation of bottle gourd germplasm from 10 different countries across four continents: Africa, Asia, Europe, and North America.

A total of 154 raw traits were initially extracted from the literature. Overlapping traits were merged, and one trait was removed, because of a lack of description of what the trait measured, which resulted in a final total of 140 raw traits. Each trait was grouped by trait type, with the categories being seed, vegetative,

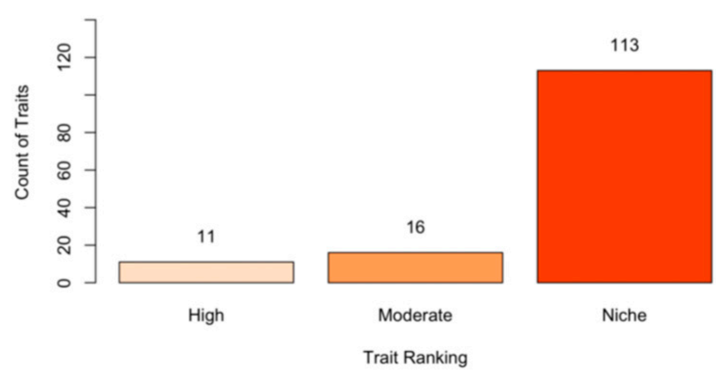

Fig. 3. Ranking of the 140 final raw traits from the literature review based on frequency of appearance in the articles, with High being the most frequently found traits and Niche appearing in five articles or less.

flower, root, and fruit (Fig. 2). Approximately 40% of the raw traits (55 of 140) were categorized under vegetative traits, which included metrics on the leaves, vines, tendrils, peduncles, cotyledons, and hypocotyls. The next largest category was fruit traits, which was 30% (n = 43) of the total traits, and included measures of fruit dimensions, coloring and pattern of the skin, flesh texture and nutritional qualities, and yield. Root, flower, and seed categories represented the smallest percentage of traits: ~2%, ~12%, and ~16%, respectively. Flower traits included 17 traits that represented flower dimensions, flowering date, number of flowers, and flower color. The 23 seed traits spanned whole seed and embryo dimensions, color, texture, and germination metrics. The root trait category included only three traits: root length, root fresh mass, and root dry mass.

The 140 raw traits were also ranked based on the number of appearances across the selected literature to understand more fully the utility of traits (general vs. niche) (Fig. 3).

High-general traits were found in at least ~43% of the articles and included only 11 of the 140 raw traits. These high-general traits included basic dimensions of seeds, vines, and fruit, as well as flowering dates (Table 3). The rank of moderate-general traits included 16 traits found in ~17% of the articles. Moderate-general traits included additional fruit phenotypes, such as shape and color, and leaf phenotypes (Table 3). The remaining 113 traits were categorized as niche traits, with limited appearances (in five articles or fewer). These niche traits addressed the diverse uses of bottle gourds, including disease resistance pertinent to locale, nutritional quality, and more detailed morphology such as the shape, color pattern, and texture of fruits, seeds, and leaves. The high number of niche traits was anticipated because of the vast diversity of market types and uses of bottle gourds at different life stages and across cultures.

After further assessment of trait and method descriptions, additional refinement was necessary to resolve more overlapping traits and create new, separate traits that measured multiple phenotypes. This refinement resulted in a total of 198 traits that were sent to stakeholders for more feedback. From these responses, and by comparing to existing bottle gourd and related cucurbit trait descriptor guides, additional traits were added for a grand total of 300 traits. The full workflow process of annotation is summarized in Fig. 4.

The bottle gourd crop ontology includes traits for vegetative structures, flowers, fruits, seeds, and roots, and covers a broad range of measurements such as size, color, olfactory, density, nutrition, texture, and disease and pest resistance (Figs. 5 and 6). The ontology is included in Supplemental File 1, and method description citations in Supplemental File 2. The ontology will be made available through the US Department of Agriculture–Agricultural Research Service (2025b).

Table 3. Rank of raw traits classified under general utility.

Trait	Rank	No. of appearances	Trait type
Fruit length	High	25	Fruit
Fruit width	High	25	Fruit
Fruit weight	High	20	Fruit
Vine length	High	19	Vegetative
Days to first pistillate flower	High	18	Flower
Fruit per unit (plot/plant)	High	18	Fruit
No. of vines	High	18	Vegetative
Seed mass	High	17	Seed
Seed width	High	16	Seed
Seed length	High	16	Seed
Days to first staminate flower	High	15	Flower
No. of seeds per fruit	Moderate	12	Seed
Days to first immature fruit harvest	Moderate	12	Vegetative
No. of nodes to first pistillate flower	Moderate	11	Flower
Fruit shape	Moderate	11	Fruit
Internode length	Moderate	10	Vegetative
Leaf width	Moderate	10	Vegetative
Leaf length	Moderate	10	Vegetative
Primary fruit color	Moderate	9	Fruit
Blossum end shape	Moderate	8	Fruit
Peduncle length	Moderate	8	Vegetative
Leaf shape	Moderate	7	Vegetative
Leaf margin type	Moderate	7	Vegetative
Pubescence of upper leaf surface	Moderate	7	Vegetative
No. of nodes to first staminate flower	Moderate	6	Flower
Stem end shape	Moderate	6	Fruit
Pubescence of lower leaf surface	Moderate	6	Vegetative
Fruit flesh Brix	Niche	5	Fruit
Fruit rind thickness	Niche	5	Fruit
Percent germination	Niche	5	Seed
Petiole length	Niche	5	Vegetative
Date of last fruit harvest	Niche	5	Vegetative
Male flower diameter	Niche	4	Flower
Female flower diameter	Niche	4	Flower
No. of female flowers	Niche	4	Flower
No. of male flowers	Niche	4	Flower
Neck presence	Niche	4	Fruit
Fruit texture	Niche	4	Fruit
Ascorbic acid fruit content	Niche	4	Fruit
Seed shape	Niche	4	Seed
Seed thickness	Niche	4	Seed
Days to germination	Niche	4	Seed
Stem shape	Niche	4	Vegetative
Tendril branching	Niche	4	Vegetative
Male flower length	Niche	3	Flower
Female flower length	Niche	3	Flower
Ovarium length	Niche	3	Flower
Neck length	Niche	3	Fruit
Fruit wart presence	Niche	3	Fruit
Total seed mass	Niche	3	Seed
Seed color	Niche	3	Seed
Growth habit	Niche	3	Vegetative
Stem pubescence	Niche	3	Vegetative
No. of leaves	Niche	3	Vegetative
Hypocotyl height	Niche	3	Vegetative
Placement of female flower	Niche	2	Flower
Sex type	Niche	2	Flower
Sex ratio	Niche	2	Flower
Flower color	Niche	2	Flower
Days to fruit maturity	Niche	2	Fruit
No. of sellable fruit	Niche	2	Fruit
Degree of neck bending	Niche	2	Fruit
Secondary fruit color	Niche	2	Fruit
Fruit color pattern	Niche	2	Fruit
Fruit ridge presence	Niche	2	Fruit
Fruit pubescence	Niche	2	Fruit
Fruit flesh texture	Niche	2	Fruit
Fruit gelatinous flesh presence	Niche	2	Fruit
Seed cavity diameter	Niche	2	Seed
Seed texture	Niche	2	Seed
Leaf protein content	Niche	2	Vegetative
No. of nodes on main vine	Niche	2	Vegetative

(Continued on next page)

Table 3. (*Continued*)

Trait	Rank	No. of appearances	Trait type
Peduncle shape	Niche	2	Vegetative
Peduncle attachment	Niche	2	Vegetative
No. of leaf lobes	Niche	2	Vegetative
Chlorophyll content	Niche	2	Vegetative
Photosynthetic rate	Niche	2	Vegetative
Fresh shoot mass	Niche	2	Vegetative
Dry shoot mass	Niche	2	Vegetative
Tendril type	Niche	2	Vegetative
Hypocotyl width	Niche	2	Vegetative
Cotyledon length	Niche	2	Vegetative
Cotyledon width	Niche	2	Vegetative
Ovarium diameter	Niche	1	Flower
Inflorescence type	Niche	1	Flower
No. of harvests of sellable fruit	Niche	1	Fruit
Length of fruit from blossom end to widest point	Niche	1	Fruit
Fruit volume	Niche	1	Fruit
Fruit shape variation	Niche	1	Fruit
Fruit luster	Niche	1	Fruit
Degree of warts	Niche	1	Fruit
Degree of corrugation	Niche	1	Fruit
Fruit flesh thickness	Niche	1	Fruit
Presence of sweet fruit flesh taste	Niche	1	Fruit
Presence of bitter fruit flesh taste	Niche	1	Fruit
Fruit flesh total sugar content	Niche	1	Fruit
Fruit flesh carbohydrate content	Niche	1	Fruit
Fruit flesh dry matter content	Niche	1	Fruit
Root length	Niche	1	Root
Root fresh mass	Niche	1	Root
Root dry mass	Niche	1	Root
Seed coat thickness	Niche	1	Seed
Seed embryo mass	Niche	1	Seed
Seed embryo width	Niche	1	Seed
Seed embryo length	Niche	1	Seed
Seed lignin content	Niche	1	Seed
Seed electrical conductivity	Niche	1	Seed
Seed imbibition	Niche	1	Seed
Seed margin	Niche	1	Seed
Seed margin color	Niche	1	Seed
Seed wings	Niche	1	Seed
Seed lines	Niche	1	Seed
Leaf isozymes	Niche	1	Vegetative
Leaf phenolic content	Niche	1	Vegetative
Leaf free amino acid content	Niche	1	Vegetative
Vine length to first fruit	Niche	1	Vegetative
Vine width at first fruit	Niche	1	Vegetative
Internodes per vine	Niche	1	Vegetative
Pedicel length	Niche	1	Vegetative
Days to fruit set	Niche	1	Vegetative
Petiole diameter	Niche	1	Vegetative
Fruit set per node	Niche	1	Vegetative
Male flower peduncle length	Niche	1	Vegetative
Female flower peduncle length	Niche	1	Vegetative
Peduncle persistence	Niche	1	Vegetative
Leaf lobe type	Niche	1	Vegetative
Leaf blistering	Niche	1	Vegetative
Secondary leaf color	Niche	1	Vegetative
Transpiration rate	Niche	1	Vegetative
Stomatal conductance	Niche	1	Vegetative
Shoot moisture	Niche	1	Vegetative
Shoot length	Niche	1	Vegetative
Tendril presence	Niche	1	Vegetative
Tendril length	Niche	1	Vegetative
Cotyledon leaf area	Niche	1	Vegetative
Cotyledon color	Niche	1	Vegetative
Cotyledon position	Niche	1	Vegetative
Early plant vigor	Niche	1	Vegetative
Leaf pubescence type	Niche	1	Vegetative

Discussion

Species that have been able to adapt to a wide range of areas and have historical use, but have been neglected in recent times, are among our most essential resources in the fight against climate change and its consequences for human and animal nutrition. Bottle gourds, which have a cultural age of 12,000 years (Erickson et al. 2005), are one of the most widely recognized underutilized species, with their vibrant history and diversity of cultural uses that span across continents. Creating common ontological standards and a unified scientific language for the identification and evaluation of underutilized species is a valuable and impactful effort in terms of public data and scientific communication.

Our bottle gourd crop ontology provides a critical resource to help renew the bottle gourd's global significance by leveraging data across available studies and small but active research programs. This comprehensive ontology encompasses 300 traits that relate to all stages of plant life, and represents diverse uses and market types. Although the most common traits included in studies focus on metrics often collected on plants targeting high fruit yield, there is a vast range of aims for bottle gourd breeding programs. These potential breeding targets can be identified by the majority of their traits in the ontology classified as niche. These niche traits represent regionally important breeding goals, including the production of edible seed, improving the nutritional quality of edible greens, and preserving diversity for cultural uses. By encompassing traits of all market types of bottle gourds, the ontology can be used to meet the needs of breeders, researchers, farmers, and other stakeholders across markets, regions, and cultures.

The ontology can take its impact a step further by facilitating the creation of a common practice for data collection. Collecting data by adhering to a crop ontology provides a standardized procedure for measuring traits and replicating those measurements from season to season. Standardization of collection renders the resulting data more valuable, allowing for the aggregation of data from studies across disciplines, regions, and time periods to perform more in-depth analyses. Without this standardization, crop data are disjointed, requiring researchers to spend excessive time aligning data from different studies, even in the best cases, or having to discard or ignore uninterpretable data in the worst cases. Data standardization is crucial for overcoming research barriers and improving accessibility in underutilized crops. As many studies currently done on underutilized crops such as the bottle gourd collect data on a small pool of germplasm grown locally, having the capacity to pool data from many small-scale studies can provide more power to accomplish large-scale research objectives. Instead of having intelligible, accessible data on only 10 to 30 varieties of the crop, combining data collected using a standardized procedure across multiple studies allows for the creation of a richer dataset that contains hundreds of varieties across various locations.

Although the current state of global bottle gourd research has been fragmented, future studies can be aligned easily by using our ontology. Because the ontology was built on current and past research, it may also serve as a helpful tool in deciphering synonymous traits to make the dataset more compatible and to create larger, accessible datasets. Larger compatible datasets lay the foundation for creating digital resources that combine phenotypic and genomic

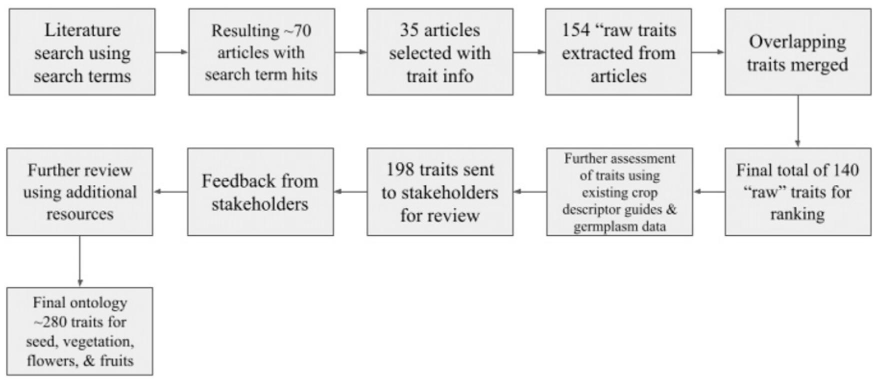

Fig. 4. Crop ontology workflow beginning with the literature search and ending an ontology based on ∼280 traits.

data for researchers, breeders, and other stakeholders, such as the Sol Genomic Network for Solanaceae family crops, which holds genetic and trait data, and has analysis tools for Basic Local Alignment Search Tool (BLAST), genome browsers, and quantitative trait loci (QTL) analysis all combined into an online user-friendly interface (Fernandez-Pozo et al. 2015). When working with a larger dataset, more substantial objectives can be achieved. Compiled datasets from ontologies can provide the foundation for integrating phenotypic data with genetic and genomic datasets. Integrating these datasets catalyzes breeding programs, enabling trait–marker associations, QTL mapping, and genome-wide association studies. By using these methodologies, improved cultivars that are disease resistant, high yielding, and locally adapted can be developed more efficiently, facilitating widespread accessibility of the crop and connecting cultural knowledge with genomic data, while exploring new market opportunities for using the crop. Some of the groundwork has already been completed, with a range of smaller scale international studies already published on resistance to stressors present in bottle gourd populations. These studies can be combined using the bottle gourd ontology as a reference and by adding to the ontology when needed. When combined with genomic data, we can begin to build a unified phenotypic and genomic resource for bottle gourds.

These compiled datasets are also foundational resources for gene banks. Germplasm accessions that have more characterization data are correlated with higher "useful"(-ness) to requestors (Rubenstein et al. 2006). Standardized phenotypic data collected on accessions allows researchers to narrow the scope of which accessions to request for a project (Byrne et al. 2018). Instead of picking accessions randomly from a database, researchers can target accessions that have, or do not have, the trait of interest, because the phenotypic data from screening of the germplasm collection has been collected and made available. Unified phenotypic data can also be used to understand more fully the diversity of the collection and the creation of core collections that capture the maximum amount of diversity in the collection as a whole in an easy-to-work-with, smaller subset of accessions (Byrne et al. 2018). Using the crop ontology developed for bottle gourds, germplasm repositories with large collections of bottle gourd germplasm, such as those held by the World Vegetable Center and USDA NPGS, could characterize germplasm and create core collections that allow for data-informed decisions on what germplasm to prioritize to improve conservation of genetic and phenotypic diversity.

Despite the potential opportunities derived from using crop ontologies, currently there are a lack of crop ontologies or other unified resources available for evaluating underutilized crops (Ali and Bhattacharjee 2023). The methods detailed here for creating the bottle gourd ontology can serve as a template or starting point for other underutilized crop species and cucurbit species that currently lack a crop ontology. For example, *Cucurbita* sp. (winter squash) does not have a crop ontology, but has similar life stage end uses as bottle gourds, such as the use of immature fruit for eating and the use of mature fruit for art. Although there will be traits that will not overlap, the abundance of uses for bottle gourds creates an ontology with a far greater diversity of traits across all plant life stages that may not or need not be represented in other crops.

Crop ontologies are essential resources for underutilized crops, but further work is needed to optimize the use of these species. Crop ontologies are often viewed as a living document, such that they can be changed and adapted over time as new technological advances, methods, and breeding objectives or market types necessitate the addition of new traits and the depreciation of outdated or obsolete traits. In some cases, refinement of a trait description might be warranted, because a better understanding of the trait's underlying biology may change how the trait should be measured. As these shifts occur in research, crop ontologies must also be allowed to adapt and expand. This requires an infrastructure to be implemented to ensure crop ontologies are updated routinely. Currently, there is no existing organization that oversees this needed periodic review, with the exception of cropontology.org, which only oversees cop ontologies for 36 crops.

Additional resources can help optimize even further the use of crop ontologies. Crop ontologies typically prioritize computer readability to support statistical analysis, data validation, integration with other "-omics" data classes, and applications of high-throughput phenotyping approaches such as remote sensing and Field Book App (Rife and Poland 2014). Although the ontology contains human-readable information (e.g., trait descriptions,

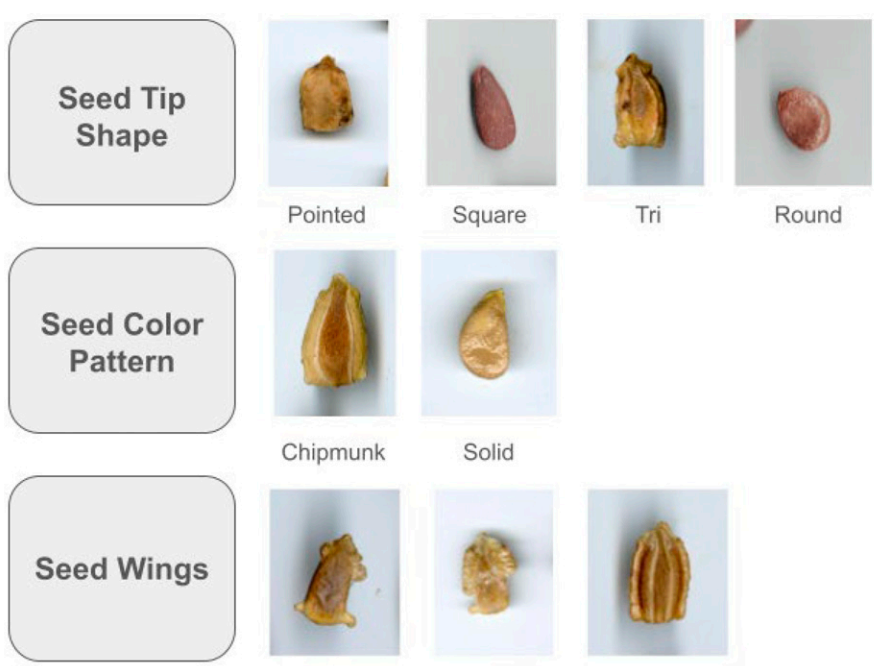

Fig. 5. Examples of seed traits included in the bottle gourd crop ontology, including seed tip shape (**top row**), seed color pattern (**middle row**), and Seed wings - excess seed coat protruding from the margin of the seed (**bottom row**).

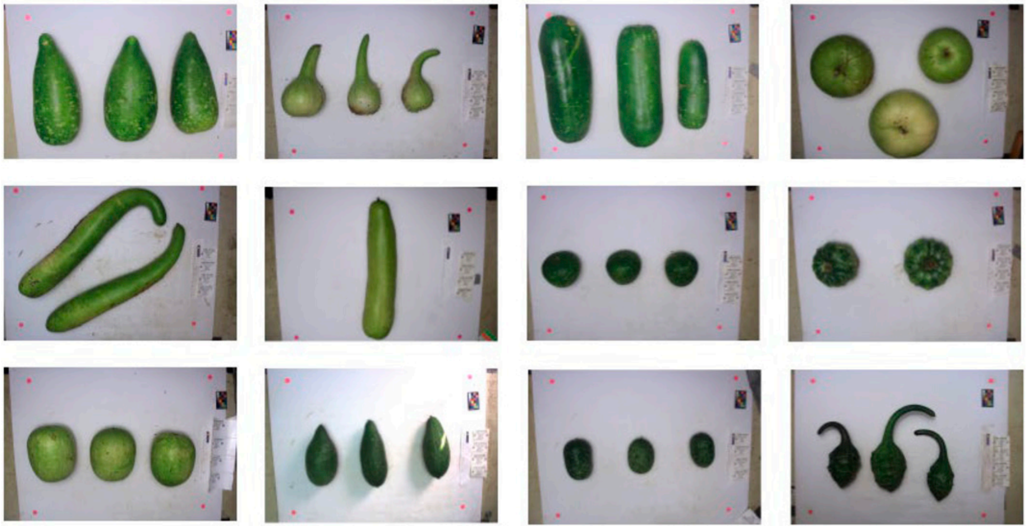

Fig. 6. Examples of the diversity of bottle gourd fruit. From standardized phenotyping methods, fruit metrics such as shape, color, pattern, dimension, luster, and texture can be extracted from a single image.

brief descriptions of the methods used to collect the trait, citations), the ontology itself may not provide sufficient details to understand and replicate the phenotyping protocol comprehensively. Crop descriptor guides are another helpful tool to supplement a crop ontology, emphasizing human readability. Compared with the spreadsheet format of a crop ontology, a crop descriptor guide is generally prepared in a text-rich document format, such as PDF, HTML, or markdown, with in-depth descriptions or discussion, photographs, and supporting URLs. These guides train scientists and technicians on how to break down the evaluation process into steps, with photos or vector images to help the user replicate complex protocols or discern different phenotypes, although they are cumbersome to manage or reference in the field. Combined with a crop descriptor guide, crop ontologies provide a comprehensive set of instructions on how to collect data for a crop that adheres to FAIR data principles.

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